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Dating the onset of motion on the Sagaing fault: Evidence from detrital zircon and titanite U-Pb geochronology from the North Minwun Basin, Myanmar

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ABSTRACT

The onset of dextral motion along SE Asia's largest active strike-slip fault, the Sagaing fault in Myanmar, has been the subject of considerable controversy, with estimates ranging from the Miocene-Pliocene boundary to possibly the late Eocene, along with displacement magnitude estimates ranging between 100 km and 400+ km. A recently identified synkinematic basin formed at a releasing bend in one of the fault strands in northern Myanmar was dated in this study using the maximum depositional ages from detrital zircons and titanites, giving an Oligocene age (28–27 Ma). This dates the onset of motion on the fault zone and favors the high-displacement models (>400 km). The higher displacement and older history of the Sagaing fault impact how the western Burma terrane interacted with the basins in the eastern Andaman Sea and indicate that high strike-slip displacements and shortening occurred during the late-stage development of the Indo-Burma Ranges.

INTRODUCTION

The dextral Sagaing fault of central Myanmar (Fig. 1) is the largest active strike-slip fault in Southeast Asia, with a modern displacement rate of ~1.8 mm/yr (Vigny et al., 2003; Maurin et al., 2010). The fault marks the eastern boundary of the Burma platelet, which is the highly deformed region that separates the northward-moving Indian plate from Southeast Asia (Rangin et al., 2013). The north-south fault is more than 1000 km long and connects extension in the Andaman Sea spreading center with contractional deformation in the Himalayas (e.g., Rangin et al., 2013; Soe Thura Tun and Watkinson, 2017). While the kinematics, seismic hazard, and geometry of the Sagaing fault are well known (e.g., Win Swe, 1970; Vigny et al., 2003; Maurin et al., 2010; Hla Hla Aung, 2011; Hurukawa and Phyo Maung Maung, 2011; Soe Thura Tun and Watkinson, 2017), the timing of the onset of displacement on the Sagaing fault is remarkably uncertain. Bertrand and Rangin (2003) argued that the fault only began activity in the late Miocene or even Pliocene, and hence extrapolation of modern displacement rates suggests maximum displacement of only ~100–150 km. Prior to the late Miocene, a large percentage of the differential motion between India and Southeast Asia was focused on the Shan Scarp region (Bertrand et al., 2001; Bertrand and Rangin, 2003). However, offset of distinctive lithologies along the Sagaing fault, in particular, ophiolite belts, suggests displacement along the fault zone could have exceeded 400 km (e.g., Mitchell, 1993; Mitchell et al., 2012), which implies either much higher displacement rates in the past, or the activity of the fault zone extends further back to the early Miocene or Oligocene. Which view is correct remains uncertain, although more recent publications favor a late Miocene or younger age for initiation (e.g., Bertrand and Rangin, 2003; Rangin et al., 2013; Soe Thura Tun and Watkinson, 2017).

South of Indaw Lake, in the Minwun Ranges (Fig. 1), satellite images show the presence of a Cenozoic synkinematic sedimentary basin (North Minwun Basin [NMB]) developed at a releasing bend configuration that could hold the key to dating the early stage of development of the Sagaing fault (Morley, 2017). This basin has geometric similarities with the Ridge Basin in California, United States (e.g., Crowell, 1974, 2003), and the Hornelen Basin of Norway (e.g., Steel, 1976; Folkestad and Steel, 2001; Osmundsen and Anderson, 2001), where major listric extensional faults, which permit tremendous expansion of the sedimentary section in their hanging walls, are bounded laterally by strike-slip faults (Morley, 2017).

