LITHOS 398-399 (2021) 106296

Contents lists available at ScienceDirect

LITHOS

journal homepage: www.elsevier.com/locate/lithos

Research Article

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

Hadi Shafaii Moghadam [a,b,*], Robert J. Stern [c]

[a] School of Earth Sciences, Damghan University, Damghan 36716-41167, Iran
[b] FB4–Dynamics of the Ocean Floor, GEOMAR, Helmholtz-Zentrum für Ozeanforschung Kiel, Wischhofstr. 1-3, Kiel 24148, Germany
[c] Geosciences Dept. University of Texas at Dallas, Richardson, TX 75083-0688, USA

ARTICLE INFO

Keywords:
Subduction initiation
Late Cretaceous ophiolites
Neotethys
Back-arc
Iran

ABSTRACT

Subduction initiation (SI) requires the sinking of one plate beneath another and this exerts extensional stress on the overlying plate. How broad a region is affected by SI-related extension is unclear because most of the clearest SI examples– such as Izu-Bonin-Mariana arc– are deep under the ocean. A major SI event is recorded in the Late Cretaceous forearc ophiolites of Iran, related to the subduction of Neotethyan oceanic lithosphere beneath Eurasia. This caused extreme extension of the Iranian plate, up to ~1000 km away from the proto-trench and generated a series of back-arc oceanic basins, sedimentary basins, and core complexes and exhumed high-P rocks. The Late Cretaceous Iran example shows that SI can cause strong extension over a much wider region of the overriding plate than heretofore imagined and offers an accessible natural laboratory for studying SI processes. This understanding also provides an attractive new explanation for the origin of the South Caspian Sea.

1. Introduction

Earth's tectonic plates are largely driven by the sinking of oceanic lithosphere in subduction zones (Coltice et al., 2019), so understanding how new subduction zones form is critical for understanding plate tectonic theory. Key constraints for reconstructing subduction initiation (SI) involve understanding how this leads to extreme extension of the overriding plate (Arculus et al., 2019; Gerya et al., 2015). Much of our understanding of SI comes from studying the Izu-Bonin-Mariana (IBM) forearc. This formed during early Eocene (~50 Ma) SI of the Pacific Plate beneath the eastern Philippine Sea Plate (Ishizuka et al., 2014). Forearcs of intra-oceanic convergent margins like the IBM convergent margin are natural foci for SI research because these inner trench slopes expose crust and upper mantle (Stern et al., 2012). However, Eocene SI-related crust was recently discovered in the Amami Basin where IODP 351 was drilled (Hickey-Vargas et al., 2018), far behind the IBM convergent plate margin. These results suggest that SI-related extension affects a broader region of the overriding plate than heretofore imagined.

Realistic numerical models are essential for understanding SI (e.g., (Nikolaeva et al., 2008)). However, we cannot construct realistic numerical models for SI unless and until we understand how extensional strain is distributed in the overriding plate. Because the evidence for SI-related extension in intra-oceanic convergent margins lies in deep water and is buried beneath thick sediments, it is difficult to identify regions of SI-related extension away from the trench without drilling. It is much easier to evaluate upper plate SI-related extension on land for a convergent margin where SI is documented. The Late Cretaceous tectonic evolution of Iran provides such an opportunity (Moghadam and Stern, 2011). The distribution and timing of Late Cretaceous Iranian ophiolites and extensional basins provide important insights for understanding SI-related upper plate extension.

This paper addresses this problem by summarizing geochronological data and synthesizing these with existing information for the well-exposed Late Cretaceous SI-related extensional regime of Iran. Iran is part of the overriding plate in the Eurasia-Arabia convergent margin. The main aim of this study is to understand the extensional regimes that affected what is now the forearc (e.g., Late Cretaceous Zagros ophiolites) and the back-arc regions as far as the Caspian Sea. We are especially interested to know the width of the upper plate region that was affected by SI-related extension and how long this extension continued. We show that Late Cretaceous ophiolites of Iran may be the best place in the world to study how SI-related extension is distributed across the upper plate. An interesting benefit of this study is that it explains how the southern

* Corresponding author at: School of Earth Sciences, Damghan University, Damghan 36716-41167, Iran.
E-mail address: hadishafaii@du.ac.ir (H.S. Moghadam).

https://doi.org/10.1016/j.lithos.2021.106296
Received 20 April 2021; Received in revised form 9 June 2021; Accepted 9 June 2021
Available online 16 June 2021

Caspian Sea formed as an upper plate response to Late Cretaceous SI.

For this study, we have compiled zircon U-Pb, K-Ar and Ar-Ar ages for ophiolites, sedimentary basins and core complexes, as well as Rb-Sr isochron ages for high-P metamorphic rocks. We also used the microfossil ages of pelagic sediments from each ophiolite. Most zircon U-Pb data on Zagros ophiolites come from first author's paper which deals with age, major-trace and isotope geochemistry of Zagros ophiolites (Moghadam et al., in press. The Middle-Late Cretaceous Zagros Ophiolites, Iran: Linking of a 3000 km swath of subduction initiation forearc lithosphere from Troodos to Oman, GSA Bulletin, *in press*). Detailed analytical procedures can be found in "Supplementary Appendix A" of this paper.

2. Forearc extension: late cretaceous Zagros ophiolites

Bitlis-Zagros ophiolites are part of the most continuous and best-studied Neotethyan ophiolite belt in the world. These ophiolites can be traced for more than 3000 km along the SW margin of Eurasia, from Cyprus through SE Turkey, NW Syria, NE Iraq, SW Iran and northern Oman. Late Cretaceous ophiolites along the Troodos-Bitlis-Zagros-Makran-Oman suture zone are remnants of Neotethys oceanic lithosphere, although these ophiolites formed along the margin of the overriding plate, at the leading edge of the Iranian plateau. These ophiolites include outer (OB) and inner (IB) Zagros ophiolites in Iran, which formed during Late Cretaceous SI of Neotethys oceanic lithosphere leading to forearc spreading and ophiolite formation (Fig. 1).

