Revisiting the 1762 Arakan earthquake

– young coastal deformation of Ramree and Cheduba Island, western Myanmar (Burma)

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Summary

The Arakan earthquake of 1762 was one of the earliest subduction-related earthquakes for which related land-level changes were noticed by geologists (Halstead, 1842 & Mallet, 1878). Field observations in 2010 and 2011 allow us to refine our understanding of the coastal uplift history of Ramree and Cheduba Islands. U-Th dating of uplifted corals indicate that the western coasts of both Cheduba and Ramree Islands experienced sudden uplift mid 18th century. We ascribe this coastal uplift during and after the 1762 Arakan earthquake.

We find the net-uplift pattern duing and after the 1762 earthquake presents a double-hump geometry perpendicular to the megathrust. This double-hump uplift pattern could reflect either non-uniform slip on a recti-planar megathrust, or slip on an upper-plate thrust fault within the accretionary wedge. However, slip on the megathrust would not explain the presence of flights of terraces, which indicate significant long-term regional tilting similar in style to the deformation in 1762. Also, it can not explain the firts-order recurrence interval of such uplift event. Therefore, we suggest the 1762 earthquake was produced, at least in part, by rupture of an upper-plate thrust fault.

Background

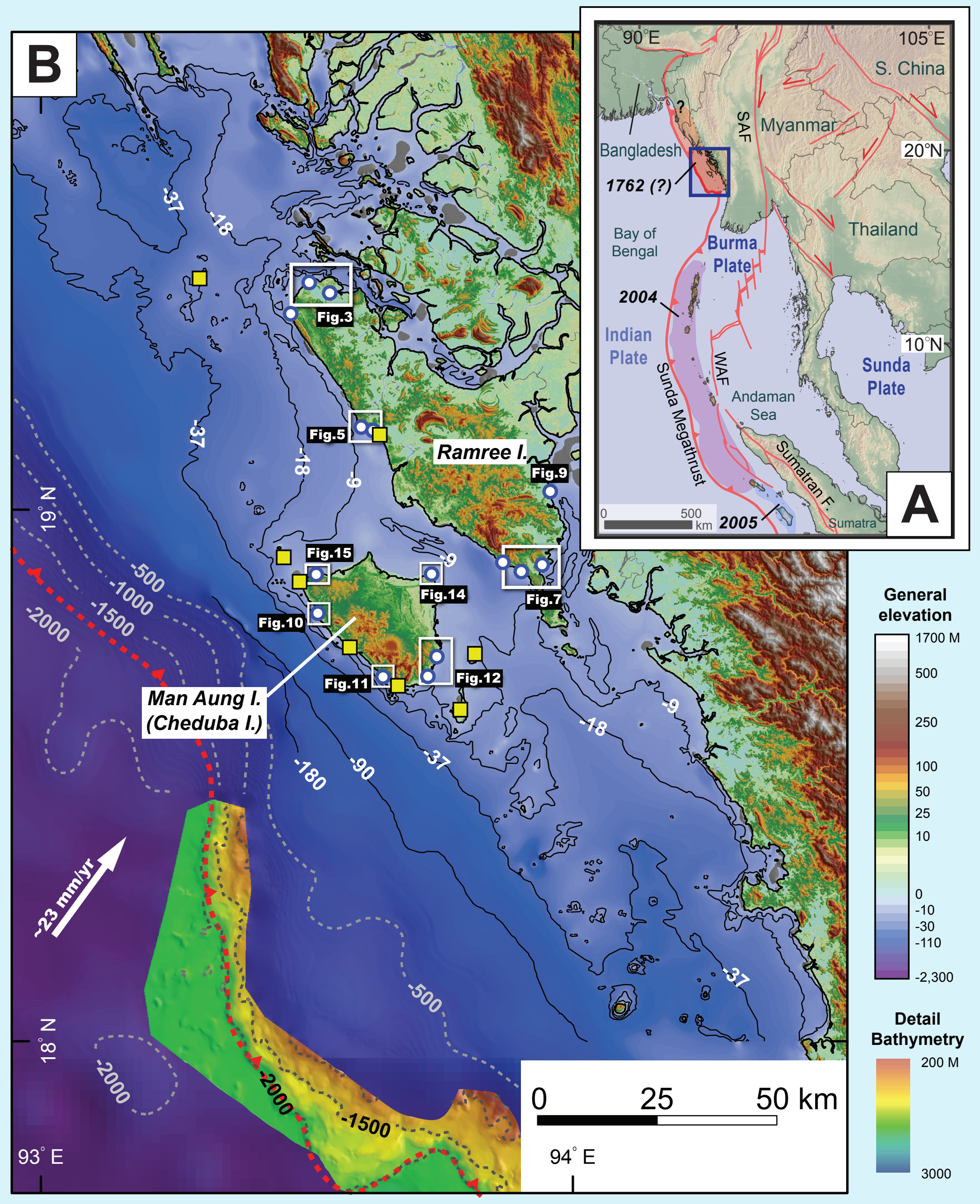


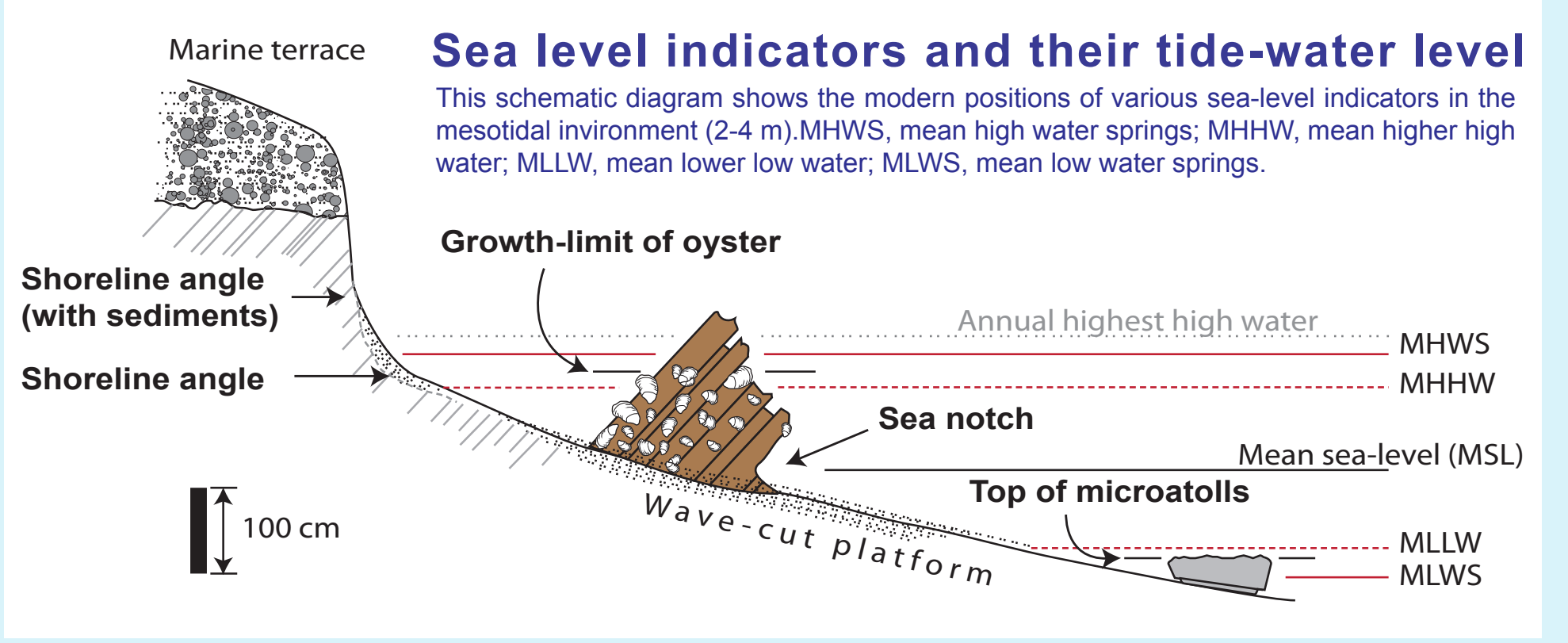
Figure 1. Cheduba (Man Aung) and Ramree Islands are the expressions of active accretions above the Sunda megathrust offshore the western coast of Myanmar.