The NWB was developed above a listric normal fault that was probably detached on a weak zone of serpentinite related to extensive ophiolites in the area (Morley, 2017). Deposition in the basin produced a distinctive series of east-west–trending to northeast-southwest–trending ridges related to eroded coarse-grained sandstones and conglomerates that were rotated to a north to northwest dip in the hanging wall of the listric fault (Figs. 1B and 1D; Morley, 2017). Based on dip direction and fault kinematics, the youngest rocks in the basin are in the north, adjacent to the fault trace, and they become older passing south (Fig. 1D; Morley, 2017). However, no sediments in the basin have been dated, and Morley (2017) suggested two main scenarios that need to be considered, one where the basin is of Neogene age, and the other where it extends back to the Oligocene or possibly the late Eocene. Hence, although the recognition of synkinematic sediments associated with the Sagaing fault was important, the crucial information about the age of the sediments remains unresolved. Given the coarse-grained, continental nature of the sediments, detrital minerals are likely to be the best way to estimate depositional age in the basin (Morley, 2017). Several studies have shown that U-Pb dating of detrital zircons from sandstones deposited in the Central Basin of Myanmar commonly yields maximum depositional ages close to the biostratigraphic ages (Wang et al., 2014; Robinson et al., 2014; Kyaw Linn Oo et al., 2015). We added extra constraints by also using detrital apatite and titanite U-Pb ages.

Other Major Cenozoic Faults of the Shan Plateau

Three major faults or shear zones lie in close proximity in central Myanmar (Fig. 1): (1) the Panluang fault (Garson et al., 1976) or Medial Myanmar shear zone of Ridd and Watkinson (2013), (2) the Shan Scarp shear zone (Bertrand et al., 2001; Bertrand and Rangin, 2003), and (3) the Sagaing fault zone. The Panluang fault

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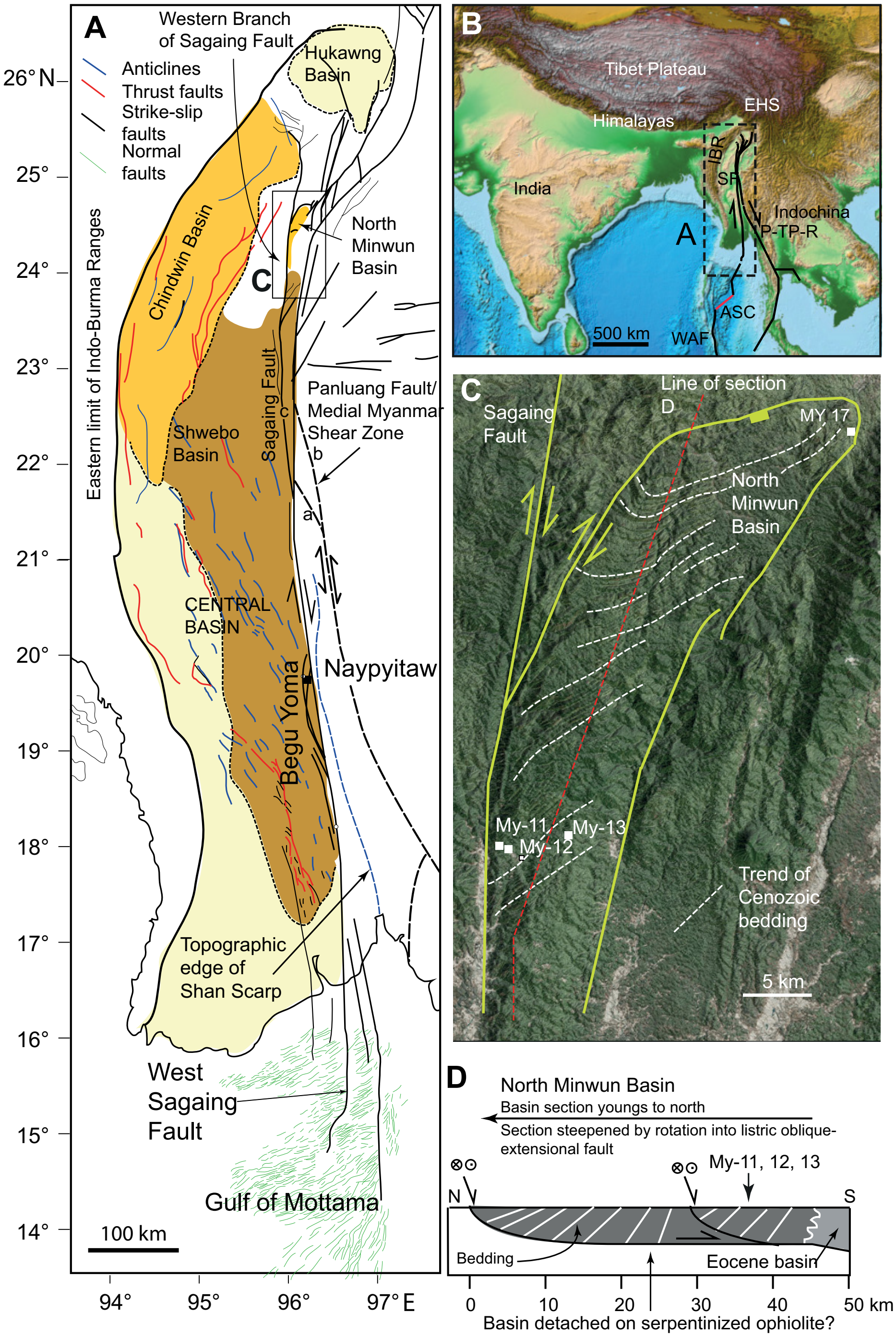

