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Active subduction and strain partitioning in western Myanmar revealed by a dense survey GNSS network

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ABSTRACT

The active tectonics of the Myanmar (formerly Burma) microplate in central Myanmar are caused by the oblique collision between the Sunda and Eurasia plates to the east and the Indian plate to the west. The kinematics of this plate boundary zone remain a subject of controversy, due in part to limited geodetic and seismic observations in the region. Here, we report 41 new and 67 updated survey-mode and continuous Global Navigation Satellite System (GNSS) velocities spanning central and western Myanmar, between 15 – 23°N and 93 – 98°E. For the first time, our network allows us to directly observe the occurrence of active convergence along the central Rakhine coast in a manner consistent with active subduction and kinematic coupling of the megathrust, at a rate of 15 – 20 mm/yr. The data also establish a nearly constant strike-slip rate of 20 – 23 mm/yr along the entire length of the Sagaing fault. Using an elastic block-modeling approach, we examine several proposed models for the partitioning of oblique convergence into strike-slip and thrust motion across the Indo-Myanmar Ranges and the Myanmar Central Basin. We find evidence for shortening perpendicular to local topography throughout the Indo-Myanmar Ranges, indicating active convergence and nearly complete strain partitioning between thrust and transform faults north of 19°N, and estimate a rate of moment-deficit accumulation along the megathrust of $0.8 - 1.5 \times 10^{19}$ N m/yr, equivalent to one M_W 9.0 earthquake every 250 to 450 years, assuming all elastic strain is released seismically. We also find that a relatively small set of major active crustal faults can explain much of the data, though the data cannot resolve smaller faults that may be active at rates lower than a few mm/yr. Our results have important implications for earthquake and tsunami preparedness across the region, and indicate areas for future study where the geodetic observations remain ambiguous about ongoing fault activity and seismic hazard, particularly within the densely populated Ayeyarwady Delta region and along the southern Rakhine coast.

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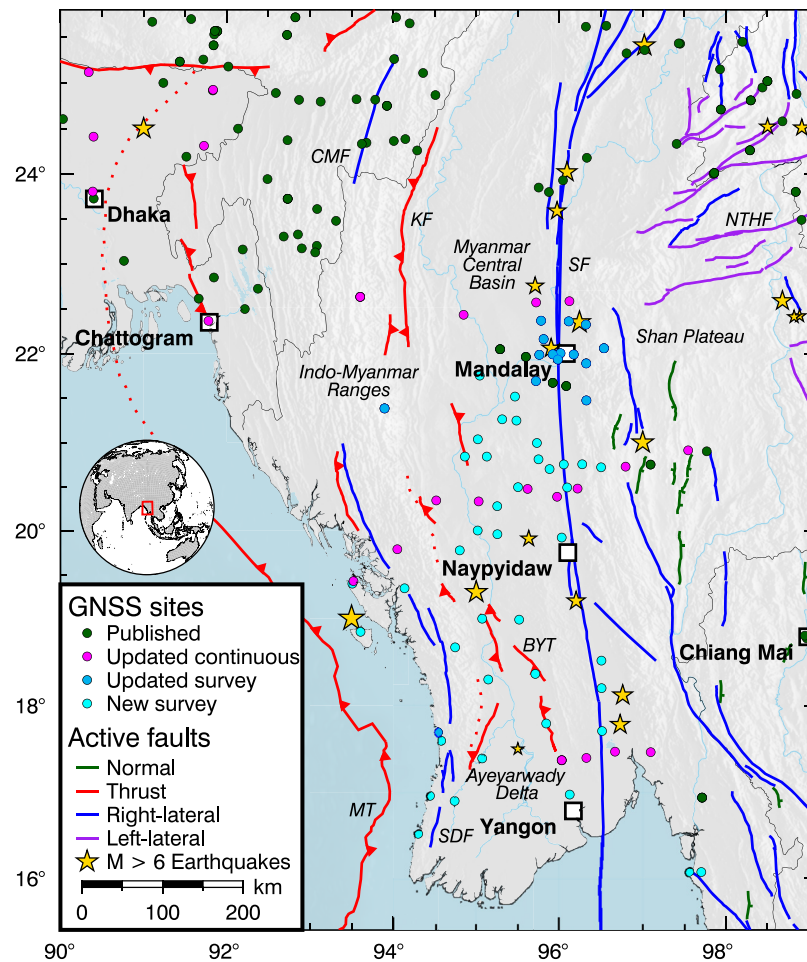


Fig. 1. Tectonic setting of Myanmar showing mapped active faults (colored lines) and historical earthquakes. Circles indicate locations of new and existing GNSS sites in our study; dark green circles indicate previously published GNSS velocities; magenta are updated continuous GNSS velocities; dark blue are revisited survey sites with previously published velocities, and light blue are new survey sites with velocities. Yellow stars indicate significant ($M > 6$) known earthquakes during the 18th – 21st centuries (Wang et al., 2014). Major faults considered in the text are shown as mapped by Wang et al. (2014) and are labeled as follows: MT (Megathrust); SF (Sagaing Fault); KF (Kabaw Fault); CMF (Churachandpur-Mao Fault); SDF (Sein-Daung Fault); BYT (Bago-Yoma Thrust); NTHF (Nantinghe Fault). North of 20°N, the megathrust trace is unclear and its location is inferred (dashed red line).

1. Introduction

The Myanmar microplate or sliver is located within the complex zone of oblique convergence between the Indian plate to the west and the Sunda and Eurasia plates to the east. This convergence occurs at a rate of 35 – 40 mm/yr (Curry, 2005; DeMets et al., 2010; Prawirodirdjo and Bock, 2004; Socquet et al., 2006), forming a right-lateral transpressive plate-boundary zone with many active faults (Fig. 1). The right-lateral Sagaing fault extends more than 1300 km from the Andaman Sea to near the eastern Himalayan syntaxis and accommodates most of the north-south transform motion (Maurin et al., 2010; Soe Thura Tun and Watkinson, 2017; Wang et al., 2011), while the Rakhine-Bangladesh megathrust accommodates north-eastward subduction of the oceanic part of the Indian plate under predominantly continental lithosphere (Mallick et al., 2019; Steckler et al., 2016). Between these two major systems, smaller faults within the Indo-Myanmar Ranges and the Myanmar Central Basin also accommodate shortening and right-lateral motion (Wang et al., 2014), but the degree of partitioning between these systems, the Sagaing fault, and the megathrust has remained uncertain (e.g. Mallick et al., 2019; Steckler et al., 2016).

This complex tectonic setting is home to more than 250 million inhabitants across Myanmar, Bangladesh and northeastern India, who are at risk of devastating consequences from large earthquakes and tsunamis (Cummins, 2007). In recent centuries, earth-

quakes of magnitude 7 or larger have occurred on all of the major fault systems throughout the region (Martin and Szeliga, 2010), but to date there has been no comprehensive study of the present-day tectonic interactions between these faults and the potential rate of future earthquakes, or their possible magnitudes (Wang et al., 2014). With the region undergoing continued rapid growth and development, characterizing these hazards is an urgent need.