Iran outer and inner belt ophiolites are separated by the Sanandaj-Sirjan Zone (SaSZ). The SaSZ is an important tectono-magmatic province, encompassing a SE-NW trending zone that is 50–100 km wide and 1200 km long. Understanding the significance of the SaSZ is critical for understanding the SI model for Iran. The SaSZ was previously thought to be a magmatic arc but this has recently been superseded by reinterpreting it as marking a NW-propagating continental rift that formed near the southern margin of Iran (see (Azizi and Stern, 2019) for discussion and references). SaSZ igneous and metamorphic activity occurred ~177–145 Ma (Azizi and Stern, 2019). The crust of Iran is dominated by Late Neoproterozoic-Early Cambrian (Cadomian; 600–500 Ma) igneous and metamorphic rocks (Hassanzadeh et al., 2008; Moghadam et al., 2021), and the presence of Cadomian basement in the SaSZ shows that it formed in-situ on the southern margin of Iran. IB ophiolites formed inboard of the SaSZ and must also have formed in-situ. The SaSZ was exhumed during Latest Cretaceous-Early Eocene time, as shown by a hiatus in sediments overlying the SaSZ and all Zagros ophiolites. The SaSZ now defines an anticlinorium structurally beneath the Zagros ophiolites (Alavi, 2004).

Recent geochemical and geochronological studies of Late Cretaceous

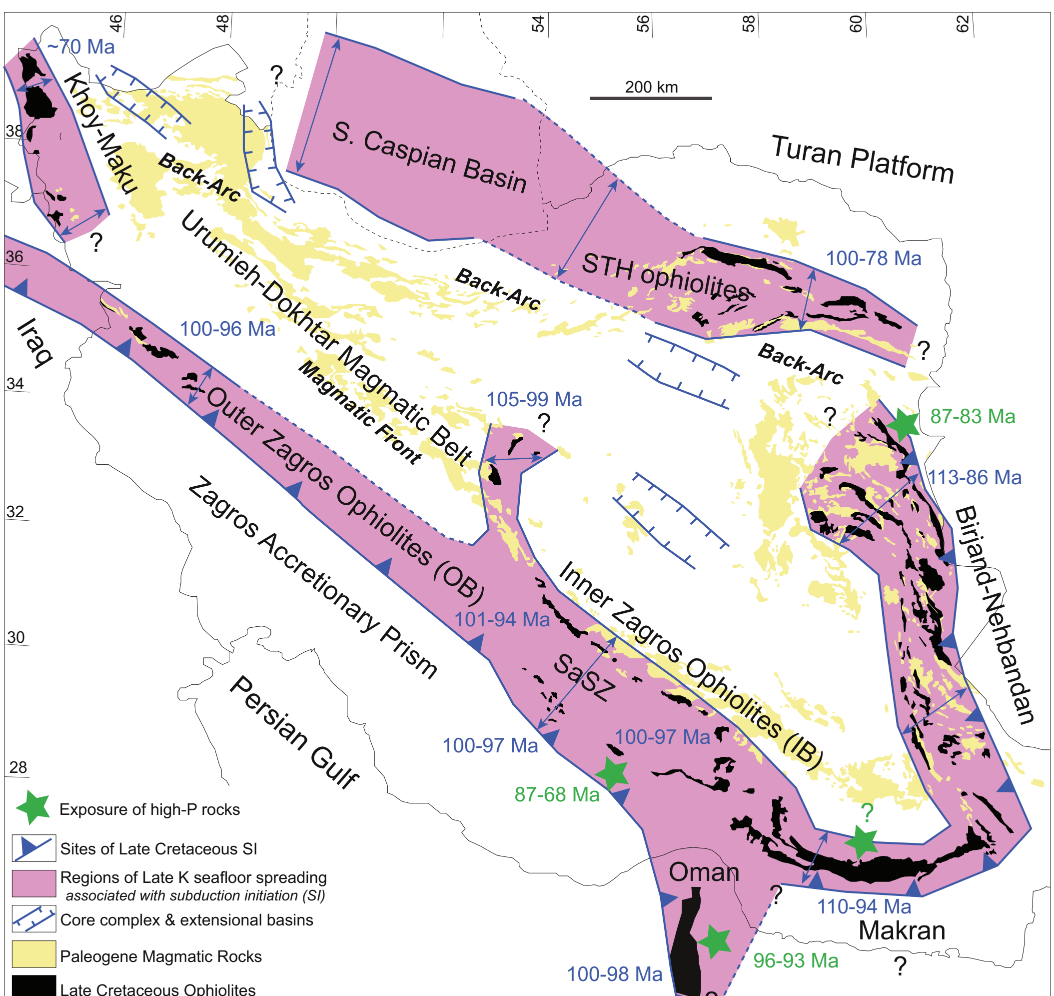

Fig. 1. Simplified geological map of Iran emphasizing Late Cretaceous ophiolites and sedimentary basins as well as Cenozoic magmatic rocks. The tectono-magmatic traces of Late Cretaceous extensional regimes and basin opening are also represented. Ages in blue are zircon U-Pb ages, representing the crystallization age of ophiolite crust, whereas ages in green are for high-P metamorphism. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Neotethyan ophiolites along the Bitlis-Zagros suture zone show a temporal evolution in the volcanic sequence from mid-ocean ridge basalt (MORB)-like tholeiitic to calc-alkaline and boninitic suites during their Late Cretaceous lifetimes (e.g. (Moghadam and Stern, 2011), which conforms to the subduction initiation rule of (Whattam and Stern, 2011). All these ophiolites are about the same age: zircon U-Pb ages of 94–90 Ma for Troodos plagiogranites (Maffione et al., 2017); 96–95 Ma for Samail ophiolite gabbros and plagiogranites (Rioux et al., 2016; Warren et al., 2005); 92–91 Ma for Kizildag plagiogranites (Dilek and Thy, 2009) and 105–94 Ma for Zagros ophiolites (Moghadam et al., in press) (Fig. 2). Our compiled geochronological data indicate that the Zagros ophiolites formed along the length of the SW Eurasia margin over around 12 m.yr. between *ca* 93 and 105 Ma (versus 15 m.yr. -from 105 to 90 Ma- for all Neotethyan Late Cretaceous forearc ophiolites; Troodos to Oman, Fig. 3); this timespan is similar to the SI-related episode of seafloor spreading determined for the IBM forearc (7–8 m.yr.; (Ishizuka et al., 2014)).