Figure 1. Sagaing fault in Myanmar. A: Regional geological map of Sagaing fault and Central Basin in Myanmar, showing location of North Minwun Basin (NMB), and faults in Shan Scarp region (see B for location). B: Satellite image of NMB area. C: Detail of sample area in southern part of NMB (see A for location). D: Schematic cross section through basin, which is bounded by low-angle normal fault that is probably detached on serpentinized ophiolite (see C for location). EHS—East Himalayan syntaxis; IBR—Indo-Burma Ranges; SF—Sagaing fault; P-TP-R—Panluang, Three Pagodas, and Ranong fault zones; ASC—Andaman spreading center; WAF—West Andaman fault.

is of Late Cretaceous–early Paleogene age (Garson et al., 1976; Ridd and Watkinson, 2013). Connecting faults in Thailand displayed dextral motion during the Late Cretaceous–early Eocene (Ridd and Watkinson, 2013), followed by sinistral motion in the late Eocene (Lacassin et al., 1997; Morley, 2004). Subsequent Oligocene–early Miocene dextral motion occurred in a zone between the Panluang fault and the western margin of the Shan Scarp and is recorded by NNW-SSE transtensional shearing, and by ^{39}Ar-^{40}Ar mica cooling ages (Bertrand et al., 2001; Bertrand and Rangin, 2003). Traditionally, the late Eocene sinistral motion and subsequent switch to dextral motion on northwest-southeast–trending to north-south–trending faults (e.g., Mae Ping, Three Pagodas, Red River) within and east of the Shan Plateau are interpreted as related to the east-to-southeast escape of crustal blocks away from the Himalayan collision zone as India moved progressively northward with time (e.g., Molnar and Tapponnier, 1975; Tapponnier et al., 1986; Replumaz and Tapponnier, 2003).

SAMPLING, METHODOLOGY, AND RESULTS

For Morley (2017), the area of the NMB comprised rugged, jungle-covered territory, with no roads, and a danger of insurgency, and it was therefore off limits for geological study. However, recently, at the very southern end of the basin, a new road for trucks was cut that provides the only opportunity to sample sediments related to the basin, which also happens to be the oldest part of the basin. Although exposures are very poor, three outcrops were sampled for detrital zircons and titanites (Fig. 1C, samples My 11, My 12, and My 13), and an additional small outcrop in the northern part of the basin was also sampled (Fig. 1B, sample My 17). This study reports the results of the heavy mineral analysis of these samples, which provides, for the first time, depositional ages that help to constrain the age of the synkinematic basin associated with the Sagaing fault, and we discuss the tectonic implications these results.

The GSA Data Repository[1] contains details of the methodology, petrology, sample locations, cathodoluminescence (CL) and backscattered electron (BSE) images, and U-Pb age data for the four samples discussed here.

In total, 499 detrital zircon (306 concordant), 473 detrital titanite (431 concordant), and 97 (45 concordant) detrital apatite U-Pb analyses from the four samples (Fig. 1C) display dominant $^{206}Pb/^{238}U$ (zircon) and ^{207}Pb-corrected $^{206}Pb/^{238}U$ (titanite, apatite) age clusters. These ages cluster mainly at 200–28 Ma (My11: 87%; My12: 69%; My13: 87%, My17: 55%), with all the main peaks being younger than Early Cretaceous, i.e., ca. 100 Ma (96–90 Ma, 69–65 Ma, 52–51 Ma, 41–40 Ma, and 29–25 Ma; Fig. 2). All the samples show subordinate peaks (less than 8% of the whole population) from ca. 2.6 to 0.3 Ga. The ages obtained from zircons, titanites, and apatites are consistent throughout the four samples: Almost all the titanite ages (oldest age 189 ± 17 Ma) and >80% of the zircon and apatite ages are younger than 100 Ma. Only detrital zircons provide relevant peaks older than ca. 100 Ma, with 15% of the ages extending back to 230 Ma, 1% to the early Cambrian, and 10% to the Neoproterozoic to Neoarchean.

