No large earthquakes in fully exposed subducted seamount

G. Bonnet*, P. Agard†, S. Angiboust*, M. Fournier*, and J. Omrani‡

*Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, ISTeP UMR 7193, CNRS-F-75005 Paris, France
†Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, CNRS, F-75005 Paris, France
‡Geological Survey of Iran, Tehran, Iran

ABSTRACT

Bathymetric highs on the ocean floor ultimately sink into highly seismic subduction zones, raising vigorous debates on their potential to trigger or arrest large earthquakes (Mw > 7.5). Many geophysical and seismological studies addressing this problem meet penetration and/or resolution issues and deal with only the most recent earthquakes. We herein present the missing piece of the puzzle with the time-integrated field and petrographic record of a unique, almost intact subducted seamount cropping out along a fossil subduction interface. We document seamount buildup and subduction down to ~30 km, and we show that this seamount did not behave as a large earthquake asperity and may have acted as a barrier.

INTRODUCTION

The bathymetric roughness of seamounts and seamount chains entering subduction zones (Hillier and Watts, 2007; Bassett and Watts, 2015) has long been suspected to impact the geometry and seismic coupling of the subduction interface (Cloos and Shreve, 1996; Scholz and Small, 1997; Agard et al., 2018). Constraining the size and/or location of megathrust ruptures is critical for assessing earthquake hazard, and it is therefore of crucial importance to understand whether seamounts can limit large earthquake rupture propagation (acting as barriers) or may generate large earthquakes (acting as asperities; Cloos, 1992; Mochizuki et al., 2008; Wang and Bilek, 2011; Geersen et al., 2015; Saffer and Wallace, 2015). Despite spectacular geophysical imaging at the trench (Ranero and von Huene, 2000), seamounts are poorly imaged once subducted beyond ~15 km depth (Kodaira et al., 2000; Singh et al., 2011; Saffer and Wallace, 2015), and their internal deformation is thus beyond reach (Park et al., 1999). Fossil exhumed examples are scarce (MacPherson, 1983), yet they are of utmost interest because they possibly preserve millions of years of seamount evolution on the ocean floor and within the subduction zone.

AN EXCEPTIONALLY PRESERVED FOSSIL SEAMOUNT

Here, we report the discovery of a unique, fully exposed subducted seamount, namely, the Siah Kuh (SK) massif, and we present its structure and evolution, which we detailed through extensive field and petrological data. This massif crops out within ophiolite fragments of the Neotethys Ocean subducted beneath Eurasia (Agard et al., 2011) in the easternmost portion of the Zagros Mountains, next to and below oceanic blueschists metamorphosed during the Late Cretaceous (Angiboust et al., 2016). This massif rises from Quaternary sediment infill as an 18 × 12-km-wide and ≥1.5-km-high feature (Figs. 1A and 1B), and it is composed of two subunits separated by tectonic contacts (Figs. 1C and 1D):

1. An ~15 × 12 km oval-shaped unit (unit A) to the southwest is composed of up to 3 km of basaltic lava flows and pillow lavas intercalated with pillow breccia. Rhodacitic subvolcanic rocks intruding this basaltic core are associated with lavas erupted on top of the basalts. Basalts and felsic lavas are overlain by a ≤500-m-thick Late Cretaceous sedimentary sequence, fully exposed on the southern limb of the unit. This base of this sequence consists of a massive limestone cap (10–50 m thick), of reef to lagoon affinity, with recrystallized fossil fragments like urchin spines, foraminifera, and gastropods. The top of the sequence is a variably thick (~100–500 m), mostly detrital, deepening-up sedimentary sequence of tuffaceous sandstone, red clay, pelagic limestone, and olistostromic debris flows. Pillow lavas (up to 1 km thick) emplaced conformably on top of these sediments indicate resumption of volcanic activity after sedimentation (Fig. 1).