(A) The last seismic ruptures of the northern Sunda megathrust, between the Indian and the Burma plate. Orange color depcits the inferred 1762 Arakan rupture from historical reports. This ~ 500 km long seismic patch is the only megathrust-related rupture north of the 2004 rupture since 18th century. Red lines are major active faults in the Southeast Asia, where most of major faults are strike-slip faults on the Burma and the Sunda plate [after La Dein et al. 1984]. Blue box shows the map area of Fig.1b. SAF, Sagaing fault system WAF, West Andaman fault.

(B) The accretion-related topography and surveyed locations in Cheduba and Ramree Islands above the Sunda megathrust. This section of megathrust receives ~ 2cm/yr oblique plate convergence from the northeastward motion of the Indian plate [Socquet et al., 2006]. The long-going plate-convergence creates a series of megathrust-parallel underwater ridges within the accretionary prism. Cheduba and Ramree Island are the two highest potions of these tectonic-ridges. Black solid-contour is modified from US Army topography maps [U.S. Army Map Service, 1955]. Grey dashed-contour is from ETOPO-1. The high-resolution bathymetry is digitized from Nelson et al., 2004. Yellow-square shows the 19th century's observation point [Halstead, 1841; Mallet, 1878]. White-dot represents the survey location of this study from 2010-2011.

Holocene uplift

Ramree Island



Sea level indicators and their tide-water level

This schematic diagram shows the modern positions of various sea-level indicators in the mesotidal environment (2-4 m).MHWS, mean high water springs; MHHW, mean higher high water; MLLW, mean lower low water; MLWS, mean low water springs.

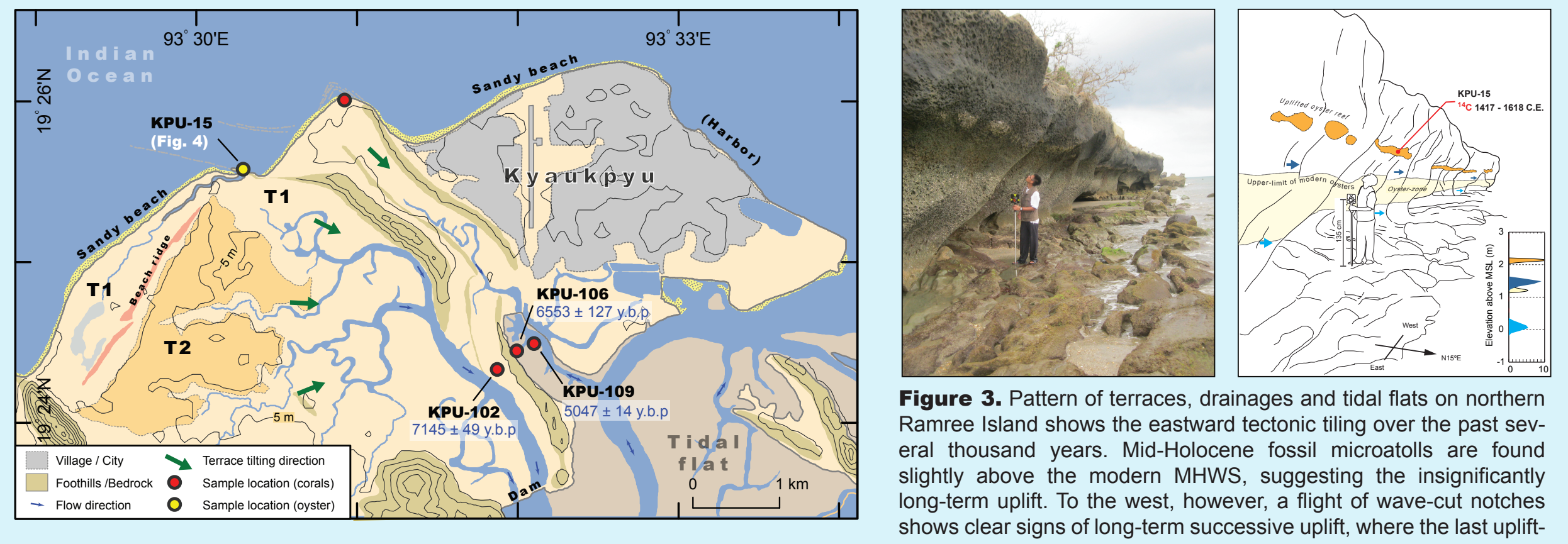
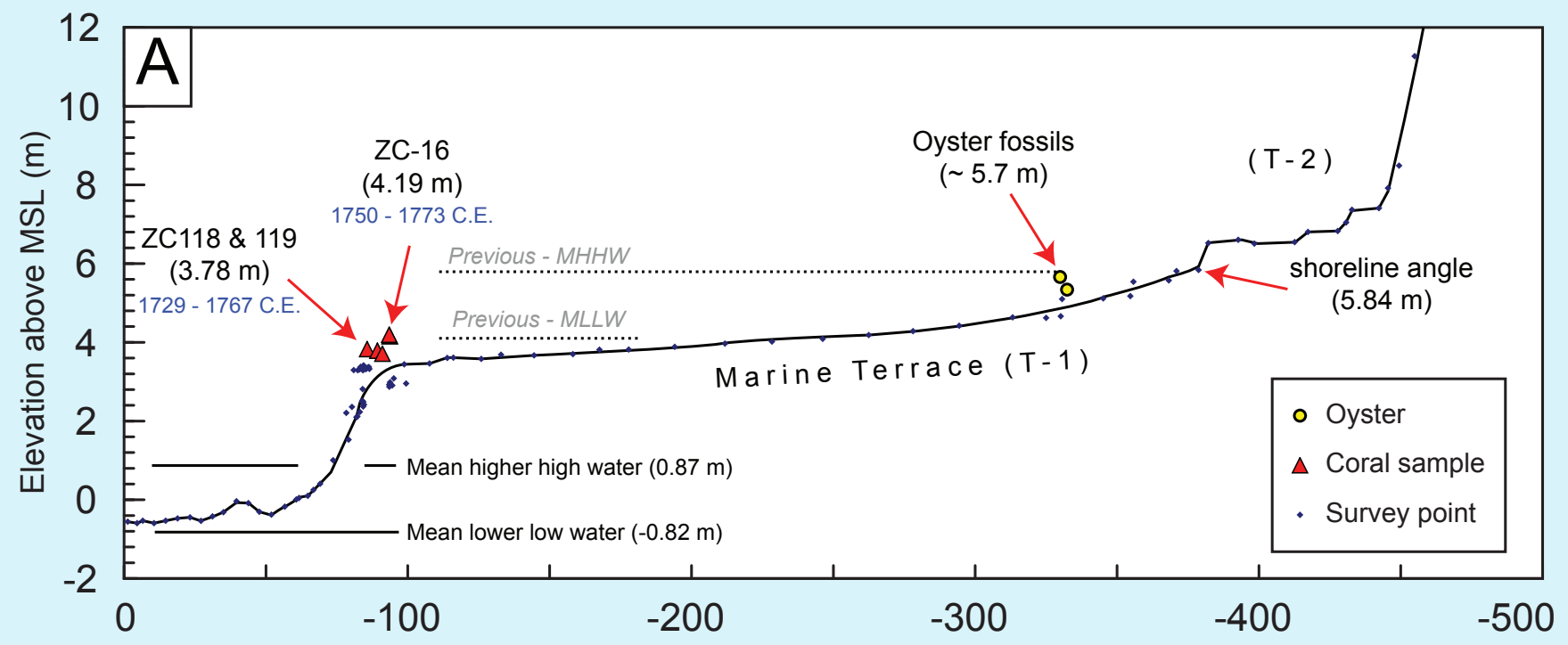


Figure 3. Pattern of terraces, drainages and tidal flats on northern Ramree Island shows the eastward tectonic tiling over the past several thousand years. Mid-Holocene fossil microatolls are found slightly above the modern MHWS, suggesting the insignificantly long-term uplift. To the west, however, a flight of wave-cut notches shows clear signs of long-term successive uplift, where the last uplifting event occurs after 16th century (**KPU-15, UP**).