[1]GSA Data Repository item 2019210, Minwun rep data (methodologies and radiometric data), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

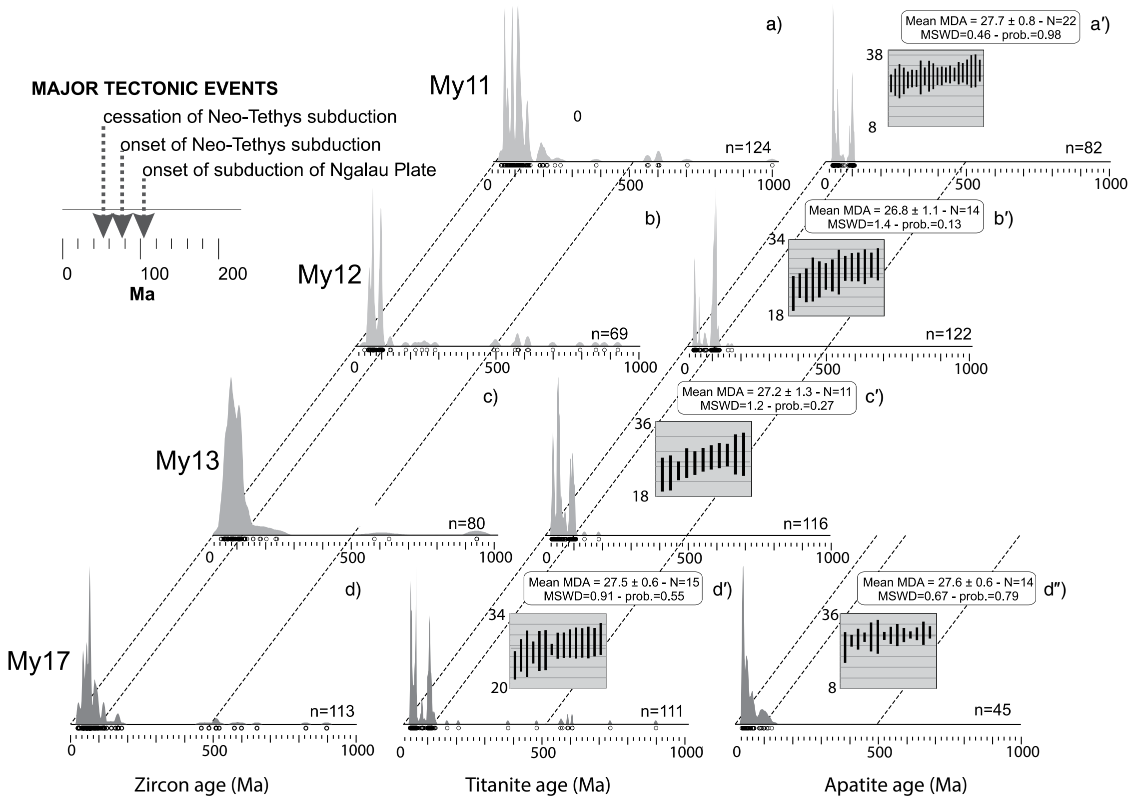

Figure 2. Detrital zircon, titanite, and apatite U-Pb age distribution plots of samples from North Minwun Basin (NMB), Myanmar. Light-gray shade represents zircon $^{206}Pb/^{238}U$ age spectra; dark-gray shade represents titanite $^{206}Pb/^{238}U$ age spectra. Dashed lines indicate major tectonic events and relative onset of possible intrusive and extrusive igneous sources in Myanmar. Errors are reported as 2σ. MDA—maximum depositional age; MSWD—mean square of weighted deviates.