2. The smaller crescent-shaped unit to the northeast of SK (unit B) consists of, from bottom to top, serpentinites with meter- to decameter-large gabbroic pods and plagiogranites, a layer of massive gabbro overlain by rhodacitic lavas, and finally kilometer-thick basaltic lavas without significant sedimentary cover.

While Unit B resembles classic ocean floor lithostratigraphy, the size and circular shape, amount of volcanism, shallow reef limestone cap—and overlying high-energy deposits (olistostromic sediments, debris flow)—indicate that unit A is a bathymetric anomaly on the seafloor, i.e., a seamount. The deepening-up sedimentary sequence hints at isostatic reequilibration of the oceanic lithosphere after the first magmatic event and/or seafloor subsidence.

Unit B was thrust southwestward onto unit A via a high-angle fault rooted in the lowermost, basal serpentinite horizon (Fig. 1D), suggesting initial strain localization beneath the oceanic Moho. Associated fault striations in gabbros strike N50°o on average, parallel to the convergence direction during subduction beneath Eurasia (Agard et al., 2011). Smaller thrust faults of similar orientation rooted in sheared sediments (mainly tuffaceous sandstone and pelagic limestone) cut across the northeastern part of unit A and delineate tectonic subunits (A1–4; Fig. 1C). Small serpentinite bodies are pinched inside these faults, and basalts located in their vicinity lack significant deformation. The Oligocene Zagros collision (Agard et al., 2011) was responsible for the final arching of the whole SK massif into a south-to-southeast-vergent anticline (with locally tight refolded limbs; Fig. 1).

CONDITIONS OF BURIAL IN A SUBDUCTION ZONE

Former subduction of the SK seamount is indicated by a high-pressure–low-temperature (HP-LT) metamorphic imprint that postdates seafloor hydrothermal alteration and contact metamorphism near felsic intrusions. This tectonic
event is best expressed at the northeastern tip of the massif near the major shear zones bounding units A and B (Fig. 1). It consists of (1) sodium-bearing amphibole crystallization in gabbro, (2) numerous quartz-lawsonite veins in basalts, and (3) metamorphic aragonite veins in carbonates and basalts. These minerals are diagnostic of low-temperature subduction zone blueschists and define a minimum pressure of ~0.5 GPa, which, if lithostatic, corresponds to a minimum depth range of ~20 km. The absence of jadeite + quartz in basalt, and the absence of antigorite + brucite in serpentinite argue for maximum pressures and temperatures of 0.9 GPa and 300 °C (~35 km).

Raman spectroscopy on organic matter–bearing metasediments from the middle part of the subducted seamount yielded an average temperature of 225 ± 30 °C (see the GSA Data Repository). Considering typical subduction gradients (<10 °C/km in mature subduction zones) and the ~7.5 °C/km inferred from lawsonite-omphacite-blueschist dehydration reactions (Bell et al., 2012; seamount-related—Bell et al., 2012; plate interface (Audet et al., 2009; Wallace et al., 2012; seamount-related—Bell et al., 2010) would favor ductile creep (as observed by Angiboust et al., 2016) and/or recurring brittle failure with earthquakes of only small magnitude.

The SK seamount preserves pristine subduction-related deformation, as demonstrated by the spatial coincidence between faults and HP-LT metamorphism (Fig. 1C). Major displacements are localized in serpentinite (with an offset of several kilometers between units A and B; Fig. 1D) and in sediments (hectometer-to-kilometer-scale offsets). Although the 25–35 km depth range is prone to brittle-ductile switches (Fagereng and den Hartog, 2017), the fact that deformation is mostly rooted in plastically deforming materials such as serpentinite and sediments suggests a dominantly ductile (creep) rather than brittle (potentially seismic) mechanical behavior. Long-term elevated pore-fluid pressure in these materials, as a result of metamorphic dehydration reactions and/or a sealed plate interface (Audet et al., 2009; Wallace et al., 2012; seamount-related—Bell et al., 2010) would favor ductile creep (as observed by Angiboust et al., 2016) and/or recurring brittle failure with earthquakes of only small magnitude.
Figure 2. Subduction metamorphism and brittle deformation. A: Estimation of peak pressure-temperature \((P-T)\) conditions reached by the Siah Kuh (SK) seamount during subduction, where stars for high-pressure metamorphism are only indicative of possible \(P-T\) conditions. B: Lawsonite vein in basalt testifying to hydraulic brecciation at high-pressure–low-temperature conditions. C: Pseudotachylyte vein in gabbro.