Figure 6. The U-Th age from uplifted microatolls on lowest terrace (T1) shows ~ 5 m of uplift occurred in the 18th century, most likely in 1762. Profile location is indicated in Figure 5. All the sea-level indicators on T-1 shows identical amount of uplifting relative to their equivalent tide-water level.



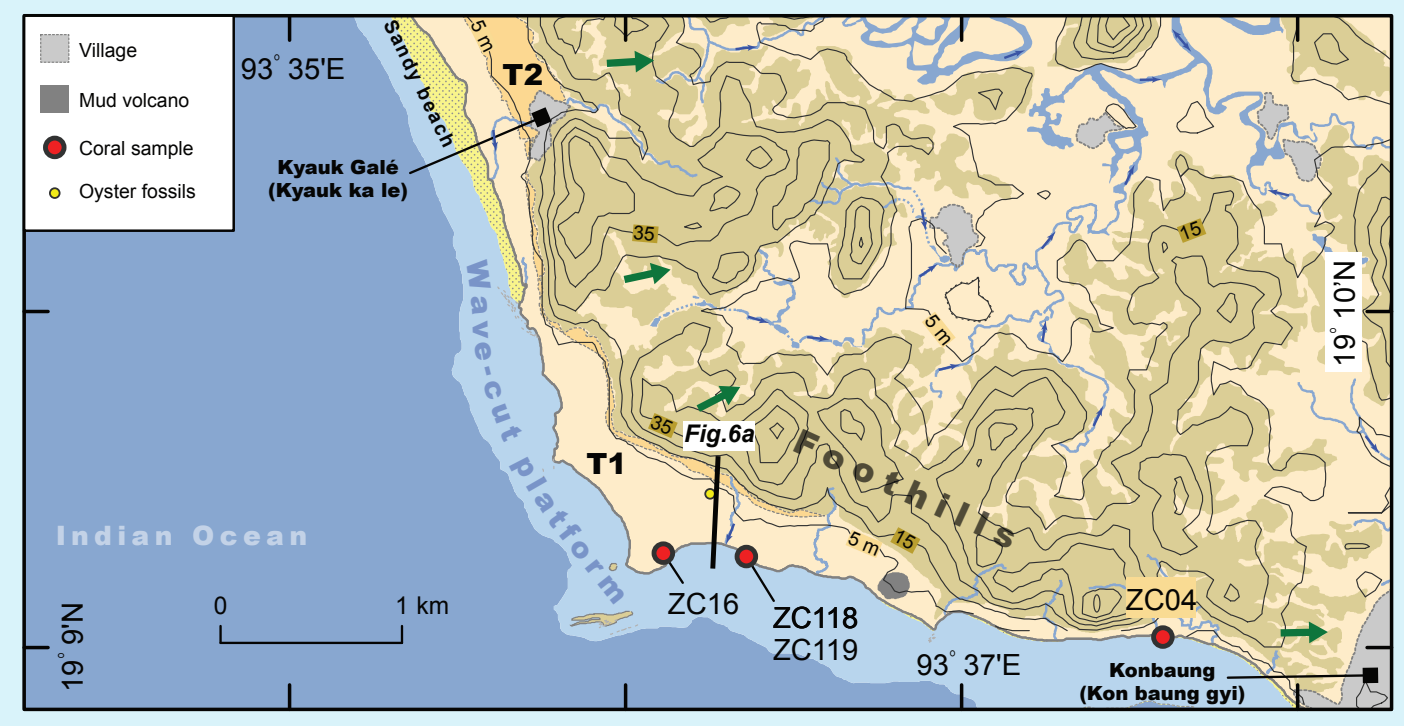


Figure 5. Drainage and terrace patterns of central west coast of Ramree Island also show eastward tilt.

The fluvial plain and terraces northeast of the foothills shows clear eastward tilting from the aerial photo survey and the drainage patterns. West of the foothills, the elevation of the lowest terrace between Kyauk Galé and Konbaung has been described by Mallet [1878] to be ~ 6 m above the water level at the time of his visit.

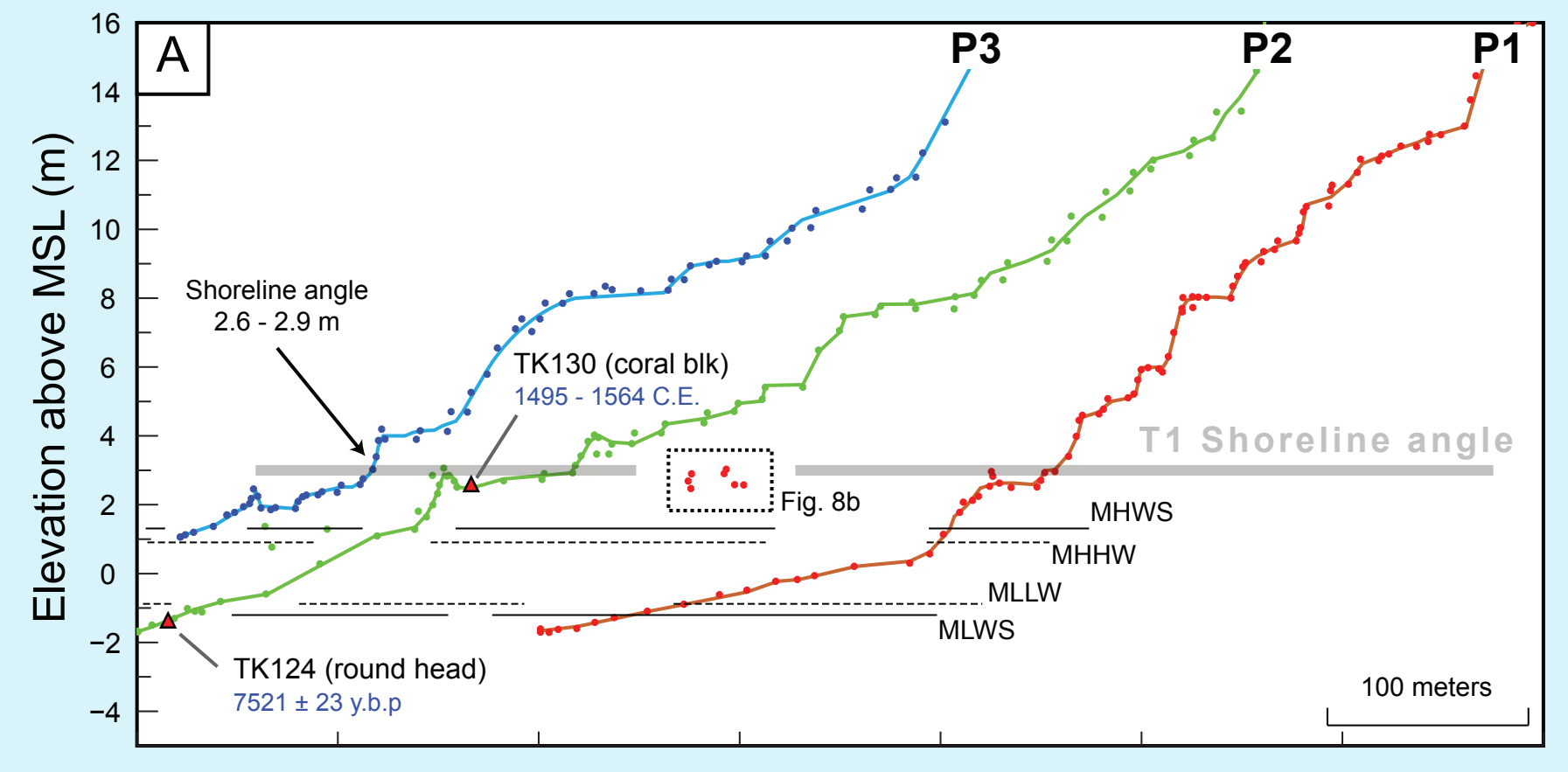


Figure 8. Topographic profiles at southwestern Ramree Island show ~ 1.5 m uplift of T1 after mid-16th century. The shoreline angle of T1 is about 1.5 m above its equivalent position in the modern tidal range. U-Th ages from coral blocks in T1's deposit suggest the uplift occurred after mid-16th century.