3. Subduction zone metamorphism

Other evidence for Late Cretaceous SI in Iran is high-P metamorphic rocks. Exhumation of high-pressure rocks from the top of the subducting slab to the overriding plate is expected to accompany SI (van Hinsbergen et al., 2015). Late Cretaceous high-pressure rocks are commonly associated with SI ophiolites in this region and give metamorphic ages of 96–93 Ma in Oman and 87–68 Ma for Zagros (Guilmette et al., 2018; Moghadam et al., 2017). Garnet Lu-Hf ages from the Oman metamorphic sole yield prograde- metamorphic ages of 104 Ma (Guilmette et al., 2018). This indicates that SI, upper plate extension and seafloor spreading were accompanied and followed by exhumation of high-P rocks from a newly-formed subduction channel.

4. Back-arc extension

4.1. Back-arc ophiolites

Protracted SI-related extension during the Late Cretaceous led to continental rifting and back-arc opening across Iran to form ophiolites. The best examples are in the NW (Khoy-Maku ophiolite = KMO), the NE (Sabzevar-Torbat-e-Heydarieh ophiolite = STHO), and in the E (Birjand-Nehbandan ophiolites = BNO). The KMO has been described as a Late Cretaceous back-arc basin north of the Zagros suture zone within the Cadomian basement of Iran (Hassanipak and Ghazi, 2000). The KMO consists of thick sequences of *E*-MORB to OIB pillow lavas which

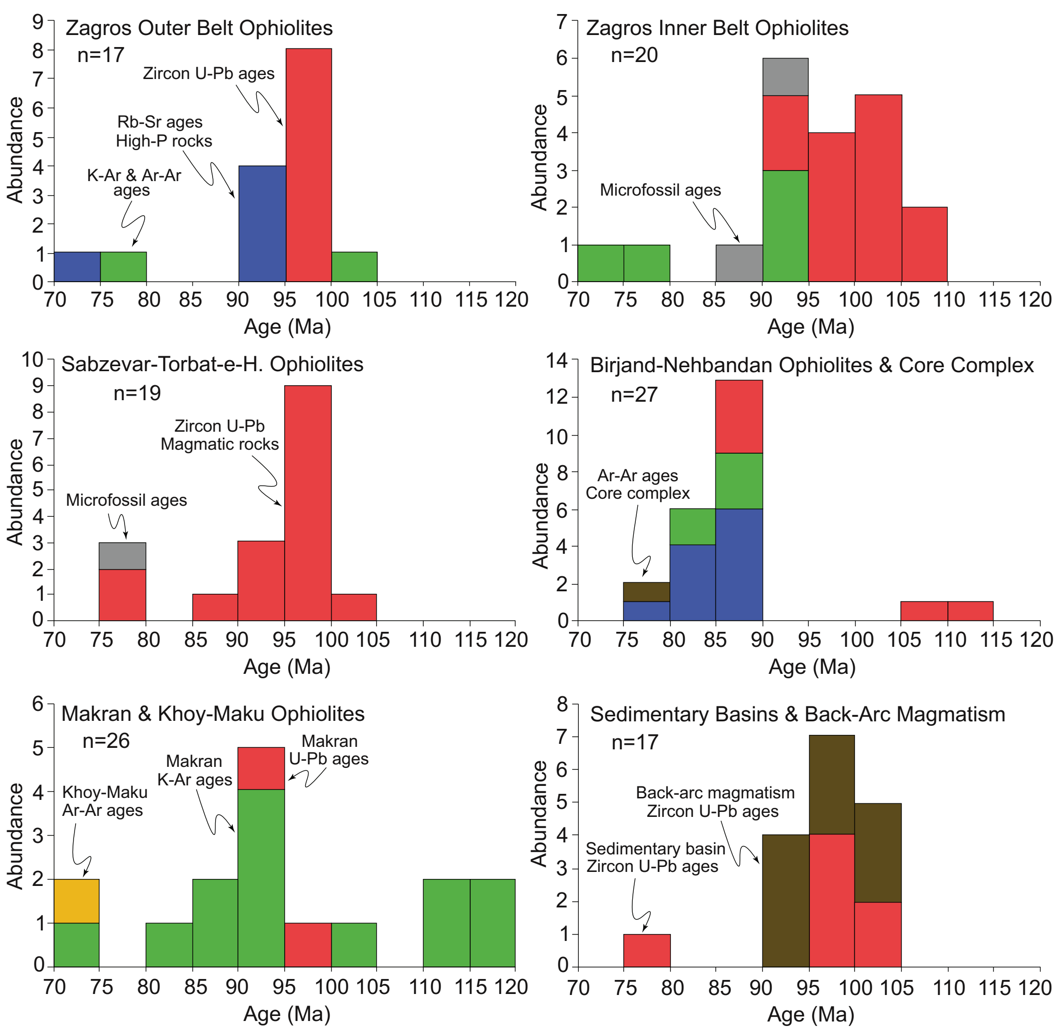

Fig. 2. Histograms showing the U-Pb, Ar-Ar, K-Ar, Rb-Sr and microfossil ages distribution of magmatism in Zagros outer and inner belt ophiolites, Sabzevar-Torbat-e-Heydarieh, Khoy-Maku and Birjand-Nehbandan back-arc ophiolites, Makran ophiolites, core complexes, back-arc sedimentary basins and rear-arc magmatism. Published zircon U-Pb data are from (Chiu et al., 2013; Esmaeili et al., 2020; Kazemi et al., 2019; Moghadam et al., 2014; Moghadam et al., 2020b; Sepidbar et al., 2019), whereas K-Ar, Ar-Ar and Rb-Sr ages are from (Babaie et al., 2006; Malekpour-Alamdari et al., 2017; McCall, 2002; Moghadam et al., 2009; Moghadam et al., 2017). Zircon U-Pb data for Zagros ophiolites are from Moghadam et al., in press.