Samples My11, My13, and My17 yielded similar detrital zircon and titanite ages, with the youngest zircons at 27.1 ± 0.6 Ma (My11), 28.7 ± 0.9Ma (My13), and 26.8 ± 0.7 Ma (My17) and the youngest titanite mean ages at 27.7 ± 0.8 Ma (mean square of weighted deviates [MSWD] = 0.46; My11), 27.2 ± 1.3 Ma (MSWD = 1.2; My13), 27.5 ± 0.6 Ma (MSWD = 0.91; My17; Fig. 2). My12 zircon and titanite populations have very similar kernel density estimate (KDE) distributions (Fig. 2); however, only the youngest titanite ages are within error to those of the previous samples 26.8 ± 1.1 Ma (MSWD = 1.4), while the youngest My12 zircon yielded a late Eocene–early Oligocene age (34.1 ± 1.2 Ma). My17 is the only sample with a high number of U-bearing apatites that allowed dating (45 out of 97 analyzed grains). The 14 youngest apatite ages yielded a mean maximum depositional age (MDA) of 27.6 ± 0.6 Ma (MSWD = 0.67), which is within the analytical error of the zircon and titanite ages of all the samples collected within the NMB.

The stratigraphic age of the NMB has never been constrained from paleontology. However, the consistent U-Pb mid-Oligocene ages from detrital zircons (excluding the late Eocene My12 zircon age), apatites, and titanites provide a robust constraint on the MDA of the NMB at 27.5 ± 0.42 Ma (MSWD = 1.7).

DISCUSSION

Within the NMB detrital zircon age distributions, ages younger than 100 Ma fall into age clusters that largely reflect the major episodes of magmatic activity around the basin (Mitchell, 2017). Following the G-Plates software (https://www.gplates.org) reconstructions of Zahirovic et al. (2016), these ages appear to coincide with two cycles of subduction beneath the Indo-Burma Ranges related to closure of the back-arc Ngalau oceanic plate (Advokaat et al., 2018) and the Neo-Tethys (Fig. 2). These distributions are typical of other Central Basin localities further south (Robinson et al., 2014; Wang et al., 2014; Kyaw Linn Oo et al., 2015; Licht et al., 2018). While the provenance of the NMB sediments is typical for the Central Basin, it is the local, synkinematic deformation by the major strike-slip faults that sets the basin apart.

The West Sagaing fault bounds the western side of the NMB (Fig. 2). A strand of this fault zone passes into the listric growth fault that controlled development of the NMB. Assuming that the MDAs of zircons, titanites, and apatites in this study are close to depositional ages, formation of the NMB indicates onset of dextral motion during the mid-Oligocene (Fig. 3). This timing postdates late Eocene sinistral displacement on the Panluang–Mae Ping–Three Pagodas fault zones, which ended around 30 Ma (Lacassin et al., 1997; Morley, 2004; Morley et al., 2011). Extrapolation of the present-day movement rate on the Sagaing fault (1.8 cm/yr) back to 27 Ma provides an estimate of 486 km of offset. This magnitude of displacement agrees with correlation of geological features across the fault that suggest ~400+ km of dextral displacement (Mitchell, 1993; Mitchell et al., 2012).

The Oligocene age for West Sagaing fault motion indicates activity synchronous with transtensional shearing in the Shan Boundary fault region, and so the Western Sagaing fault can be interpreted as either an early segment of the Sagaing fault (Fig. 3A, scenario 1), or the northward continuation of the Panluang fault (Fig. 3B, scenario 2), which was subsequently incorporated into the splaying Sagaing fault (Figs. 3C and 3D). In scenario 1, the Sagaing fault may have extended into the central part of the Andaman Sea (Fig. 1B), although it did not necessarily follow the modern path through the Andaman spreading center and West Andaman fault (ASC and WAF in Fig. 1B). For scenario 2, the motion was transferred further east through the Mae Ping, Panluang, Three Pagodas, Khlong Marui, and Ranong fault zones (MP and P-TP-R in Fig. 1B). For large-scale Cenozoic motions on the West Burma block, these two options have very significant consequences. At the southern end of the MP–P-TP-R trend, the Rayong fault dies out into a simple Oligocene–Miocene half graben offshore (Morley, 2014), which eliminates the possibility that large-scale plate motions followed this trend during the Oligocene or Neogene. Instead, any large-scale strike-slip motions in northern Myanmar must have dissipated into the extensive network of strike-slip faults of the Shan Plateau and peninsular Myanmar and Thailand (Morley, 2004). In scenario 1, the limitations on large motions on the West Burma block through the central Andaman Sea region are much less constrained and are consequently more feasible.