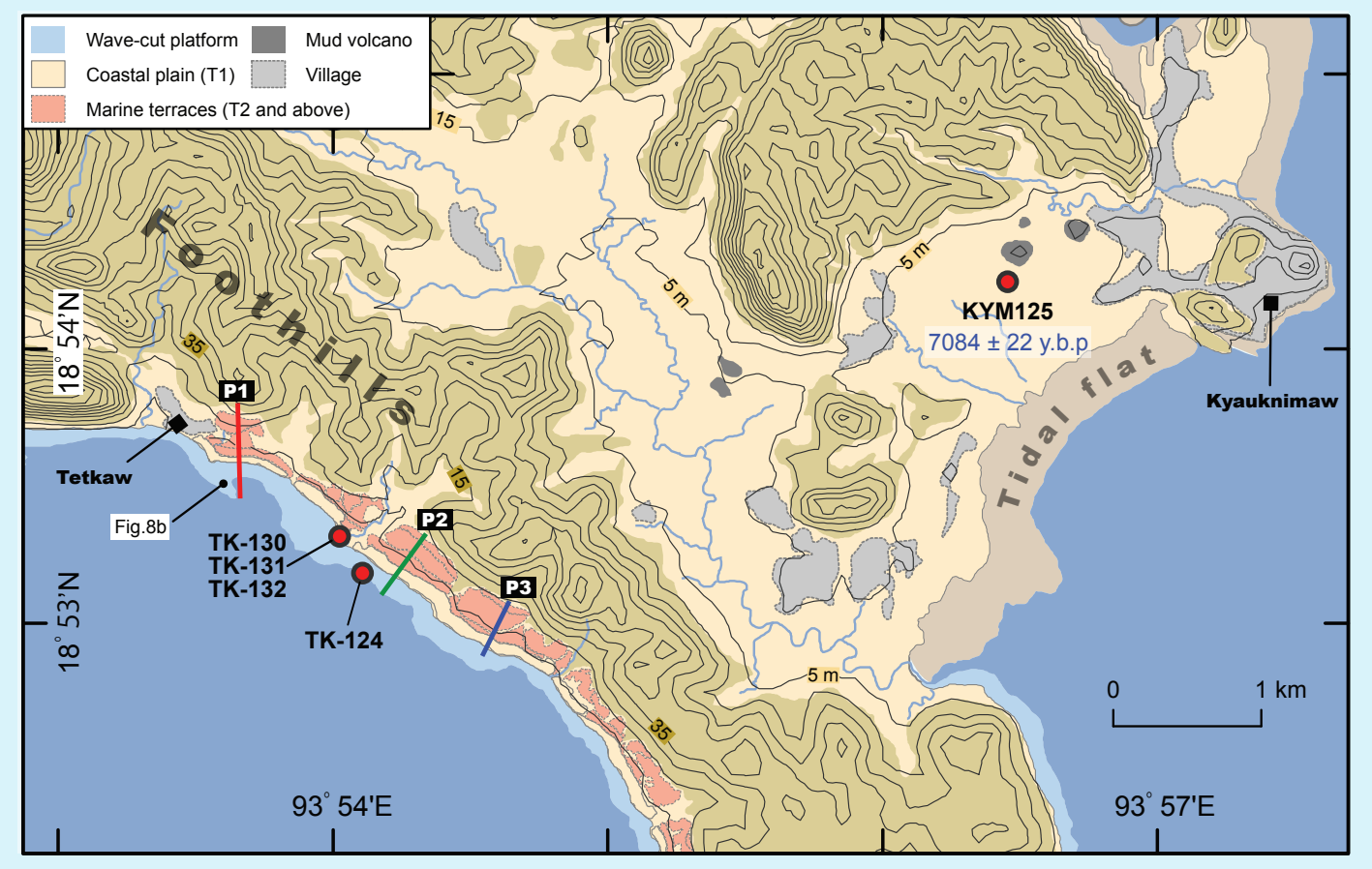


Figure 7. Contrast in geomorphology in west side and east side of southern Ramree Island implies uplift and eastward tilt. Colored lines are topography profiles across these marine terraces. Red dots show locations of dated corals.

Figure 15 Dated terrace on the northern Cheduba Island appears to suggest large uplift during 1762 earthquake. **(A)** We separate the lowest marine terrace T1 into three sub-terraces (T1a, T1b and T1c); however, these terrace raisers are not clearly separable in the field, perhaps due to the recent agricultural disturbance. **(B)** Oyster bed and preserved uplift shoreline angles of T1 suggests ~ 7 – 7.5 m uplift after 15th – 17th century.

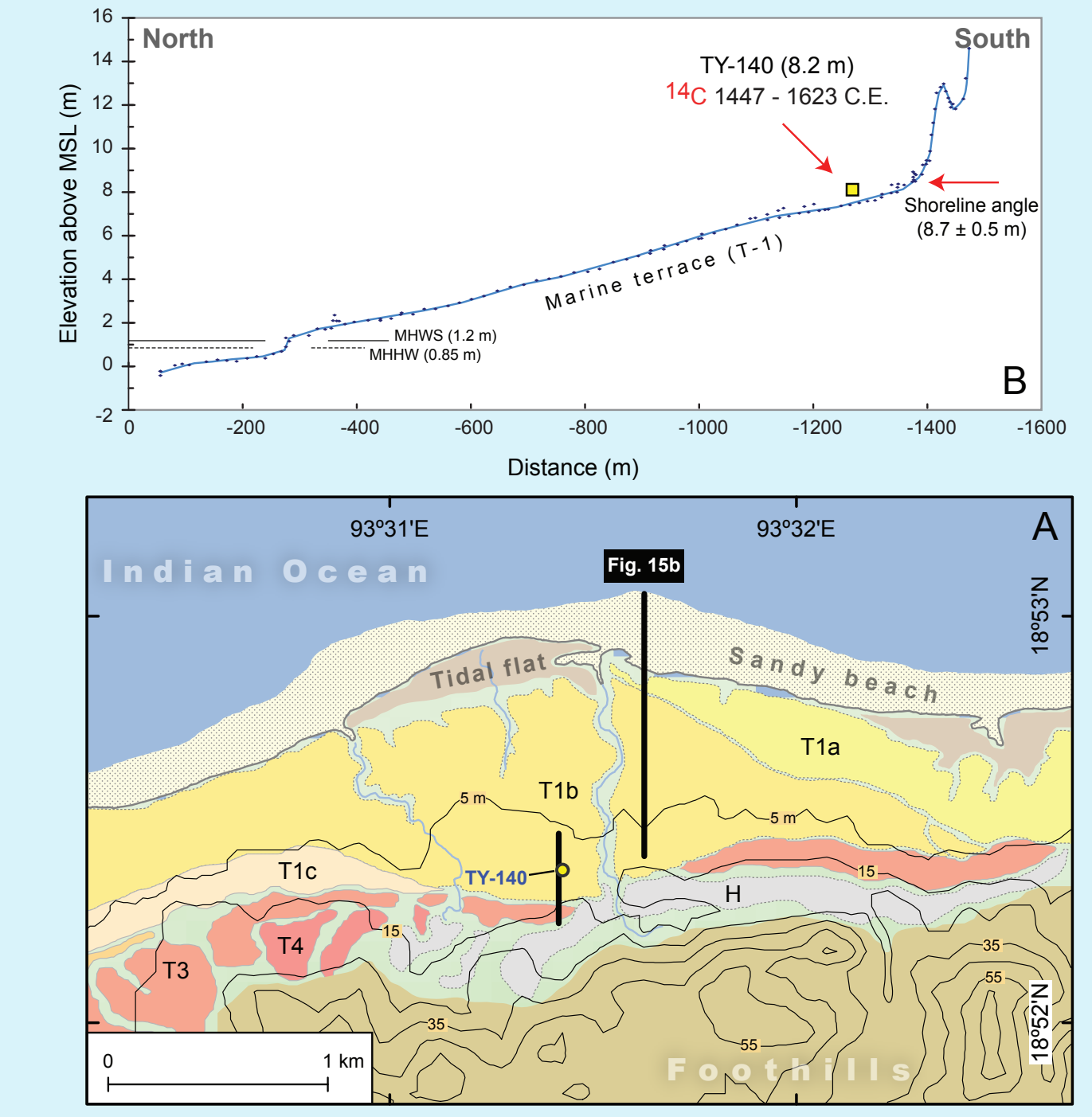


Figure 10. **(Right)** The flight of marine terraces along the western coast of Cheduba Island shows successive uplift. Black-dashed line depicts the approximate location of Fig.10b. **(Left)** U-Th age from an eroded microatoll (KM144) on the lowest terrace (T1a) suggests ~ 4.2 m uplifting after mid-15th century. The relief between T1a and T1 is ~ 0.4 m. The U-Th age from KM143 is explained in main text. Terrace elevation is inferred from the surveyed coral elevations.