The Sagaing fault is a major right-lateral transform fault which runs north-south through the center of Myanmar. The fault has hosted a series of eight $M_w > 7$ earthquakes during the past century (Fig. 1). Paleointensity observations record a long history of such events during the previous two millennia, with some locations having experienced more than a dozen large events over this period (Win Swe, 2013). The locations of the most recent events (Fig. 1) have left a notable seismic gap in the central part of the fault, close to the recently constructed capital city of Naypyidaw (Hurukawa and Maung, 2011). Nevertheless, the magnitude and along-strike extent of many of these earthquakes remain uncertain due to limited observations (Soe Thura Tun and Watkinson, 2017). Because the Sagaing fault strikes almost directly north-south, InSAR observations are not well oriented to measure the fault slip rate or locking depth accurately (Simons and Rosen, 2015), though GNSS studies have established a relatively constant slip rate of approximately 18–24 mm/yr along the central and northern parts of

the fault (Maurin et al., 2010; Socquet et al., 2006; Vigny et al., 2003).

The Rakhine-Bangladesh megathrust is the continuation of the Sunda megathrust north of the Andaman Sea, and lies in a highly oblique convergence zone (Nielsen et al., 2004). The most recent large event believed to have occurred on this fault was in 1762 (Cummins, 2007) and produced several meters of uplift on coastal islands near 18°N (Wang et al., 2013). Geodetic (Socquet et al., 2006), geologic (Nielsen et al., 2004; Wang et al., 2014) and geomorphological studies (Maneerat and Bürgmann, 2022) suggest that partitioning of thrust and strike-slip motion between the megathrust and crustal faults may occur throughout the Indo-Myanmar Ranges between 15–25°N, but the degree of strain partitioning has not been ascertained, highlighting the need for additional geodetic data spanning the western part of Myanmar. Recently, geologic and geodetic studies in Bangladesh have found evidence for active and ongoing subduction (Betka et al., 2018; Mallick et al., 2019; Steckler et al., 2016), although the long-term convergence rate is still highly debated (Panda et al., 2020; Panda and Kundu, 2022). The megathrust thus represents a significant but still poorly understood earthquake hazard for the whole Bay of Bengal (Cummins, 2007; Mallick et al., 2019; Steckler et al., 2016), with the potential for $M > 8$ events and subsequent tsunamis.

Tectonic deformation within the Myanmar microplate has been little studied in comparison to regions with comparable seismic hazard, such as Turkey and California (Curry, 2005). Geomorphic studies have only recently begun to include modern methods (Maneerat, Dreger, et al., 2022; Maneerat and Bürgmann, 2022; Soe Thura Tun and Watkinson, 2017; Wang et al., 2011, 2013). As a result, little is known about long-term slip rates aside from the Sagaing fault; identifying which faults are active and mapping their connections remains an ongoing challenge (Wang et al., 2014). Several studies proposed significant strike-slip motion within the wedge overlying the northern part of the Rakhine-Bangladesh megathrust, including the Churachandpur-Mao fault (Gahalaut et al., 2013; Kundu and Gahalaut, 2013) and the Kabaw fault (Betka et al., 2018; Steckler et al., 2016). However, it is not clear how the partitioned deformation transitions southward through the Rakhine segment of the megathrust into the largely strike-slip interface of the Andaman islands portion of the megathrust (Nielsen et al., 2004). Wang et al. (2014) proposed that the partitioned strike-slip motion continues southward within the Indo-Myanmar Ranges as the Sein-Daung fault, before running offshore at the southwestern tip of the range. Other possibilities include that the strike-slip deformation connects to the megathrust offshore further north, or that it is only partially partitioned off the megathrust, which would then slip obliquely.

Prior GNSS observations in Myanmar initially focused on a dense network surrounding Mandalay (Vigny et al., 2003), plus a few widely-spaced sites to help constrain the overall plate motion (Socquet et al., 2006; Vigny et al., 2003). These data were sufficient to establish the overall tectonic picture and show that the Sagaing fault is deeply locked near Mandalay. Further work to the north of Mandalay showed that the slip rate remains relatively constant as far as 25°N, and established which of the several strands of the Sagaing fault is most active at that latitude (Maurin et al., 2010). Recently, we used a subset of the GNSS observations described here to determine that the slip rate of the Sagaing fault is relatively constant along its entire length but with a possible reduction toward the south (Tha Zin Htet Tin et al., 2022), in agreement with paleoseismic observations (Wang et al., 2011).

Here, we report complete results from the first large-scale survey GNSS network in central Myanmar, spanning the southwestern part of Myanmar from Yangon to Mandalay to the Rakhine coast (Fig. 1). This network of 113 stations (17 continuous and 96 survey) was built through a collaboration between the Myanmar

Earthquake Committee, Myanmar Department of Meteorology and Hydrology, Myanmar Survey Department (MSD), and the Earth Observatory of Singapore. Many of the sites are re-surveyed ground control points installed during early surveys by the MSD between 2000 – 2003. The use of stable, pre-existing markers with known coordinates enabled us to estimate an interseismic velocity field with good precision after as little as one revisit for some sites, thanks to the long interval between the two surveys, although significant uncertainties remain (see Methods). We use our new velocity field to construct a series of block models in an effort to map the partitioning of strain between the megathrust and crustal faults in the Indo-Myanmar Ranges between 15–20°N, and show that the Myanmar Central Basin is comparatively tectonically stable, though ongoing seismicity there indicates at least some internal deformation (Mon et al., 2020). These results provide important new insights into the activity and rates of motion along the Rakhine-Bangladesh megathrust and major crustal faults within Myanmar and will enable an update of hazard models for this understudied but densely populated area.

2. Methods

2.1. GNSS observations and processing

Our primary dataset comprises a total of 108 new and updated survey-mode GNSS velocities, derived from surveys of monuments installed as early as 1998, plus updated velocities from 24 continuous sites installed between 2011 – 2018. We processed all data using GAMIT/GLOBK version 10.61 (Herring et al., 2010). We then estimated velocities for the continuous sites by fitting a trend together with annual and semiannual seasonal cycles, which are significant in the region as a result of the Monsoon (Materna et al., 2021). The seasonal cycles in this region are significant and largely driven by hydrologic loading associated with the Indian Monsoon (Materna et al., 2021). Time series for these sites in the ITRF 2014 reference frame (Altamimi et al., 2016) are shown in Fig. S1.

Two continuous sites, SDWN and SWBO were affected by the November 11, 2012 M_w 6.8 Thabeikkyin earthquake; for these sites we estimated a coseismic offset and amplitudes of two exponential postseismic terms with assumed time constants of 0.1 and 2 years. The assumed values of these time constants have a minimal effect on the inferred station velocity for a reasonable range of values (Tha Zin Htet Tin et al., 2022). The coseismic offsets and postseismic amplitudes for these sites are reported in Supplementary Table S1, and the model fits are shown in Supplementary Fig. S5. Compared to previous published estimates of the velocities for these sites (Mallick et al., 2019; Pyae Sone Aung et al., 2016; Tha Zin Htet Tin et al., 2022) our results here extend the timeseries through the end of 2020 and represent the most precise estimate of the velocities.