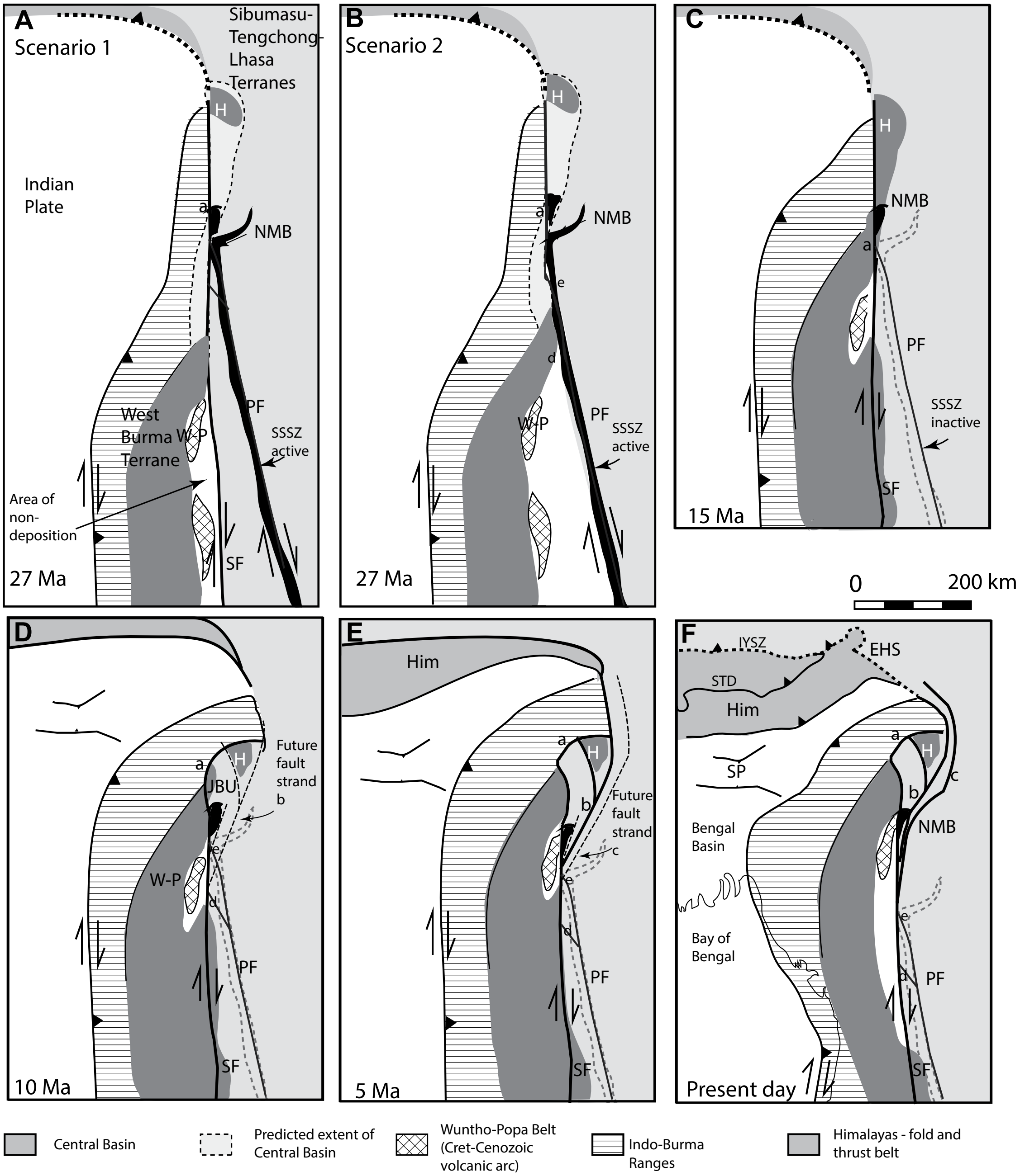

Figure 3. Scenarios for development of Sagaing fault (SF), Myanmar, if it was initiated in mid-Oligocene, as indicated by North Minwun Basin (NMB) deposition. A: Scenario 1, simultaneous activity of SF and Shan Scarp shear zone to east. B: Scenario 2, West Sagaing fault (a) is northern extension of Panluang fault (PF). Scenarios 1 and 2 follow same evolution in C–F. C: 27–15 Ma: Central Basin has onlapped and covered old ranges of Wuntho-Popa arc. Northward translation of West Burma terrane, with dextral transpression causing shortening in Indo-Burma Ranges. D: 15–10 Ma: Indo-Burma Ranges run up against shortening within India plate (Shillong area, Himalayas), and fault 'a' becomes inactive as it is bent, causing strand 'b' to develop. Jade belt uplift (JBU) is exhumed. E: 10–5 Ma: Dextral motion switches from west side of North Minwun Basin (NMB) to east side when strand 'b' becomes active. F: Present-day setting. EHS—East Himalayan syntaxis; H—Hukawng Basin; Him—Himalayas fold-and-thrust belt; IYSZ—Indus-Yarlung suture zone; PF—Panluang fault; SF—Sagaing fault; SP—Shillong Plateau; SSSZ—Shan Scarp shear zone; STD—South Tibet detachment; W-P—Wuntho-Popa region; a,b,c—strands of Sagaing fault zone, where a—West Sagaing fault, d and e—spays of the Panluang fault.

However, one issue for scenario 1 is that industry seismic data from the Gulf of Mottama (Fig. 1A) can only identify the impact of the Sagaing fault on basin sediments back to the late Miocene, and the fault can be seen to link with the late Miocene or Pliocene–recent opening of Andaman spreading center (e.g., Bertrand and Rangin, 2003; Rangin et al., 2013; Morley and Alvey, 2015). Hence, ideally, further evidence for the older history of the Sagaing fault in the Andaman Sea is needed to support scenario 1.

The restoration in Figure 3 follows the model discussed in Ridd et al. (2019), which infers that the Hukawng Basin was deposited on the Tengchong-Sibumasu terrane(s) and is separated by a major strike-slip fault zone (either the Sagaing or Panluang fault) from the rest of the Central Basin, which lies on the West Burma terrane. Northward motion of the West Burma terrane resulted in