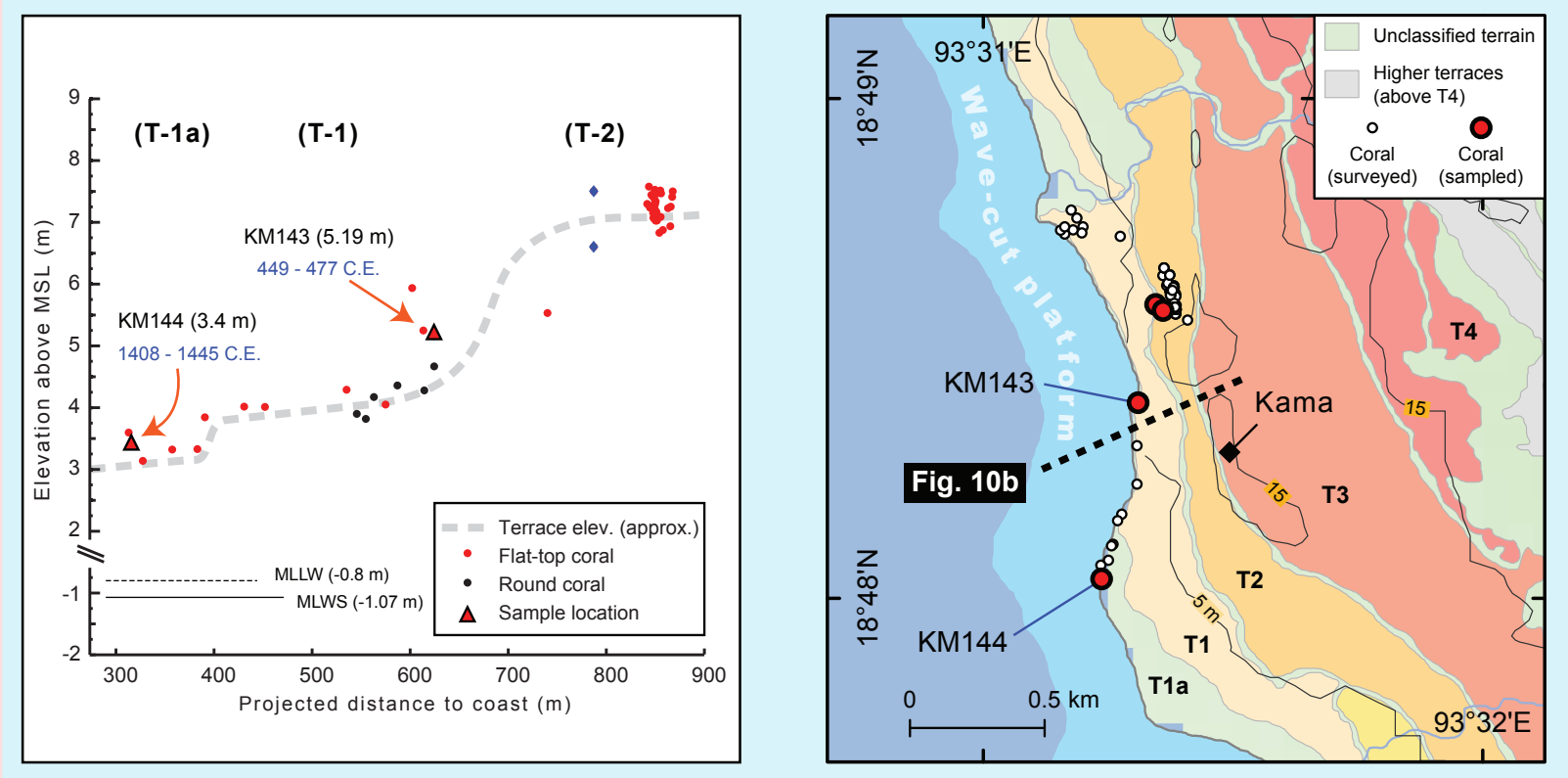
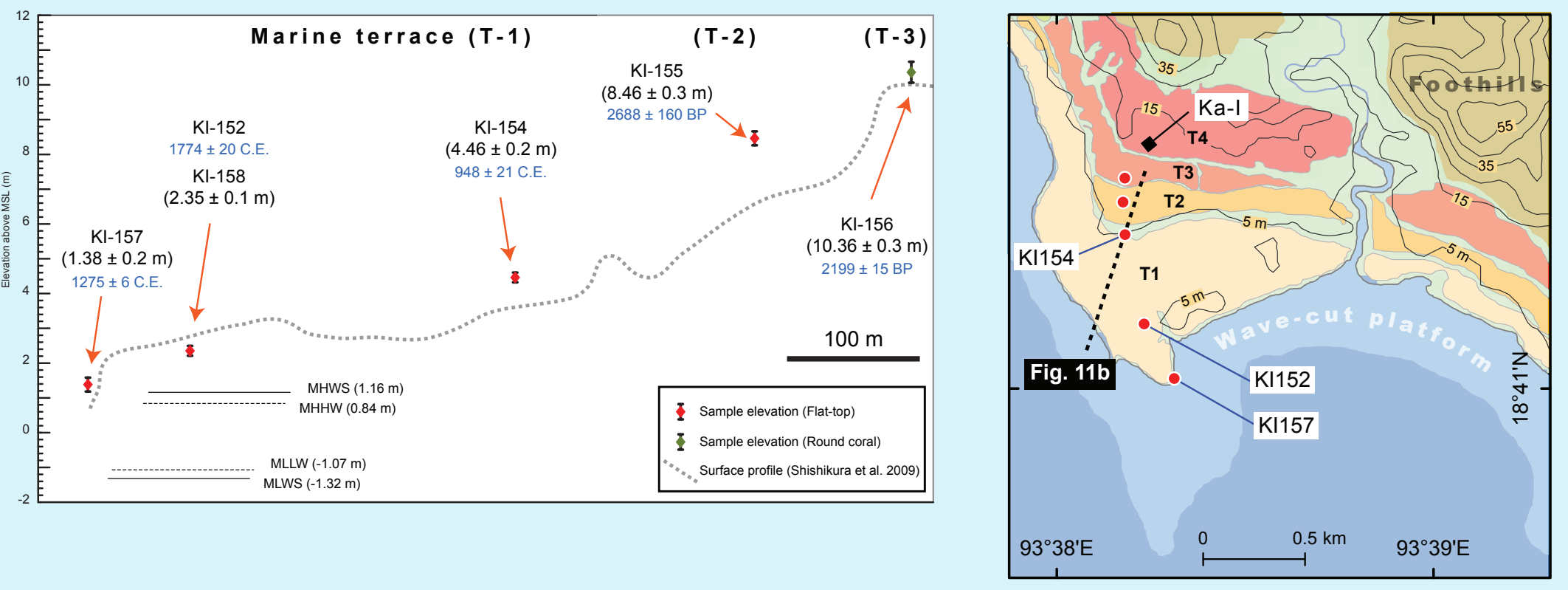


Figure 11. Map and topographic profile of marine terraces near south tip of Cheduba Island showing progressive late Holocene uplift. The U-Th age of sample KI-152 from microatoll on T1 shows ~ 3.4 m of uplift since 1724 to 1832 C.E., most likely in 1762. Other ages are likely indicating the timing of uplift events prior to 1872 C.E.