The survey data comprise a combination of monuments we surveyed; those installed and first surveyed by Vigny et al. (2003) or Maurin et al. (2010) and those initially installed and surveyed by the Myanmar Survey Department (MSD). For the first two types of sites, we reprocessed all raw data together using GAMIT/GLOBK and determined their coordinates and velocities in the ITRF2014 reference frame (Altamimi et al., 2016).

For sites installed by the MSD between 2000 – 2003, the original reported coordinates were found to disagree systematically from their expected positions in ITRF2014 by several meters, likely reflecting the use of an unknown reference frame in their original determination. Raw GNSS data from the original surveys were available for 9 primary sites that were surveyed simultaneously in Fall 2000 (Supplementary Fig. S2), but raw data were not preserved for the remaining sites. We re-processed the raw data from

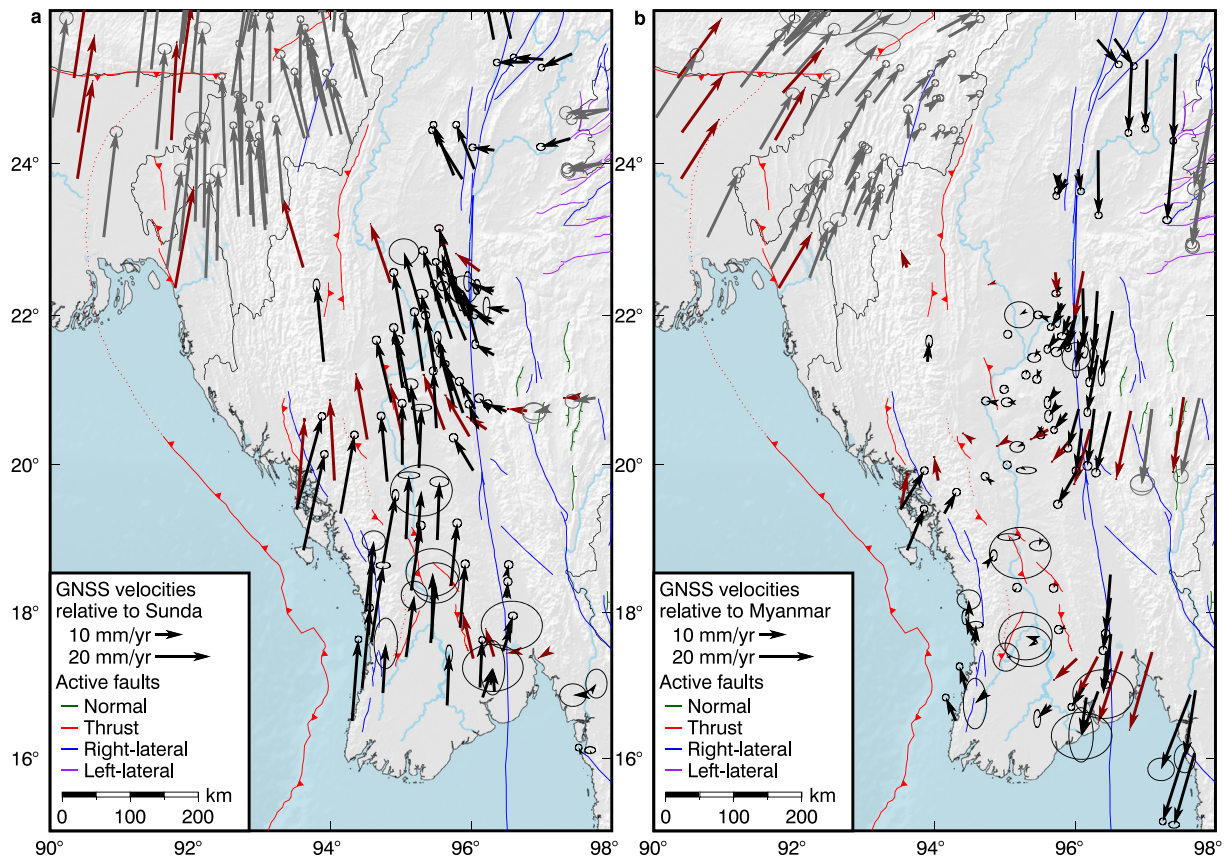


Fig. 2. (a) Final GNSS velocities in the Sunda plate reference frame and (b) relative to the Myanmar microplate, defined in text. Velocities from survey sites are shown in black, from continuous sites in red, and previously published velocities are shown in gray (Zheng et al., 2017). Mapped faults are from Wang et al. (2014). Ellipses represent 2-sigma uncertainties.

the 9 primary sites using GAMIT/GLOBK to determine their initial coordinates in the ITRF2014 reference frame, then estimated a 7-parameter Helmert transformation (three translations, three rotations, and one scale parameter) between the original, unknown frame and ITRF2014. This transformation has residuals at the few-cm level (Supplementary Fig. S2). By applying this transformation to the reported coordinates of other MSD sites, we bring their initial reported coordinates into the ITRF2014 reference frame.

A further correction is necessary to account for motion caused by the 2004 M_w 9.2 Sumatra-Andaman earthquake, which is modeled to have caused up to 14 cm of co- and post-seismic deformation in southern Myanmar (Qiu et al., 2018), resulting in a potential bias in the estimated site velocities for the southernmost sites at the cm/yr level, and mm/yr level for the remainder of the sites. We applied a static coseismic offset correction to all positions obtained after 2004 (Konca et al., 2008), and additionally a postseismic offset reflecting estimated motion between 2004 – 2013 from the model of Qiu et al. (2018) sampled at our observation sites to all survey positions recorded after 2015. The apparent southwestward motion of sites in the far southeast of Myanmar (located on the stable Sunda block) is reduced from more than 1 cm/yr in the Sunda reference frame before the correction to nearly zero motion following the correction (Supplementary Fig. S4), implying the correction works well. However, some biases likely remain at the few-mm/yr level due to a lack of data to constrain the true northward extent of the 2004 rupture and its postseismic effects, particularly along the southwestern coast of Myanmar. Thus, results in this area should be interpreted with caution.

The survey and processing methods are described in more detail in supplementary text S1 – S4. We combine our estimated velocities with 110 additional previously published GNSS veloci-

ties reported in the ITRF2008 frame in India, China, Bangladesh and Thailand from a recent compilation (Zheng et al., 2017) to form a complete dataset representing 209 velocities (see supplement) with which we examine the active tectonics of this complex convergence zone. The final velocities are shown in Fig. 2, relative to the Sunda plate (Fig. 2a) and relative to the central part of the Myanmar microplate (Fig. 2b).

2.2. Horizontal interseismic strain rates

In addition to a clear signal of dextral motion along the Sagaing fault, our velocity field reveals for the first time the presence of active convergence along the central Rakhine coast (18°–20°N) and indicates a relatively stable Myanmar Central Basin. To further examine the relative rates of deformation in various parts of the Myanmar microplate, we use our derived velocities to compute the pattern of horizontal interseismic strain rates across the region.