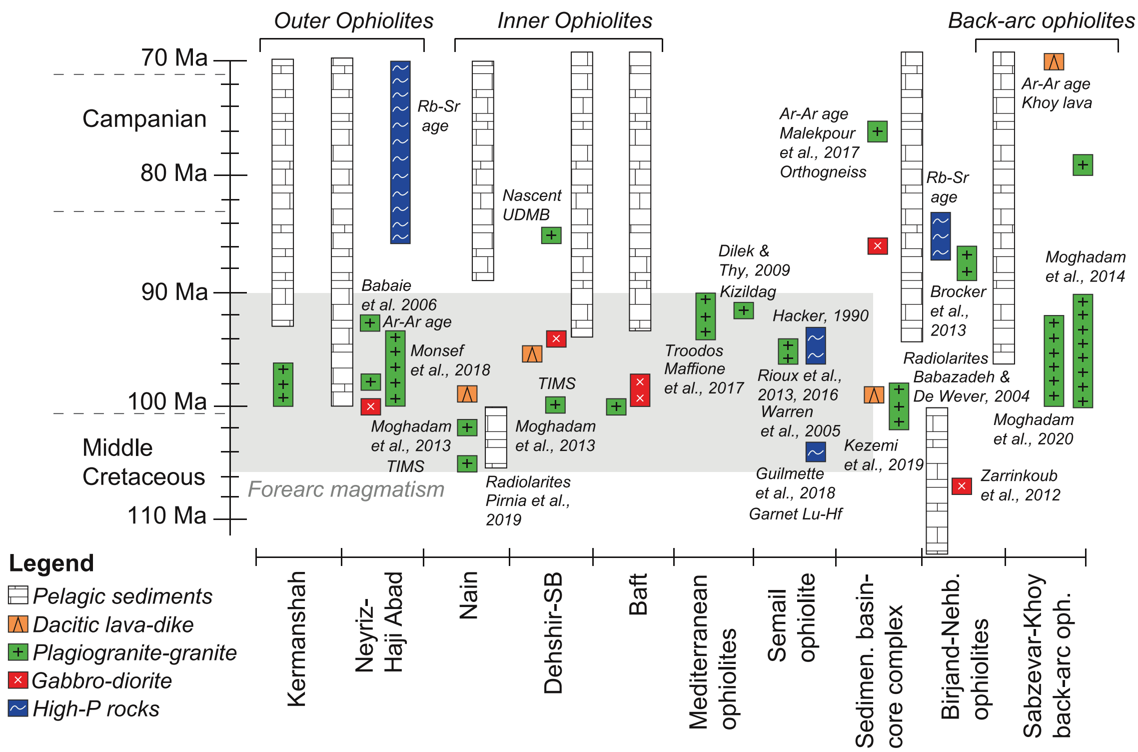

Fig. 3. Simplified chart showing the ages of magmatic, high-P metamorphic and sedimentary sequences of the Zagros outer and inner belt ophiolites. Age data from Troodos, Kizildag and Semail ophiolites, core complex and sedimentary basins of Iran as well as Sabzevar and Khoy Late Cretaceous oceanic back-arc basins are also shown to unravel the time-scale of SI and extension in the Iranian Platea and its relations to the other Tethyan ophiolites. Geochronological data are from (Babaie et al., 2006; Babazadeh and De Wever, 2004; Esmaeili et al., 2020; Kazemi et al., 2019; Maffione et al., 2017; Malekpour-Alamdari et al., 2017; McCall, 2002; Moghadam et al., 2009; Moghadam et al., 2014; Moghadam et al., 2017; Moghadam et al., 2020b; Monsef et al., 2018; Pirnia et al., 2020; Rioux et al., 2013; Rioux et al., 2016; Sepidbar et al., 2019; Warren et al., 2005).

transition upwards into island-arc tholeiitic (IAT) massive lavas and dikes. Amphibole separated from OIB-like KMO pillow lavas show $^{40}Ar/^{39}Ar$ ages of *ca* 70 Ma. STHO zircon U-Pb ages range from ~100 to 78 Ma, but most are 100–90 Ma (Moghadam et al., 2014; Moghadam et al., 2020b). STHO rock chemical compositions are mostly MORB, IAT-type basalts, Back-Arc Basin Basalts (BABB), and calc-alkaline lavas (Moghadam et al., 2020b). The presence of sheeted dikes in both KMO and STHO reveals seafloor spreading to form these basins. Thick sequences of turbidites and tuffaceous sandstones to mudstones along with mass wasting deposits and pelagic sediments indicate these were substantial, tectonically active marine basins.

The BNO contains mid-Cretaceous MORB-like (~113 Ma) to younger arc-like (~107 Ma) magmatic rocks (Zarrinkoub et al., 2012) as well as abundant Late Cretaceous plagiogranites (zircon U-Pb ages 89–86 Ma) along with exhumed high-P eclogites and blueschists (with Rb-Sr isochron and ^{40}Ar-^{39}Ar ages of 87–83 Ma) (Bröcker et al., 2013). These show that this oceanic basin began to form slightly earlier than other Iran SI sequences and experienced continued extension during regional SI along with exhumation of high-P rocks during the Late Cretaceous. Makran ophiolites in south Iran also include Early and Late Cretaceous components, but new zircon U-Pb ages (Fig. 1, (Burg, 2018; Esmaeili et al., 2020)) suggest that regional SI in Makran also started in the Late Cretaceous. Further studies are needed to understand whether Iran SI began in the east and propagated south and west.