Toward the northern Sunda megathrust

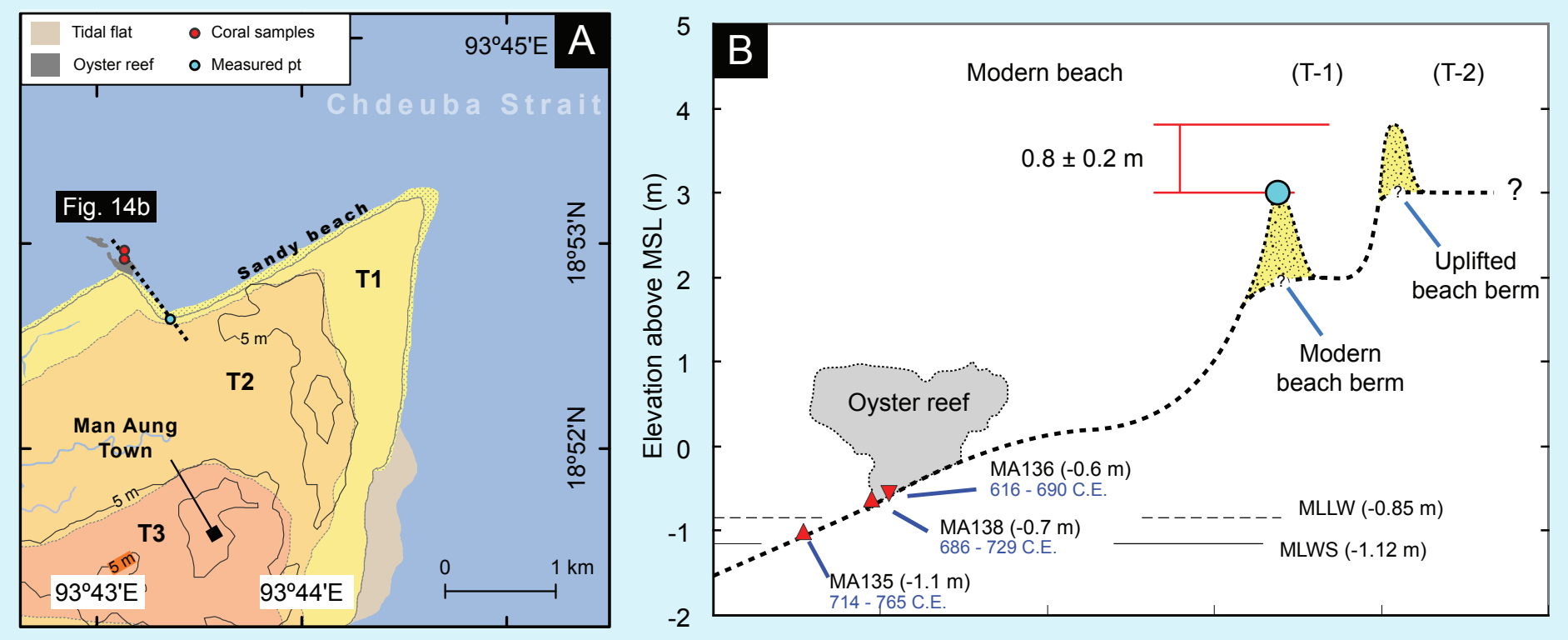


Figure 14.

(a) Marine terraces on the northeastern tip of Cheduba Island are lower than their equivalents on the western Cheduba coast. The elevation of T2 near Man Aung town is less than 5 m, reading from the SRTM contour, whereas T2 is higher than the 5 m contour along the western coast of Cheduba Island (Fig.10 & 11).

(b) The elevation difference between modern and uplifted beach berm implies < 1 m of uplift during the latest tectonic event. U-Th ages from uplifted corals beneath the modern oyster reef suggest the event occurred after the 8th century. Black-dashed line shows the approximate topography from field observations. Blue point is the top of modern beach berm on T1.

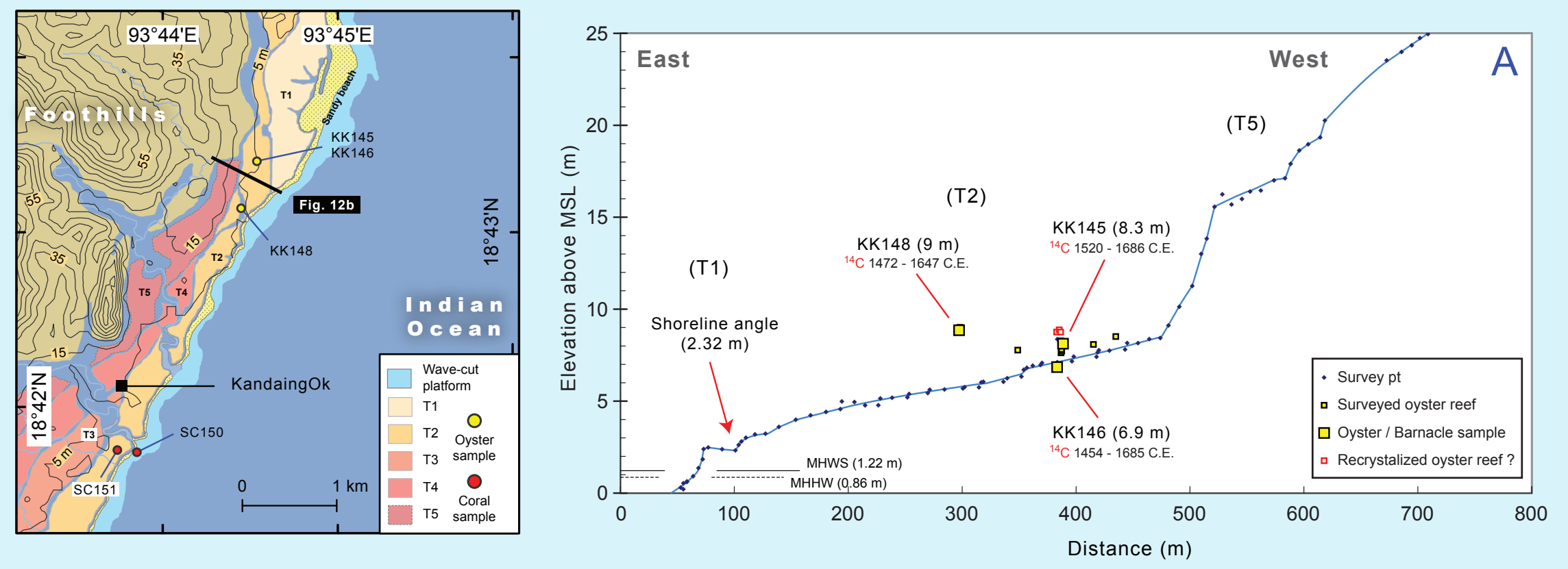
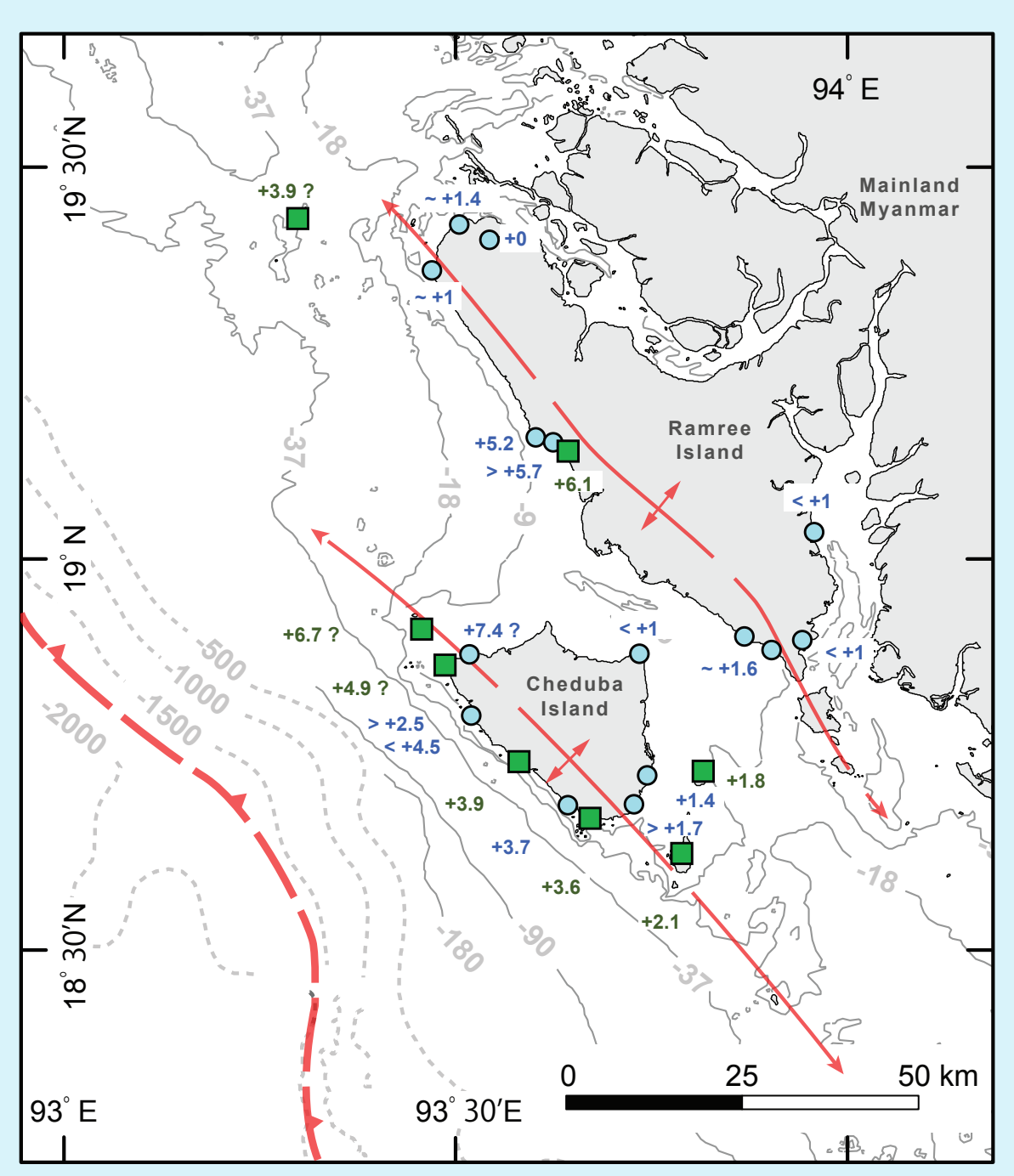