To compute horizontal strain rates, we first interpolate the East- and North-directed components of the velocity field onto a regular grid at 5 arc-minute sampling using a minimum curvature spline interpolation on a spherical surface (Parker, 1994), as implemented by the Generic Mapping Tools function ‘greenspline’ (Wessel, 2009). To enforce a smooth strain field, we keep only the 300 largest eigenvalues for the interpolation greens functions. We next compute the directional gradients of the interpolated velocity field (components of the strain rate tensor), then determine the principal axes of the strain rate tensor and its second invariant.

The strain rate principal axes (arrows) and magnitude of the second invariant (colors) are shown in Fig. 3a. The results demonstrate a significant improvement in our ability to resolve the strain rate field in the Myanmar region, compared to earlier ef-

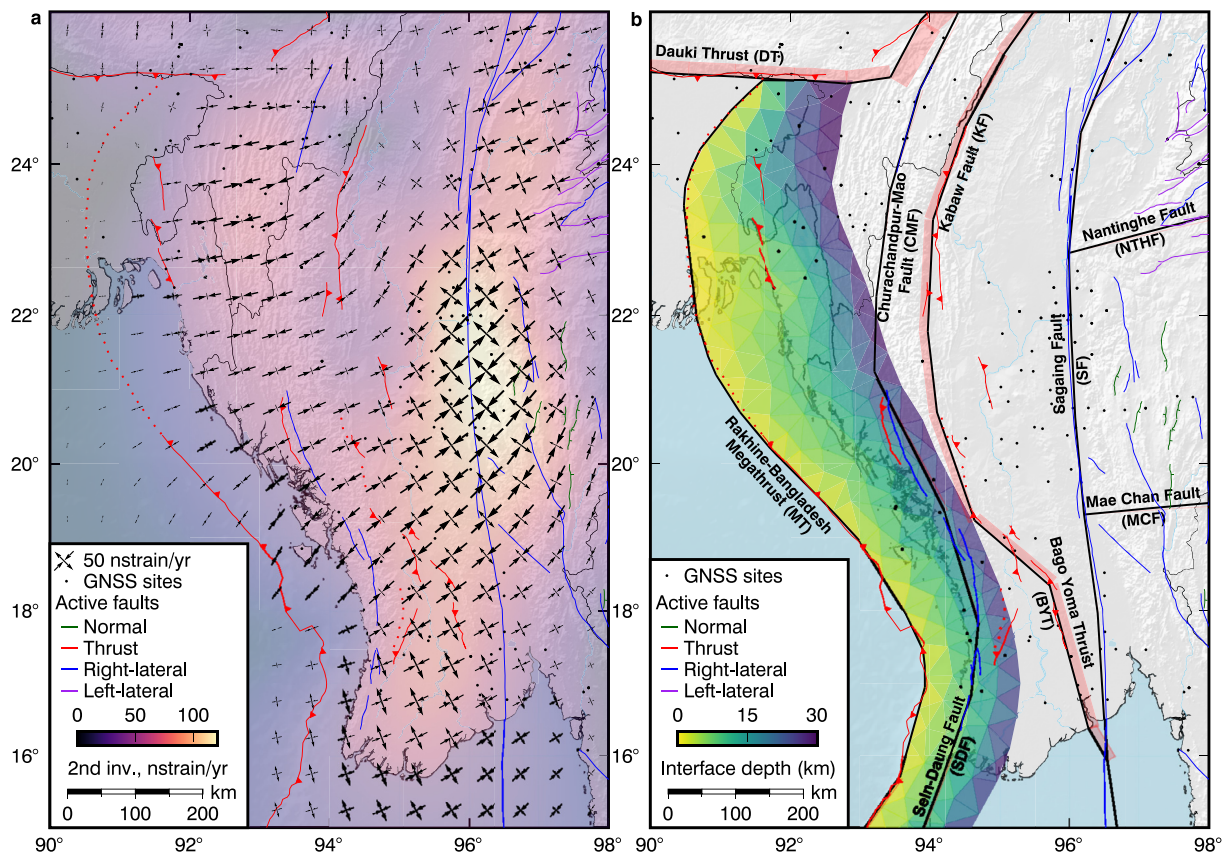


Fig. 3. (a) Horizontal interseismic strain rates and principal strain orientations computed from GNSS velocities (locations shown as dots). Arrows show principal strain axes; background colors show the second invariant of the strain tensor (equation (1)), a measure of the total horizontal strain rate. Strain rates within the western Indo-Myanmar Ranges are nearly pure shortening and perpendicular to the local topographic features between 19°–25°N, indicating that strike slip motion has been largely partitioned onto faults farther east. (b) Fault geometry used for block models. The megathrust depths are from Slab2 (Hayes et al., 2018), extended upward to meet the free surface at the fault trace. Red transparent rectangles indicate the surface projection of dipping crustal faults, assuming a constant locking depth of 15 km. Faults have been extended to connect in a simple fashion although we note that the true fault network is likely far more complex; at present the GNSS data density does not permit a more complete model. Mapped faults in both panels are from Wang et al. (2014).

forts (e.g., Hao et al., 2019). Notably, the strain rate throughout the western Indo-Myanmar Ranges north of 18°N reflects nearly pure convergence perpendicular to the coastline, while along the central Sagaing fault significant rates of simple shear are observed. The northern Myanmar Central Basin has comparatively low strain rates, but within the southern part of the basin and the Ayeyarwady Delta, the data suggests a combination of shear and N-S-directed extension, which may reflect either a deeper tectonic process, or ongoing compaction and extension within the sedimentary package (e.g. Wang et al., 2014). Overall, the present-day strain field suggests a relatively simple interpretation of the Myanmar microplate's overall tectonic setting, with the subduction zone and the Sagaing fault effectively partitioning strain into a pure-thrust component and a dextral strike-slip component. However, our strain rate field is still relatively low resolution due to the sparsity of stations, and we cannot use it to directly identify which individual faults presently accommodate this motion. Strains are computed in the ocean as well, but should not be considered reliable – lacking data in this area, our models ignore the possibility of permanent deformation in the oceanic part of the Indian plate, though this likely occurs farther south, as evidenced by recent intraplate earthquakes (Bradley et al., 2017; Hill et al., 2015).

2.3. Interseismic modeling

To address the question of the present-day seismic hazard across the region, we constructed a set of 3D interseismic tectonic block models to explore the data's implications for fault activity

across the central and southern part of Myanmar. This effort builds on the successes of previous highly simplified block models of the region (Mallick et al., 2019; Socquet et al., 2006), and extends them with a more complete fault network and a 3D triangular mesh for the megathrust. The modeled fault geometry is shown in Fig. 3b.