4.2. Sedimentary basins

Late Cretaceous extensional volcano-sedimentary basins are found in north and northwest Iran (e.g., N Tabriz and *E*-SE Ardabil, (Burtman, 1994; Omidvar et al., 2018)) (Fig. 1). Extension in NE Iran also generated a volcano-sedimentary basin, the Southern Sabzevar basin, which was filled by Late Cretaceous pelagic sediments, green siliceous tuffs and submarine volcanic rocks as well as plutonic rocks with zircon U-Pb ages of 102 to 76 Ma (Kazemi et al., 2019) (Fig. 3). These rift basins rest on or are faulted against older Iran continental crust and lie near Late Cretaceous arc volcanoes. They contain mafic and felsic volcanic rocks accompanied by deep marine lithofacies such as pillow lavas and pelagic sediments. Mass wasting deposits including polylithic breccias and tuffaceous turbidites are abundant and commonly mingled and cemented by pelagic carbonates. Late-stage intrusions crosscut these lithofacies. Such basins and deposits are common in modern extensional arcs and are characterized by high subsidence and sedimentation rates (>200–300 m/m.yr.). This is similar to sedimentation rates determined for Late Cretaceous sediments in the Sabzevar basin, where zircon U-Pb ages show that it took ~26 m.yr. for >5000 m of volcanic rocks and marine sediments to accumulate (Kazemi et al., 2019).

4.3. Magmatism and core complexes

Other geologic features show extreme extension in the back-arc region of Iran during Late Cretaceous time. This includes core complexes, where extension exhumed Ediacaran crust along low-angle normal faults as well as caused block faulting in some places; e.g., in Torud, where exhumation of the core complex seems to have started in the Late Cretaceous ($^{40}Ar/^{39}Ar$ age of *ca* 76 Ma, (Malekpour-Alamdari et al., 2017)), synchronous with latest ophiolitic magmatism in Sabzevar back-arc ophiolites at ~78 Ma. Another line of evidence is found in abundant igneous rocks; back-arc Iran crust is pervasively invaded by Late Cretaceous juvenile igneous rocks. Late Cretaceous intrusions in NE Iran at ~105–95 Ma show depleted mantle-like radiogenic Hf and Nd isotopic compositions (Kazemi et al., 2019; Moghadam et al., 2020a).

5. Discussion

There are three questions regarding the SI in Iran, including (1) the timing and lateral extent of SI in SW Eurasia, (2) the relation between SI and Caspian Sea and (3) comparison of other Late Cretaceous SI in Iran to other SI-related oceanic basins worldwide.

5.1. Timing and lateral extent of SI in SW Eurasia

Recent geochronological and geochemical data show that SI and its related supra-subduction zone magmatism along SW Eurasia started at *ca* 105 Ma. SI along the southern margin of Eurasia in Tibet farther east occurred earlier (Hu and Stern, 2020). The N-S trending Owen Transform Fault can be traced via the Murray Ridge on-land into the Chaman Fault of Pakistan. The Owen-Murray-Chaman shear system (OMCSS) is a fundamental lithospheric boundary in the Indian Ocean and southern Eurasia that separates regions with fundamentally different tectonic histories in the west such as Iran, from those in the east such as Tibet. It is clear that seafloor spreading and presumably subduction has been going on east of the OMCSS since Early Cretaceous time, but there is no such evidence that this also occurred to the west, including Iran (Gibbons et al., 2015). In further support of this conclusion, Jurassic ophiolites and associated exhumed high-P rocks reflecting SI are unknown from the Zagros, but Late Cretaceous ophiolites are abundant.

IB ophiolites are supposed to originate from a Neo-Tethyan oceanic branch between the SaSZ and Cadomian crust of the Lut block. In this scenario, IB ophiolites represent a suture on the site of a series of Campanian pull-apart and/or back-arc basins with a number of microcontinents (Moghadam et al., 2009). These small oceanic basins are suggested to have formed at *ca* 100 Ma, i.e., 40 m.yr. after shutdown of SaSZ magmatism at 140 Ma, during highly oblique subduction of Neotethyan oceanic lithosphere beneath Iran (Moghadam et al., 2009), and/or change in the slab geometry from steep to shallow (Hosseini et al., 2017). However, it is ambiguous how oblique and/or shallow subduction can generate extension in the overlying plate to form back-arc basins. (Azizi and Stern, 2019) made a compelling argument that Late Jurassic SaSZ magmatism represented a NW-propagating continental rift. We agree with this re-interpretation because SaSZ igneous rocks evolve toward more alkaline rocks with time. We find that a model calling for subduction initiation at *ca* 200 Ma beneath SW Iran to be unsatisfactory because (1) it is inconsistent with the composition of associated igneous rocks and NW propagation of the system; (2) the purported convergent margin did not trigger the extensional forces needed for the opening of many back-arc basins until Late Cretaceous time; (3) the purported SaSZ arc waned in the Early Cretaceous time; and (4) there is no trace of Early Jurassic fossilized oceanic crust along the SaSZ. Our dataset of all available U-Pb zircon age data for forearc Zagros and back-arc ophiolites show that subduction of Neotethyan oceanic lithosphere beneath Eurasia started at ~105 Ma with a peak of magmatism at *ca* 100–95 (Fig. 2). These data confirm that SI-related magmatism was nearly simultaneous along the Late Cretaceous Neotethyan ophiolite belt from Oman to Cyprus and that SI-related forearc and back-arc seafloor spreading, and strong extension occurred during an ~12 m.yr. interval (*ca* 105 to 93 Ma) immediately before the establishment of a focused magmatic arc - the Urumieh-Dokhtar Magmatic Belt - at ~93 Ma (Fig. 3). These age results also indicate that protracted Late Cretaceous extension of Iranian crust accompanying SI led to rifting and back-arc opening at ~100 Ma. Zagros forearc ophiolites are slightly older (*ca* 105–95 Ma) than back-arc ophiolites (*ca* 100–70 Ma), which may reflect the migration of extension accompanying subduction initiation from what became the fore-arc to the back-arc, which is also observed in the IBM arc system. Our compiled age data also suggest that SI and exhumation of high-P rocks within the Birjand-Nehbandan and Makran oceanic basins were simultaneous (Fig. 2).