Figure 12. Topographic profiles and sample locations on the marine terraces along the eastern coast of Cheduba Island.
(B, Right) Uplifted shoreline angle and oyster reef show ~ 1.1 m uplift after 17th century, north of KandaingOk village (Fig. 12). Fifteenth to sixteenth century radiocarbon ages from the oysters on T2 suggest the lowest terrace (T1) rose after 17th century, likely during the 1762 earthquake.

Cheduba Island

Net-uplift since 1762 earthquake

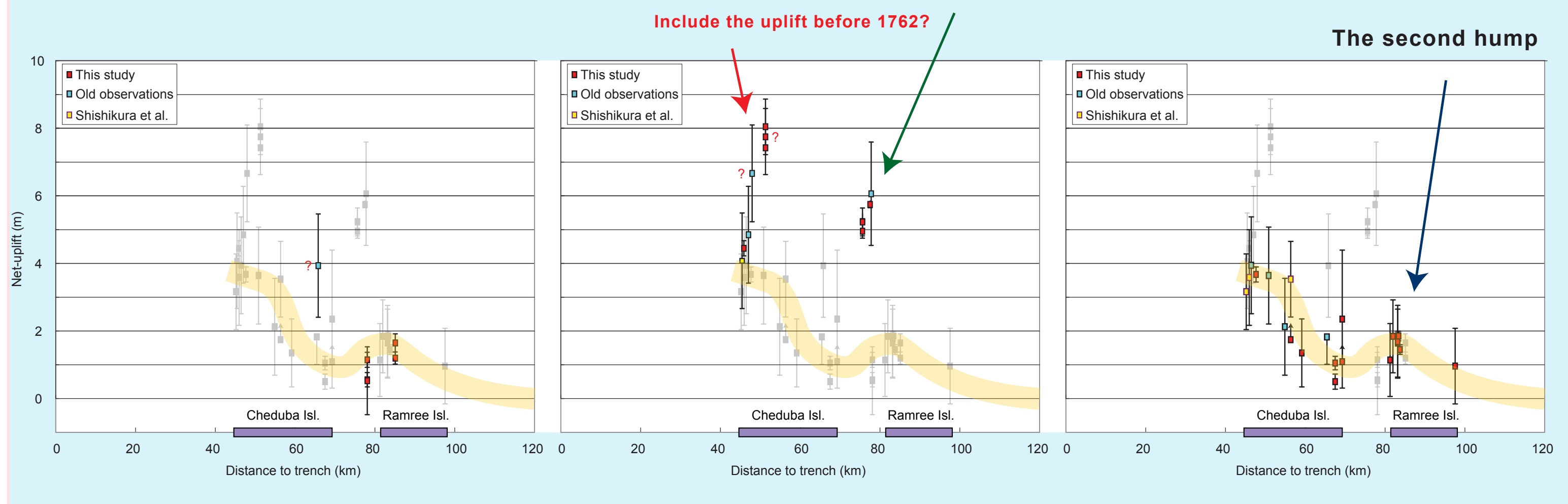


The land-level change (Uz) that we observed along the coast is affected by both the tectonic deformation (Ut) and non-tectonic water-level change through time (S*T). To ensure our observations correspond to the tectonic deformation (Ut), we therefore remove the amount of sea level rise from our survey results. The global sea-level models from late-18th and 19th century [Jevrejeva et al., 2008; Church and White, 2011] yield about 0.25 m sea-level rise since 19th century. Most of the sea level rise occurred within the 20th century (~ 0.2 m). This result suggests only the modern survey data were contaminated by sea-level rise. In contrast, the mid-19th century observations have much less influence from the rise of sea level.

After removing the sea-level change effec, We found the largest tectonic uplift occurred at the western coast of Cheduba, about 3 - 4 m in average. In the rest of Cheduba Island, the uplift ranges from ~2 to ~1 m from indicators on the lowest terrace (T1). The smallest uplift appears at the northwest corner of the island, where we believe the uplift is less than 1 meter based on the observation from the uplifted beach berm.

Toward the western coast of Ramree Island, the net-deformation pattern becomes much complicate. In general, just like most of the ground deformation pattern along the megathrust, the vertical deformations decrease away from the trench. However, at the central western Island, the uplift abruptly rises up to nearly 6 m, standing out from the ~ 1 to 2 m general emergence at the rest of western Ramree Island. Even the general ~1 to 2 m uplift is also higher than the uplift at the northeastern corner of Cheduba Island, representing a secondary uplift high along the western coast of Ramree Island.

Figure 16. This compilation of ours and the 19th century measurements of 1762 uplift suggests separate domal uplifts of Cheduba and Ramree Island. This pattern is consistent with the onshore and offshore topography. We therefore suggest that the 1762 event included incremental uplift on two double-plunging antiforms above the megathrust.