We constructed several models using the Blocks software (Meade and Loveless, 2009), following an iterative approach to identify the most important subset of faults required to fit the geodetic data, beginning from the large set identified by Wang et al. (2014). We compare this model against a simpler one with just two main faults bounding the Myanmar microplate – the Sagaing fault and the megathrust. For a given fault network, Blocks determines the best-fitting set of Euler pole rotation parameters for each discrete block enclosed by faults and uses these relative motions to determine the effective slip rates on each fault segment. Elastic strain accumulation on each fault segment is computed using the back-slip formulation, assuming zero slip down to an assumed locking depth except for the megathrust, which has variable slip (or kinematic coupling) expressed as a ratio of the long-term relative plate motion at each fault patch (Savage, 1983). Optimal block rotation and kinematic coupling parameters are estimated by minimizing the misfit between the observed velocities and model predictions in a least squares sense.

For crustal faults we assumed a uniform locking depth of 15 km and fault dips corresponding to earlier geodetic models (Mallick et al., 2019; Panda et al., 2020; Steckler et al., 2016), or based on focal mechanism observations for the Bago Yoma thrust (Fadil et al., 2021). We used the Slab2 interface model of the Sunda megathrust

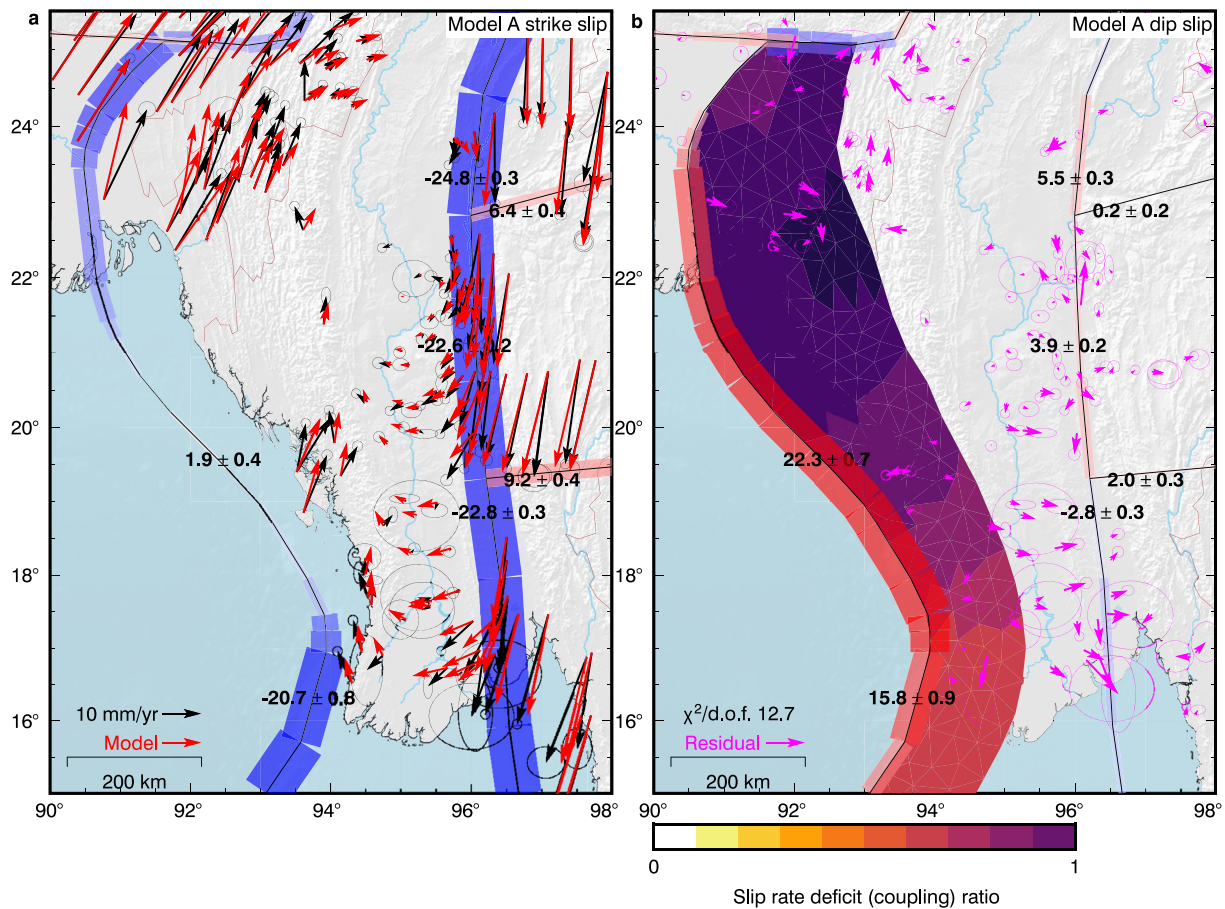


Fig. 4. Block modeling results for model A, with a non-deforming Myanmar microplate bounded only by the Sagaing fault and Rakhine-Bangladesh megathrust (not our preferred model). Slip rates inferred by the model are shown with line thickness proportional to slip rate on each segment, and in bold lettering for several segments. Panel (a) shows strike-slip rates with negative indicating right-lateral motion (blue), and GNSS velocities (black) and modeled velocities (red) relative to the Myanmar microplate. Panel (b) shows convergent motions with thrust motion in red and normal motion in blue, residual velocities (model – data) in magenta, and kinematic coupling (slip deficit ratio) on the megathrust shown as the colored triangular mesh. Ellipses represent 2-sigma uncertainties.

rust (Hayes et al., 2018) to construct a triangular mesh representing the Rakhine-Bangladesh megathrust. In central and northern Bangladesh this interface model does not extend to the surface; we extended it upward using linear interpolation to meet the mapped surface trace in this area (Wang et al., 2014). Because the geodetic velocities are observed to vary smoothly across the fault trace, we infer that the megathrust is not creeping near the surface. Thus, the specific location of the surface trace has little effect on the block modeling results, though it does affect the inferred total seismic moment deficit.

3. Results: active faults in the Myanmar sliver

Based on our observations from the velocity and strain fields above, we considered two primary models. In Model A, the Myanmar microplate has no active internal faults, and any internal deformation is attributed to elastic strain accumulation from either the Sagaing fault or the megathrust. In Model B, we consider the addition of a vertical strike-slip fault running through the Indo-Myanmar Ranges (connecting the Churachandpur-Mao fault in the north to the Sein-Daung fault in the south), and a dipping structure connecting the Kabaw fault to the Bago Yoma thrust. These models represent a basic hypothesis test regarding the presence of active faults within the Myanmar microplate but are by no means an exhaustive set of the possibilities. We discuss possible alternative and additional structures and connections between these faults below.

The simplest tectonic block model (model A; Fig. 4) has just two faults bounding the Myanmar microplate: the Sagaing Fault

in the east, and the Rakhine-Bangladesh megathrust in the west. The data suggest that both faults are fully kinematically coupled and the model fits the GNSS data reasonably well near the faults and in central Myanmar. This model is structurally similar to other oblique subduction zones where translation of a rigid sliver serves to partition strike slip and dip slip onto two separate faults and enables more nearly perpendicular subduction (e.g. Sumatra; Bradley et al., 2017). Very few earthquake focal mechanisms from the Rakhine-Bangladesh megathrust interface have been observed, but those available are consistent with this interpretation (Fadil et al., 2023; Maneerat, Dreger, et al., 2022). Notably, however, the orientation of maximum contraction within the Indo-Myanmar Ranges (IMR) in Fig. 3 is perpendicular to the inferred direction of maximum compression within the down-going slab from focal mechanisms there (Maneerat, Dreger, et al., 2022), suggesting a decoupling between the two plates and their stress states.