5.2. SI and formation of the Caspian Sea

Understanding that the upper plate is broadly affected by extreme extension during SI allows a breakthrough in figuring out how one of the greatest sedimentary basins on Earth - the southern Caspian Sea - formed. The Caspian Sea is deepest in the south where it is about 1000 m deep. Southern Caspian Sea crust is buried beneath up to 30 km of sediments. Nevertheless, it has seismic velocities consistent with mafic oceanic crust although it is thicker than normal oceanic crust (Mangino and Priestley, 1998; Piip et al., 2012). The tract of buried oceanic crust is oriented WNW-ESE and is ~300 km wide and ~ 500 km long. S. Caspian Sea oceanic crust is aligned with Late Cretaceous ophiolitic rocks and basin sediments in the Sabzevar region of NE Iran. The tremendous thickness of sediments makes it impossible to determine the age of this crust by drilling to recover crust or the oldest overlying sediments. Consequently, hypotheses for its origin are loosely constrained. Postulated ages range from Jurassic to Paleocene-Eocene (e.g., (Abdullayev et al., 2017)) but these do not find support in our understanding of regional tectonic evolution. Our new understanding of the role of upper plate extension during SI allows a more attractive hypothesis: that South Caspian basin oceanic crust formed in Late Cretaceous time as the northernmost expression of this extensional regime. However, it is unclear why South Caspian basin crust was not deformed by later compressional events, which uplifted and deformed Sabzevar-Torbat-e-Heydarieh oceanic crust to the ESE and Khoy-Maku ophiolites to the west.

5.3. Comparison with other SI-related oceanic basins

The overall width of the Iranian upper plate affected by Late Cretaceous SI-related extension is ~1000 km. This is consistent with what we are learning about the width of upper plate extensional zones in Western Pacific Eocene SI examples of IBM and Tonga-Kermadec. We don't know the westernmost extent of SI-related upper plate extension behind the IBM arc, but since IODP 351 drilled to oceanic crust in the Amami Basin, we know that it affected the upper plate for several hundred kilometers to the west (Hickey-Vargas et al., 2018). The present Kyushu-Palau Ridge (KPR) is thought to approximate the trend of the fracture zone along which IBM SI occurred. Significant SI-related extension west of the KPR may explain why the trace of the KPR does not resemble a small circle, as expected for fracture zones (Taylor and Goodliffe, 2004). The width of the SI-related extensional zone for the Tonga-Kermadec system in the S Pacific is easier to constrain because Zealandia continental crust was involved, so rifts can be identified by bathymetry. IODP 371 drilling indicates that the New Caledonia Trough opened during the Eocene (Sutherland et al., 2018); depending on the age of the S. Fiji Basin (~37 Ma, (Whattam et al., 2008)), the zone of upper plate SI-related extension may be about 1000 km across, similar to what we propose for Late Cretaceous SI-related extension in Iran. (Leng and Gurnis, 2011) showed that SI involving old, dense oceanic lithosphere can result in rapid slab foundering accompanied by strong upper plate extension over a wide region. In contrast, SI involving foundering of younger, more buoyant oceanic lithosphere was accompanied by less slab foundering and less extension of the overriding plate. All these considerations indicate that SI-related extension involving old oceanic lithosphere can affect much broader regions of the overriding plate than heretofore imagined, up to about 1000 km distant from the new convergent margin, as is seen for Eocene SI to form the present IBM and Tonga-Kermadec convergent margins. A similar mechanism may explain the broad region of upper plate extension we document for the Late Cretaceous SI of Iran.

6. Conclusions

Subduction initiation is an increasingly "hot topic" in geoscience research. Subduction initiation (SI) requires the sinking of one plate beneath another and this exerts extension stress on the overlying plate.

How broad a region is affected by SI-related extension is unclear because most SI examples are deep under the ocean, for example the IBM and Tonga-Kermadec convergent margins. Our study of Late Cretaceous Iran ophiolites shows that SI-related extension involving old oceanic lithosphere can affect much broader regions of the overriding plate than heretofore imagined, up to about 1000 km distant from the new convergent margin.

Declaration of Competing Interest

We have no pecuniary or other personal interest, direct or indirect, in any matter that raises or may raise a conflict of interest.

Acknowledgments

We are very grateful to Scott A. Whattam and Orhan Karsli for their constructive reviews of the manuscript. Editorial suggestions by Xian-Hua Li are also appreciated. We thank Paul Kapp for reading an early draft of this manuscript and providing constructive comments. The first author acknowledges the Alexander von Humboldt Foundation and GEOMAR Helmholtz Centre for their financial support while preparing these results for publication. This is UTD Geoscience's contribution 1671. Logistical supports came also from Damghan University, Iran.

References

Abdullayev, N., Kadirov, F., Guliyev, I., 2017. Subsidence history and basin-fill evolution in the South Caspian Basin from geophysical mapping, flexural backstripping, forward lithospheric modelling and gravity modelling. Geol. Soc. Lond., Spec. Publ. 427, 175–196.

Alavi, M., 2004. Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution. Am. J. Sci. 304, 1–20.

Arculus, R.J., Gurnis, M., Ishizuka, O., Reagan, M.K., Pearce, J.A., Sutherland, R., 2019. How to create new subduction zones. Oceanography 32, 160–174.

Azizi, H., Stern, R.J., 2019. Jurassic igneous rocks of the Central Sanandaj–Sirjan zone (Iran) mark a propagating continental rift, not a magmatic arc. Terra Nova 31, 415–423.

Babaie, H.A., Babaei, A., Ghazi, A.M., Arvin, M., 2006. Geochemical, Ar-40/Ar-39 age, and isotopic data for crustal rocks of the Neyriz ophiolite, Iran. Can. J. Earth Sci. 43, 57–70.

Babazadeh, S.A., De Wever, P., 2004. Radiolarian cretaceous age of Soulabest radiolarites in ophiolite suite of eastern Iran. Bull. Soc. Geol. Fr. 175, 121–129.

Bröcker, M., Fotoohi Rad, G.F., Burgess, R., Theunissen, S., Paderin, I., Rodionov, N., Salimi, Z., 2013. New age constraints for the geodynamic evolution of the Sistan Suture Zone, eastern Iran. Lithos 170, 17–34.

Burg, J.-P., 2018. Geology of the onshore Makran accretionary wedge: synthesis and tectonic interpretation. Earth Sci. Rev. 185, 1210–1231.

Burtman, V., 1994. Meso-Tethyan oceanic sutures and their deformation. Tectonophysics 234, 305–327.

Chiu, H.Y., Chung, S.L., Zarrinkoub, M.H., Mohammadi, S.S., Khatib, M.M., Iizuka, Y., 2013. Zircon U-Pb age constraints from Iran on the magmatic evolution related to Neotethyan subduction and Zagros orogeny. Lithos 162, 70–87.