considerable dextral transpressional translation and shortening within the Indo-Burma Ranges (e.g., Maurin and Rangin, 2009). Northward-directed translation was retarded by interaction with the Indian continental crust in the vicinity of the Shillong Plateau (Fig. 3), and consequently the Indo-Burma Ranges became more arcuate, particularly as the Eastern Himalayan syntaxis grew. The West Sagaing fault (a in Fig. 3D) became curved and disrupted during collision, and initially straighter strands of the Sagaing fault (b and c in Fig. 3) developed successively to the east with time, causing the NMB to be transferred from the eastern side of the active Sagaing fault (Figs. 3A–3C) to the western side (Figs. 3D–3F). The Jade belt (and adjacent amber deposits) lies between strands of the Sagaing fault and experienced its final phase of exhumation during this time. Work in progress on paleomagnetic data (A. Licht, 2018, 2019, personal commun.; J. Westerweel and P. Roperch, 2019, personal commun.) suggests that large-displacement activity occurred on the West Burma terrane during the Eocene to recent. Scenario 1 is favored because such displacement on the West Burma terrane is more easily accommodated through the central Andaman Sea than the displacement in scenario 2.

CONCLUSIONS

The most southern and oldest sediments in the NMB have been dated at ca. 27 Ma, which dates a key synkinematic basin along the Sagaing fault for the first time. Previous estimates for the onset of motion favored the middle or late Miocene; consequently, with the older age, higher displacement estimates for the fault (>400 km) are favored over the lower estimates (~100 km). The higher displacement and older history of the Sagaing fault impact our understanding of the way in which the Western Burma terrane interacted with the basins in the western Andaman Sea and indicate high strike-slip displacements and shortening occurred during the late-stage development of the Indo-Burma Ranges (Fig. 3). Progressive eastward activation of younger faults splays of the northern Sagaing fault area resulted in exhumation of jade and amber resources in the southern Hukawng Basin area.

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