However, two significant anomalies are notable in the velocity residuals of this model (Fig. 4b): unmodeled northward motions within the northern IMR, and southeastward motion in the Ayeyarwady plain and southern Myanmar. Thus, the most significant second-order tectonic process within the Burma block appears to be a general north-south shear, with a minor component of either east-west shortening or rotation.

In comparison, model B (Fig. 5) includes the Churachandpur-Mao fault (CMF) and fits the data in the northern IMR much better than the 2-fault model, while maintaining a more nearly fault-perpendicular sense of slip along the megathrust. This result is in good agreement with most previous studies of this northern

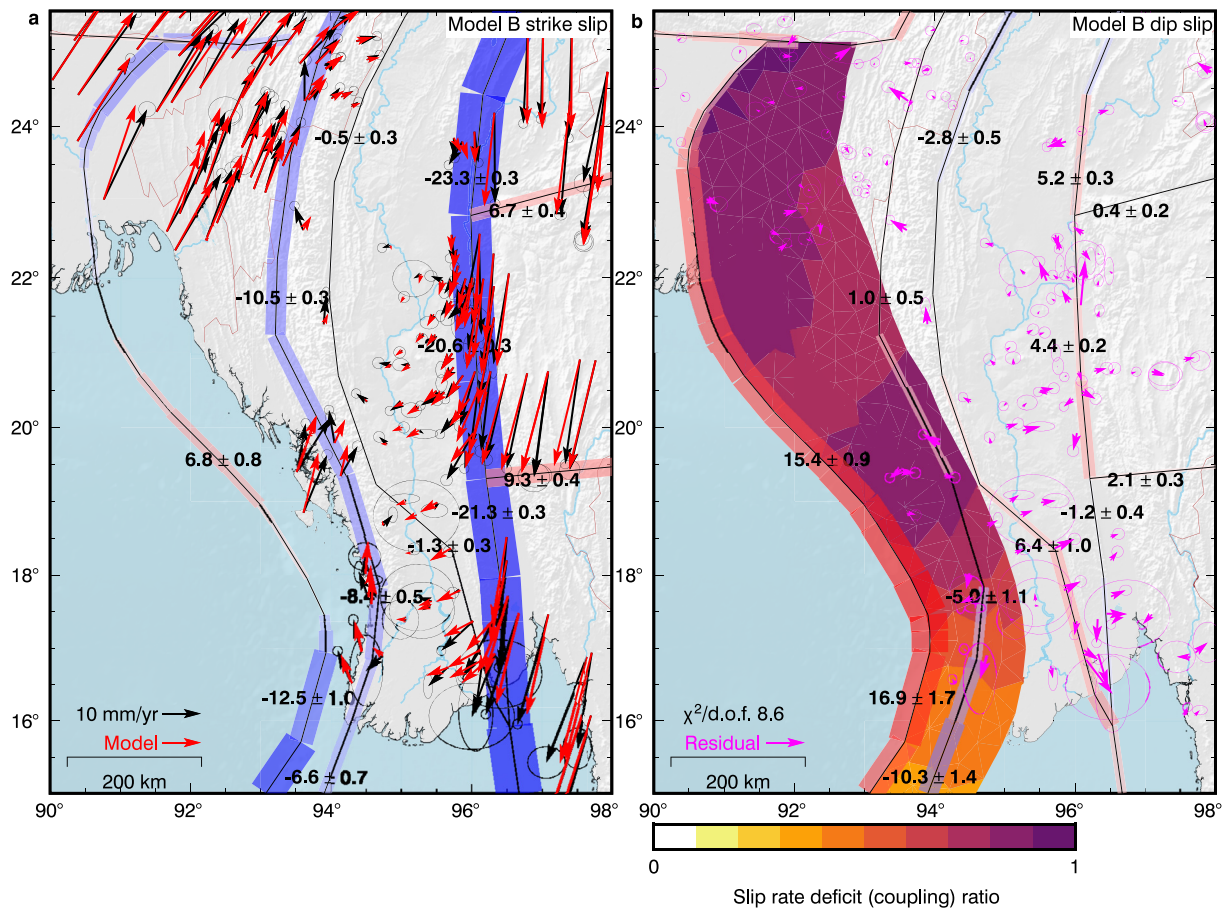


Fig. 5. Block modeling results for model B, our preferred model, which adds two additional internal faults running parallel to the coast throughout Myanmar. Slip rates inferred by the model are shown with line thickness proportional to slip rate on each segment, and in bold lettering for several segments. Panel (a) shows strike-slip rates with negative indicating right-lateral motion (blue), and GNSS velocities (black) and modeled velocities (red) relative to the Myanmar microplate. Panel (b) shows convergent motions with thrust motion in red and normal motion in blue, residual velocities (model - data) in magenta, and kinematic coupling (slip deficit ratio) on the megathrust shown as the colored triangular mesh. Fit to the data is greatly improved compared to model A (Fig. 4).

portion of the system (Mallick et al., 2019; Panda et al., 2020; Steckler et al., 2016). However, it remains unclear both from geomorphic observations (Maneerat and Bürgmann, 2022; Wang et al., 2014) and from our geodetic data how or whether the CMF connects with other structures to the south. Offshore surveys near 15–16°N indicate that the megathrust itself accommodates significant strike-slip motion to the south of the Rakhine coast (Nielsen et al., 2004), so it is likely that the strike-slip motion accommodated by the CMF is eventually transferred onto the main plate boundary, but the mechanism of this transfer remains unclear.

The option considered in model B is that the CMF continues southward within the IMR and runs offshore at the southernmost tip of the Rakhine coast. In combination with the Sagaing Fault, this creates effectively two long slivers translating northward at different rates (see Fig. 6). There is some geomorphic evidence for the inferred sense of strike-slip motion in the southernmost IMR along the Sein-Daung fault (Wang et al., 2014) but no geologic rates are available. In the central IMR, geologic and seismic evidence of significant strike-slip deformation remains elusive, so the question of the connection between the CMF and southern faults will likely require additional geophysical, geodetic or geomorphic evidence to resolve.