Coltice, N., Husson, L., Faccenna, C., Arnould, M., 2019. What Drives Tectonic Plates? Science Advances 5, eaax4295.

Dilek, Y., Thy, P., 2009. Island arc tholeiite to boninitic melt evolution of the cretaceous Kizildag (Turkey) ophiolite: model for multi-stage early arc-forearc magmatism in Tethyan subduction factories. Lithos 113, 68–87.

Esmaeili, R., Xiao, W., Griffin, W.L., Moghadam, H.S., Zhang, Z., Ebrahimi, M., Zhang, J., Wan, B., Ao, S., Bhandari, S., 2020. Reconstructing the source and growth of the Makran accretionary complex: constraints from Detrital Zircon U-Pb Geochronology. Tectonics 39.

Gerya, T.V., Stern, R.J., Baes, M., Sobolev, S.V., Whattam, S.A., 2015. Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature 527, 221–225.

Gibbons, A.D., Zahirovic, S., Muller, R.D., Whittaker, J.M., Yatheesh, V., 2015. A tectonic model reconciling evidence for the collisions between India, Eurasia and intra-oceanic arcs of the central-eastern Tethys. Gondwana Res. 28, 451–492.

Guilmette, C., Smit, M.A., van Hinsbergen, D.J.J., Gürer, D., Corfu, F., Charette, B., Maffione, M., Rabeau, O., Savard, D., 2018. Forced subduction initiation recorded in the sole and crust of the Semail Ophiolite of Oman. Nat. Geosci. 11, 688–695.

Hassanipak, A.A., Ghazi, A.M., 2000. Petrology, geochemistry and tectonic setting of the Khoy ophiolite, Northwest Iran: implications for Tethyan tectonics. J. Asian Earth Sci. 18, 109–121.

Hassanzadeh, J., Stockli, D.F., Horton, B.K., Axen, G.J., Stockli, L.D., Grove, M., Schmitt, A.K., Walker, J.D., 2008. U-Pb zircon geochronology of late Neoproterozoic-early Cambrian granitoids in Iran: implications for paleogeography, magmatism, and exhumation history of Iranian basement. Tectonophysics 451, 71–96.

Hickey-Vargas, R., Yogodzinski, G., Ishizuka, O., McCarthy, A., Bizimis, M., Kusano, Y., Savov, I., Arculus, R., 2018. Origin of depleted basalts during subduction initiation and early development of the Izu-Bonin-Mariana Island arc: evidence from IODP Expedition 351 Site U1438, Amami-Sankaku Basin. Geochim. Cosmochim. Acta 229, 85–111.

Hosseini, M.R., Hassanzadeh, J., Alirezaei, S., Sun, W., Li, C.-Y., 2017. Age revision of the Neotethyan arc migration into the southeast Urumieh-Dokhtar belt of Iran: geochemistry and U–Pb zircon geochronology. Lithos. 284, 296–309.

Hu, H., Stern, R.J., 2020. Early cretaceous subduction initiation beneath southern Tibet caused the northward flight of India. Geosci. Front. 11, 1123–1131.

Ishizuka, O., Tani, K., Reagan, M.K., 2014. Izu-Bonin-Mariana Forearc Crust as a Modern Ophiolite Analogue. Elements 10, 115–120.

Kazemi, Z., Ghasemi, H., Tilhac, R., Griffin, W., Moghadam, H.S., O'Reilly, S., Mousivand, F., 2019. Late cretaceous subduction-related magmatism on the southern edge of Sabzevar basin, NE Iran. J. Geol. Soc. 176, 530–552.

Leng, W., Gurnis, M., 2011. Dynamics of subduction initiation with different evolutionary pathways. Geochem. Geophys. Geosyst. 12.

Maffione, M., Hinsbergen, D.J., Gelder, G.I., Goes, F.C., Morris, A., 2017. Kinematics of late cretaceous subduction initiation in the Neo-Tethys Ocean reconstructed from ophiolites of Turkey, Cyprus, and Syria. J. Geophys. Res. Solid Earth 122, 3953–3976.

Malekpour-Alamdari, A., Axen, G., Heizler, M., Hassanzadeh, J., 2017. Large-magnitude continental extension in the northeastern Iranian Plateau: insight from K-feldspar 40Ar/39Ar thermochronology from the Shotor Kuh–Biarjmand metamorphic core complex. Geosphere 13, 1207–1233.

Mangino, S., Priestley, K., 1998. The crustal structure of the southern Caspian region. Geophys. J. Int. 133, 630–648.

McCall, G.J.H., 2002. A summary of the geology of the Iranian Makran. Tecton. Clim. Evol. Arab. Sea Reg. 195, 147–204.

Moghadam, H.S., Stern, R.J., 2011. Geodynamic evolution of Upper cretaceous Zagros ophiolites: formation of oceanic lithosphere above a nascent subduction zone. Geol. Mag. 148, 762–801.

Moghadam, H.S., Whitechurch, H., Rahgoshay, M., Monsef, I., 2009. Significance of Nain-Baft ophiolitic belt (Iran): short-lived, transtensional cretaceous back-arc oceanic basins over the Tethyan subduction zone. Compt. Rendus Geosci. 341, 1016–1028.

Moghadam, H.S., Corfu, F., Chiaradia, M., Stern, R.J., Ghorbani, G., 2014. Sabzevar Ophiolite, NE Iran: progress from embryonic oceanic lithosphere into magmatic arc constrained by new isotopic and geochemical data. Lithos 210, 224–241.

Moghadam, H.S., Bröcker, M., Griffin, W.L., Li, X.H., Chen, R.X., O'Reilly, S.Y., 2017. Subduction, high-P metamorphism, and collision fingerprints in South Iran: constraints from zircon U-Pb and mica Rb-Sr geochronology. Geochem. Geophys. Geosyst. 18, 306–332.