NO RECORD OF LARGE-MAGNITUDE EARTHQUAKES

Large-magnitude fossil earthquakes are commonly inferred from the presence of pseudotachylytes, i.e., glassy fault rocks formed by highly localized frictional heating during earthquakes (Austrheim and Andersen, 2004; Di Toro et al., 2005) on large, kilometer-scale faults with significant amounts of slip (meter scale). Extensive field investigations of the SK seamount revealed only one ~10-m-long pseudotachylyte (Fig. 2C) formed during subduction in gabbros of unit B (as shown by glaucophane crystallized from glass; see the Data Repository), pointing to seismic events with maximum centimeter- to decimeter-scale slip (i.e., \(M_s < 2-3\)). This has important consequences for the seismic behavior of SK, as it shows that no major earthquake went through or was generated in the seamount during subduction. This demonstrates that the SK seamount did not host very large seismic rupture (Mochizuki et al., 2008; Wang and Bilek, 2011).

Whether the SK seamount behaved as a barrier is more difficult to assess, because megathrust earthquakes could tentatively have propagated outside the seamount without damaging it. Above the contact, however, no pseudotachylytes or damage were observed in the upper plate (Fig. 1). The contact below, where slicing and detachment of the seamount from the subducting slab occurred prior to exhumation (Figs. 1D and 3), is unfortunately not exposed. With a plate convergence rate of ~5 cm/yr (Agard et al., 2011) and a 20-km-long seamount, detachment of the SK seamount must have lasted ~400 k.y. (only a fraction of a million years). This could in principle have been accommodated by creep or by ~2000 very large earthquakes if one \(M_s \sim 8\) earthquake with ~1–10 m slip occurred every 200 yr (as along Chile today). Yet, no major subduction earthquake affected SK, pointing again to deformation mostly by creep. We therefore propose (Fig. 3) that the SK seamount acted as a barrier to earthquake propagation on the subduction interface, possibly controlling the segmentation of seismic coupling (Geersen et al., 2015; Métois et al., 2016). Other examples of fossil and actively subducted seamounts should be sought to assess whether their size or structure may control their behavior as asperities and/or barriers.

The presence of sediments is commonly considered to smooth contact zones, to facilitate rupture propagation (Scholl et al., 2015; Shillington et al., 2015). In this exceptionally well-preserved seamount, the dearth of weak sediments, as, in fact, in most seamounts (Kodaira et al., 2000; Bassett and Watts, 2015), may have prevented the nucleation of large earthquakes. The presence of soft material (limited sediment intercalations—frequent in seamounts—and serpentinite) was nevertheless essential in promoting strain localization along the major contacts (Fig. 1C). The scarcity of exhumed seamounts in the geological record (MacPherson, 1983) indicates that effective decapitation of seamounts during subduction is generally impeded. We suggest that specific structural heterogeneities in the basal oceanic crust or within the seamount and/or strain localization into serpentinite (Ruh et al., 2015; Guillot et al., 2015), beneath the Moho (Fig. 3), are essential to prevent seamounts from sinking into the mantle.

ACKNOWLEDGMENTS

We thank E. Delairis (Institut des Sciences de la Terre de Paris [ISTeP]) for the preparation of thin sections, and O. Boudouma (ISTeP) and D. Deldicque (Ecole Normale Supérieure de Paris) for analytical support at the SEM. This study was funded by the project “Zooming in Between Plates” (Marie Curie International Training Network no. 604713).

REFERENCES CITED


Printed in USA