Model B also includes a fourth fault connecting the Kabaw fault and the Bago-Yoma thrust, representing compression throughout the central basin that has been responsible for recent moderate-magnitude earthquakes and post-Pleistocene deformation (Fadil et al., 2021; Lin Thu Aung et al., 2020). The best-fitting slip rates along this fault are relatively low in most areas, except for a mod-

erate rate of thrust motion (6.4 ± 1.0 mm/yr) south of 19°N that partially resolves the eastward residuals in this area from Model A. However, this modeled thrust motion is also associated with reduced coupling along the megathrust, as well as significant normal/extensional motion along the southernmost Sein-Daung fault, for which there is little geomorphic evidence. Together, the two faults indicate that sites in the Ayeyarwady Delta are translating eastward relative to the rest of the Myanmar microplate, at a rate faster than consistent with shortening only caused by kinematic coupling along the megathrust. We are presently unable to resolve this dilemma, but hypothesize that these effects could be related to unmodeled post-seismic effects from the 2004 Andaman-Aceh event (Supplementary Fig. S4), or presently unknown faults within the deep sedimentary basin here. Thus, results from this southernmost portion of the model (including the reduced coupling along the megathrust) should be interpreted with caution.

4. Discussion

4.1. The Rakhine-Bangladesh megathrust

The geodetic observations presented here indicate that significant interseismic contraction is occurring across the central Rakhine coast (Fig. 2); we conclude that the megathrust in this area is likely active and kinematically highly coupled. The strain rates derived from the new velocity field (Fig. 3a) indicate nearly pure convergence throughout the central and northern IMR. This observation lends additional support to the interpretation that

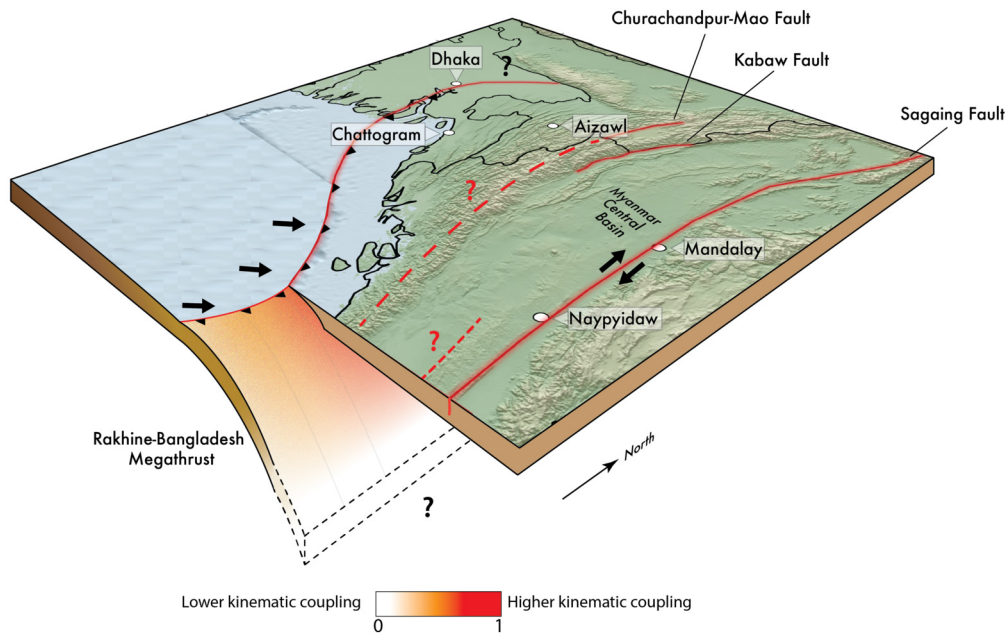


Fig. 6. Perspective view of the plates and the slip partitioning onto major active structures.

northeastward subduction of the Indian oceanic lithosphere is ongoing in this region (Mallick et al., 2019; Oryan et al., 2023; Steckler et al., 2016), in contrast to an earlier hypothesis that uplift of the Indo-Myanmar Ranges could be driven by lithospheric flow around the Eastern Himalayan Syntaxis, leading to westward motion of the Shan plateau and Myanmar central basin, and that subduction is presently inactive (Le Dain et al., 1984; Rangin et al., 2013). While we do see evidence of this westward motion in northern Myanmar, this hypothesis cannot explain the eastward motion of the central Rakhine coast (Fig. 2).

The convergence is not perfectly trench-perpendicular, however, and our block modeling results prefer partially oblique slip on the megathrust in several areas. Model A is the simplest model of the fault system in the region with just two major faults (Fig. 4) and indicates a peak thrust slip rate along the central Rakhine coast at 22.4 ± 0.9 mm/yr, but the megathrust becomes nearly pure strike-slip at the northern and southern edges of our model domain. This model predicts a total seismic moment deficit accumulation rate of 1.5×10^{20} N-m/yr across the megathrust, which we consider an upper bound. This rate is equivalent to a minimum recurrence rate of one M_w 9.0 earthquake every 240 years, if a single event were to release the entire slip deficit.

The more complex Model B has two additional internal faults that accommodate part of the relative motion between India and the Myanmar microplate, resulting in a lower but variable degree of obliquity along the megathrust (Fig. 5), and also a lower overall slip rate and degree of kinematic coupling. In this model, the megathrust accumulates seismic moment deficit at a lower rate of 8.5×10^{19} N-m/yr, equivalent to a minimum recurrence rate of one M_w 9.0 earthquake every 420 years. This rate of moment accumulation is in better agreement with paleoseismic observations inferring that large uplift has occurred along the coast once every 500 – 700 years (Wang et al., 2013). As numerous active fold-and-thrust structures in the outer belt of the IMR accommodate some of the shortening (Betka et al., 2018; Maneerat, Bürgmann, et al., 2022), part of the seismic potential of the subduction zone may be released along such splay thrusts in the forearc wedge.

Both models indicate that the megathrust is primarily pure thrust along the central Rakhine coast ($18 - 22^\circ$ N), with increasing obliquity associated with changes in the fault strike to the north and south of this segment. This is consistent with earlier

geodetic and geophysical observations in both areas (Mallick et al., 2019; Nielsen et al., 2004). While it is difficult to identify potential rupture boundaries or variations in the kinematic coupling along strike with our limited dataset, this variation in rake means the most likely potential tsunami source would be along the central Rakhine coast.

4.2. Fault connectivity within the Indo-Myanmar Ranges

Geodetic evidence for strike-slip fault activity, particularly in the northern IMR, has been reported but remains controversial. Galalaut et al. (2013) reported velocities for a regional GNSS network within the northern Indo-Myanmar Ranges in India, and suggested that a sharp offset between two nearby sites indicates a shallow creep signal across the CMF, hypothesized to be one of the major strike-slip faults within the northern part of the range. However, the relative site velocities also include an unlikely normal component of motion; thus, the possibility of a data outlier and a locked fault has also been argued (Mallick et al., 2019; Steckler et al., 2016).

Part of the difficulty in assigning significant strike-slip motion to the CMF is the observation that clear geomorphic evidence of the CMF is sparse south of the India-Myanmar border (Wang et al., 2014), suggesting a discontinuous fault network that does not accommodate significant long-term motion, or does so in a highly distributed fashion. Our modeling shows that the GNSS data in the northern Indo-Myanmar Ranges are poorly fit when the CMF is not included (Model A, Fig. 4), but we still lack sufficient geodetic observations in the critical central portion of the ranges to determine how this fault continues southward. In Model B, we connect the fault to the Sein-Daung fault in the southern IMR (Wang et al., 2014). However, connecting these faults tends to produce significant East-West-oriented opening along the Sein-Daung fault or within the Ayeyarwady basin (Fig. 5). Geomorphically, the Sein-Daung fault does not appear to have a significant normal offset and we consider this prediction of the model unlikely. Most of the GNSS data in this region are affected by the 2004 Andaman-Aceh earthquake, which resulted in significant deformation in this region (Supplementary Fig. S4), which may not have been adequately removed by our correction (Supplementary Text S4).