Moghadam, H.S., Li, Q.L., Li, X.H., Stern, R.J., Levresse, G., Santos, J.F., Lopez Martinez, M., Ducea, M.N., Ghorbani, G., Hassannezhad, A., 2020a. Neotethyan subduction ignited the Iran Arc and Backarc differently. J. Geophys. Res. Solid Earth 125.

Moghadam, H.S., Stern, R.J., Griffin, W.L., Khedr, M., Kirchenbaur, M., Ottley, C., Whattam, S., Kimura, J.-I., Ghorbani, G., Gain, S., 2020b. Subduction initiation and back-arc opening north of Neo-Tethys: evidence from the late cretaceous Torbat-e-Heydarieh ophiolite of NE Iran. GSA Bull. 132, 1083–1105.

Moghadam, H.S., Li, Q.-L., Griffin, W.L., Chiaradia, M., Hoernle, K., O'Reilly, S.Y., Esmaeili, R., in press. The Middle-Late Cretaceous Zagros Ophiolites, Iran: Linking of a 3000 km swath of subduction initiation forearc lithosphere from Troodos to Oman. GSA Bulletin.

Moghadam, H.S., Li, Q., Griffin, W., Stern, R., Santos, J., Lucci, F., Beyarslan, M., Ghorbani, G., Ravankhah, A., Tilhac, R., 2021. Prolonged magmatism and growth of the Iran-Anatolia Cadomian continental arc segment in Northern Gondwana. Lithos 105940.

Monsef, I., Monsef, R., Mata, J., Zhang, Z.Y., Pirouz, M., Rezaeian, M., Esmaeili, R., Xiao, W.J., 2018. Evidence for an early-MORB to fore-arc evolution within the Zagros suture zone: constraints from zircon U-Pb geochronology and geochemistry of the Neyriz ophiolite (South Iran). Gondwana Res. 62, 287–305.

Nikolaeva, K., Gerya, T.V., Connolly, J.A., 2008. Numerical modelling of crustal growth in intraoceanic volcanic arcs. Phys. Earth Planet. Inter. 171, 336–356.

Omidvar, M., Safari, A., Vaziri-Moghaddam, H., Ghalavand, H., 2018. Foraminiferal biostratigraphy of Upper cretaceous (Campanian–Maastrichtian) sequences in the Peri-Tethys basin; Moghan area, NW Iran. J. Afr. Earth Sci. 140, 94–113.

Piip, V., Rodnikov, A., Buvaev, N., 2012. The deep structure of the lithosphere along the Caucasus-South Caspian Basin-Apsheron Threshold-Middle-Caspian Basin-Turan plate seismic profile. Mosc. Univ. Geol. Bull. 67, 125–132.

Pirnia, T., Saccani, E., Torabi, G., Chiari, M., Goričan, Š., Barbero, E., 2020. Cretaceous tectonic evolution of the Neo-Tethys in Central Iran: evidence from petrology and age of the Nain-Ashin ophiolitic basalts. Geosci. Front. 11 (1), 57–81.

Rioux, M., Bowring, S., Kelemen, P., Gordon, S., Miller, R., Dudas, F., 2013. Tectonic development of the Samail ophiolite: high-precision U-Pb zircon geochronology and Sm-Nd isotopic constraints on crustal growth and emplacement. J. Geophys. Res. Solid Earth 118, 2085–2101.

Rioux, M., Garber, J., Bauer, A., Bowring, S., Searle, M., Kelemen, P., Hacker, B., 2016. Synchronous formation of the metamorphic sole and igneous crust of the Semail ophiolite: new constraints on the tectonic evolution during ophiolite formation from high-precision U-Pb zircon geochronology. Earth Planet. Sci. Lett. 451, 185–195.

Sepidbar, F., Shafaii Moghadam, H., Zhang, L., Li, J.-W., Ma, J., Stern, R.J., Lin, C., 2019. Across-arc geochemical variations in the Paleogene magmatic belt of Iran. Lithos 344-345, 280–296.

Stern, R.J., Reagan, M., Ishizuka, O., Ohara, Y., Whattam, S., 2012. To understand subduction initiation, study forearc crust: to understand forearc crust, study ophiolites. Lithosphere 4, 469–483.
Sutherland, R., Dickens, G.R., Blum, P., Agnini, C., Alegret, L., Bhattacharya, J., Bordenave, A., Chang, L., Collot, J., Cramwinckel, M.J., 2018. International ocean discovery program expedition 371 preliminary report: Tasman frontier subduction initiation and paleogene climate. In: Integrated Ocean Drilling Program: Preliminary Reports.
Taylor, B., Goodliffe, A.M., 2004. The West Philippine Basin and the initiation of subduction, revisited. Geophys. Res. Lett. 31.
van Hinsbergen, D.J.J., Peters, K., Maffione, M., Spakman, W., Guilmette, C., Thieulot, C., Plumper, O., Gurer, D., Brouwer, F.M., Aldanmaz, E., Kaymakci, N., 2015. Dynamics of intraoceanic subduction initiation: 2. Suprasubduction zone ophiolite formation and metamorphic sole exhumation in context of absolute plate motions. Geochem. Geophys. Geosyst. 16, 1771–1785.
Warren, C.J., Parrish, R.R., Waters, D.J., Searle, M.P., 2005. Dating the geologic history of Oman's Semail ophiolite: insights from U-Pb geochronology. Contrib. Mineral. Petrol. 150, 403–422.
Whattam, S.A., Stern, R.J., 2011. The 'subduction initiation rule': a key for linking ophiolites, intra-oceanic forearcs, and subduction initiation. Contrib. Mineral. Petrol. 162, 1031–1045.
Whattam, S.A., Malpas, J., Ali, J.R., Smith, I.E., 2008. New SW Pacific tectonic model: cyclical intraoceanic magmatic arc construction and near-coeval emplacement along the Australia-Pacific margin in the Cenozoic. Geochem. Geophys. Geosyst. 9.
Zarrinkoub, M.H., Pang, K.N., Chung, S.L., Khatib, M.M., Mohammadi, S.S., Chiu, H.Y., Lee, H.Y., 2012. Zircon U-Pb age and geochemical constraints on the origin of the Birjand ophiolite, Sistan suture zone, eastern Iran. Lithos 154, 392–405.