An alternative possibility is that the strain becomes distributed in the central IMR and ultimately transfers through the overriding plate onto the megathrust, with a lower rate of strike-slip motion on the Sein-Daung fault. We constructed a third block model that connects the CMF directly to the megathrust at 18°N, simulating this possibility in an approximate way (Supplementary Fig. S6). We found that this model fits the data slightly better overall than Model B ($\chi^2/\text{d.o.f.}$ 8.5 vs. 8.6) but results in a sharp change in the megathrust slip rate and coupling ratio at the fault intersection, and fails to fit the data in the southwestern IMR. A more complex model with many connecting faults could potentially better fit the observations, but we lack sufficient data density to justify such a model. Thus, while some strike-slip motion within the northern IMR is preferred by our modeling, our data are inconclusive regarding the southward continuation of this slip and its connection to faults within the southern IMR and Andaman Sea.

4.3. Myanmar Central Basin

Recent geologic and geomorphic observations (Lin Thu Aung et al., 2020; Maneerat and Bürgmann, 2022) and seismicity and focal mechanism data (Fadil et al., 2023; Mon et al., 2020) indicate activity on faults and anticlines within the inverted Myanmar Central Basin (MCB) (Fig. 1), though the rates of such activity have not been determined. Additionally, several damaging earthquakes within the central basin have occurred recently, most not associated with previously known active faults (Fadil et al., 2021). Therefore, an important question for our geodetic network is whether the data suggest significant tectonic deformation within the MCB.

In model B, the Bago-Yoma thrust running through the southern MCB has a thrust slip rate of 6.4 ± 1.0 mm/yr. This sense of motion is consistent with elevated topography within the Bago Yoma Range and recent earthquakes in this location (Fadil et al., 2021). However, the rate of motion on this fault may trade off with over-predicted normal slip on the Sein-Daung fault discussed above, and therefore this value may be an upper bound. Our dataset spans a region similar in size and complexity of deformation to the Pacific-North America plate boundary in the western United States, but has less than 10% of the GNSS observations (e.g., Kreemer et al., 2014). Thus, the data density is not sufficient to resolve strain from proposed additional minor faults, particularly within the MCB to the north (Mon et al., 2020), but our estimated strain rates are consistent with a NE-SW-oriented sense of shortening throughout the MCB (Fig. 3a).

4.4. Sagaing fault

The re-surveyed GNSS sites near Mandalay confirm previous observations that the center of strain accumulation beneath the Sagaing fault is offset to the east of the fault trace by 5 – 10 km, and suggest that the locking depth is 15 km, indicating an eastward dip of 60–70° (Tha Zin Htet Tin et al., 2022). This locking depth is relatively deep in comparison to other strike-slip faults, though shallower than previously estimated at this location (Vigny et al., 2003; Maurin et al., 2010). A similar degree of asymmetry has previously been noted across the San Andreas fault (Fialko, 2006; Fuis et al., 2012; Lindsey and Fialko, 2013), where modeling suggested a non-vertical fault geometry could best explain the observations. However, a dip significantly different from 90° on a strike-slip fault is unlikely to evolve independently, because it is not the lowest-energy configuration of the fault, unless other significant forces or inheritance are at play.

One possible explanation for a non-vertical Sagaing fault is that westward motion of the Shan plateau is driven by gravitational collapse of the Tibetan Plateau (Rangin et al., 2013). An eastward dip

could evolve during this process if the upper crust is moving westward at a rate faster than the lower crust and lithosphere, leaving the deeper shear zone associated with the Sagaing fault behind as the fault itself moves west. This is similar to hypotheses regarding the causes of dip in the San Andreas fault system (Lindsey and Fialko, 2013). Alternatively, it could simply reflect shallower inherited structures with an eastward dip that have been reactivated as the Sagaing fault. These scenarios would have very different implications for viscosities in the Shan plateau lithosphere, and the processes responsible for motion of the Tibetan lithosphere around the eastern Himalayan Syntaxis. A critical discriminant between these several hypotheses would be information about the viscosity profile of the lithosphere in the Shan plateau.

5. Conclusions

The geodetic observations presented here include more than 70 new survey-mode and continuous GNSS velocities spanning central and western Myanmar, from 15 – 23°N and 93 – 98°E. We use these data to infer strain rates across the Myanmar microplate at much higher resolution than previously possible, and construct several possible block models of the active fault network within Myanmar, eastern India and Bangladesh. Our data confirm the presence of active convergence perpendicular to the local topography throughout the central and northern IMR and along the Rakhine coast, in a manner consistent with active subduction and strong kinematic coupling of the megathrust, at a rate of 15 – 22 mm/yr, representing the potential for a M_w 9.0 earthquake as often as every 240 – 420 years, if all accumulated strain is released seismically on the plate interface. The data also establish a nearly constant strike-slip rate of 20 – 23 mm/yr along the length of the Sagaing fault, with additional strike-slip motion located within the IMR required to fit the data. We examine several proposed models for the connectivity of secondary strike-slip and thrust faults across the IMR and MCB, and find that a relatively small set of active faults can explain many of the data, though more work is required to unambiguously identify the fault kinematics. Our results have important implications for earthquake and tsunami preparedness across the region, and indicate areas for future study where the observations remain ambiguous about ongoing fault activity and seismic hazard, particularly within the densely populated Ayeyarwady Delta region and around the Bay of Bengal.

CRedit authorship contribution statement

Eric O. Lindsey: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yu Wang:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Conceptualization. **Lin Thu Aung:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Jeng-Hann Chong:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis. **Qiang Qiu:** Writing – review & editing, Software, Investigation, Formal analysis. **Rishav Mallick:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lujia Feng:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation, Data curation. **Pyae Sone Aung:** Writing – review & editing, Validation, Software, Methodology, Investigation, Data curation. **Tha Zin Htet Tin:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Saw Myat Min:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Kyle Bradley:** Writing – review & editing, Software, Resources, Methodology, Inves-

tigation, Formal analysis, Conceptualization. **Oo Than:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Data curation. **Kyaw Moe Oo:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Data curation. **Myo Thant:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Frederic Masson:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Roland Bürgmann:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Emma M. Hill:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data & code used in the analyses presented here are publicly available. The raw GNSS observations from continuous sites maintained by the Earth Observatory of Singapore are available online at http://ftp.earthobservatory.sg/MIBB_Data/. Velocities for all sites are available in the supplementary data. Timeseries for all sites, raw survey GNSS observations, metadata from the survey sites, and modeling software and scripts are available at the Digital Repository of NTU at <https://doi.org/10.21979/N9/QK3AKA>.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.epsl.2023.118384>.

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