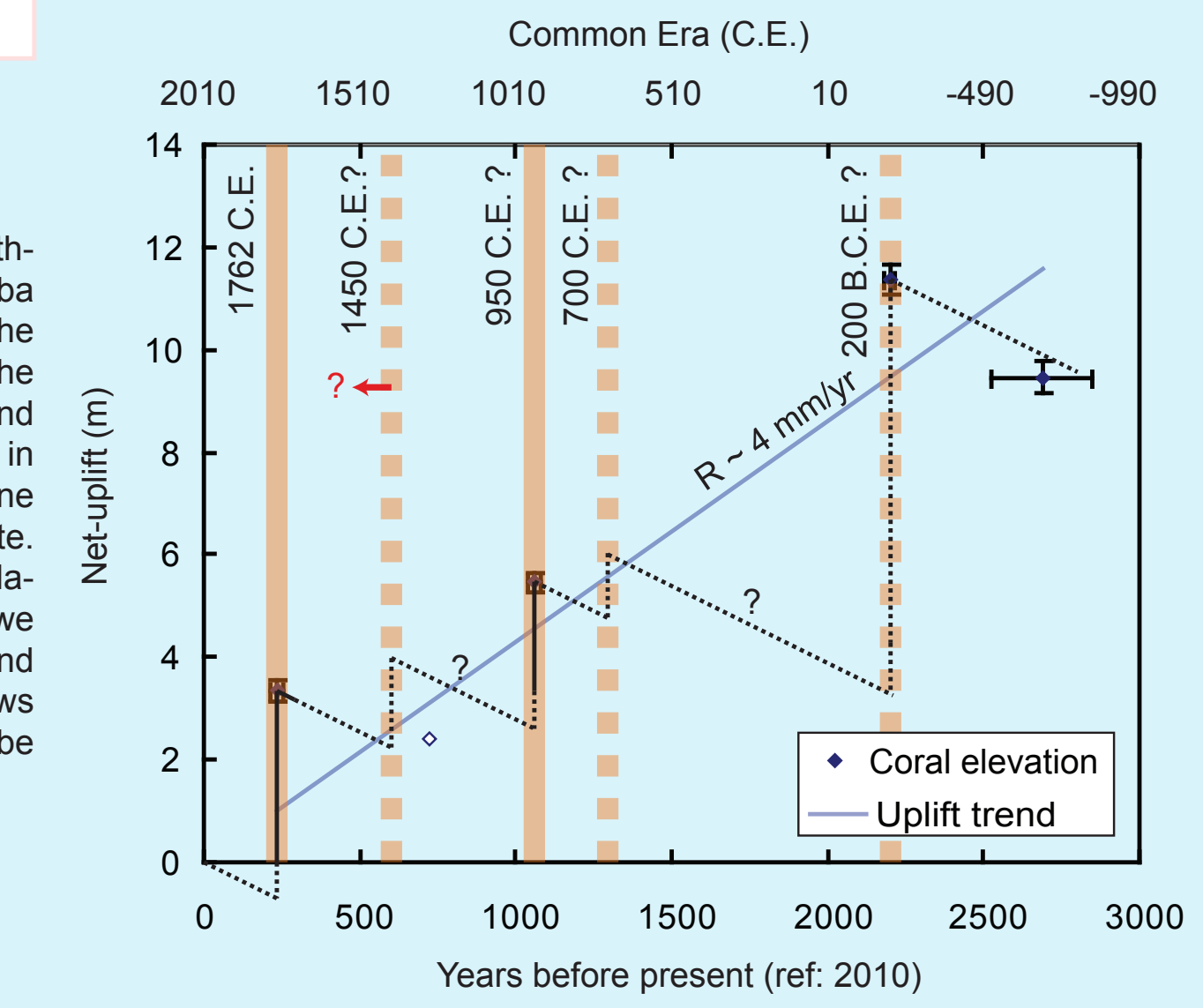


Northern Ramree Island **Central Ramree Island** **Southern Ramree Island**

Figure 17. Three profiles perpendicular to the megathrust show uplift pattern during and after the 1762 earthquake from north to south. The yellow band shows the inferred general uplift pattern in this area. The highest uplifts appear along the central profile. This suggests either high fault slip on the subjacent megathrust or a change in fault geometry beneath the profile. Grey points are our measurements that are related to the latest uplift event. Error bars indicate our uncertainty in sea-level indicators.

Inferred recurrance interval

Figure 17.
Inferred uplift history at southwestern corner of Cheduba Island. The orange bands is the uplift date inferred from the coral U-Th age around Cheduba and Ramree Island in the past 3000 years. Blue line shows the long-term uplift rate. The black line shows the relative sea-level history that we inferred from the elevation and age of corals. This figure shows the seismic interval must be shorter than 1000 years.



$$\frac{\Delta Z}{\Delta T} + i = R \qquad (1)$$

$$\Delta Z + iT = Uz \qquad (2)$$

$$\Delta T = \frac{(Uz - iT)}{(R - i)} \qquad (3)$$

Here we use equations list on the left to estimate the possible range of recurrence interval (ΔT) from the long-term uplift rate (R), the interseismic deformation rate (I), and the co-seismic uplift (ΔZ).
In the equation (1), we apply the general assumption that the long-term deformation is the summary of the interseismic deformation and the co-seismic+ postseismic deformations. Therefore, if the uplift event (ΔZ) occurred regularly, This relationship can be re-write as the form of Eq(1), where theΔT represents the recurrence interval of uplift event. Because theΔZ is poorly constrained from geomorphology study after the earthquake, we therefore use the observed net-uplift (Ut) in Eq(2) to replace the "co-seismic" deformation (ΔZ) by combining Eq(1) and Eq(2). The result is showed in the figure below.

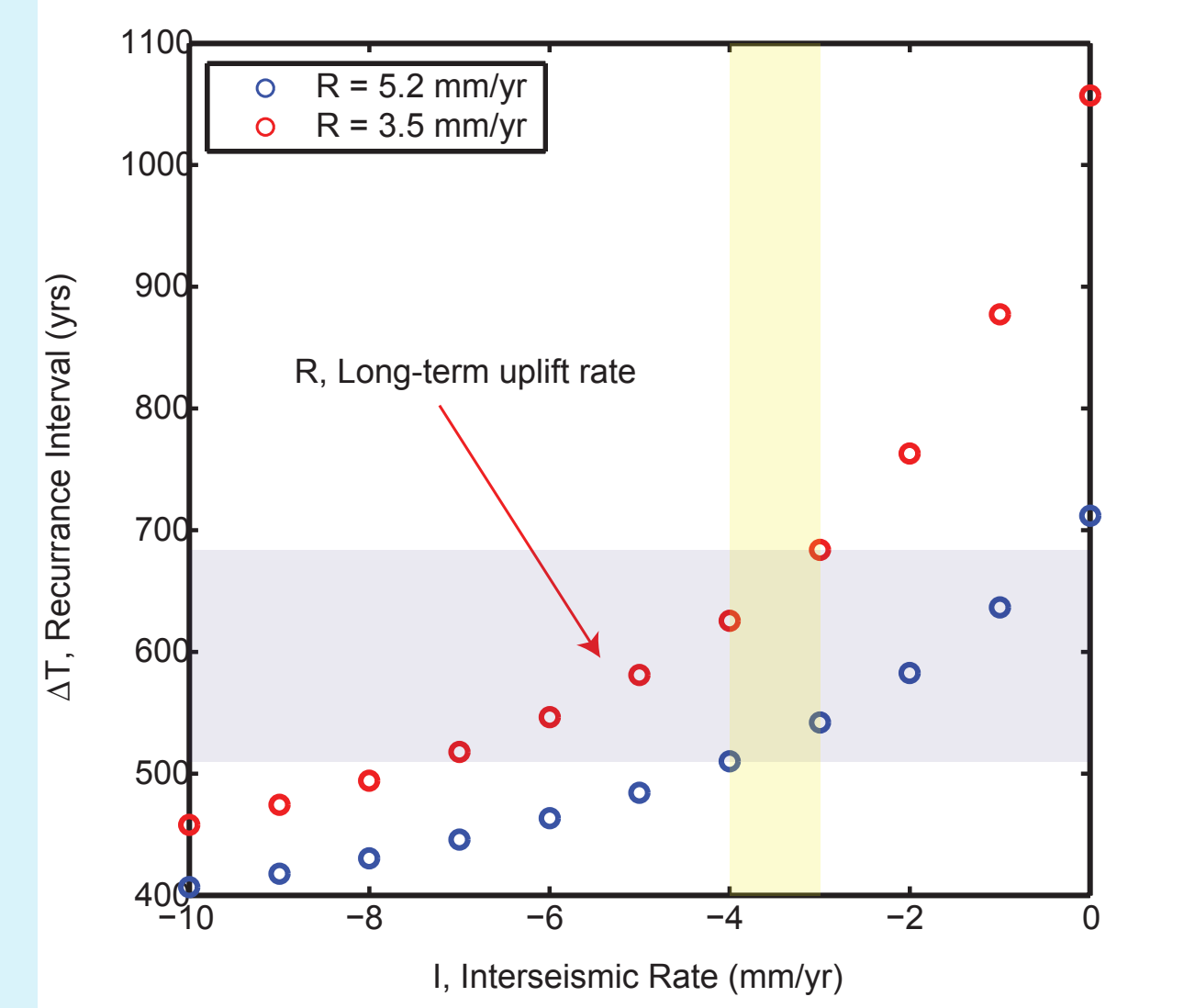


Figure 18.
The range of recurrence interval that estimate from the long-term uplift rate (R), the interseismic subsidence rate (i) and the observed land-level change from last event. Yellow zone shows the prefered range of interseismic subsidence rate from coral study and field observations. This figure shows the recurrence interval of 1762-type earthquake is about 500 – 700 years based on the long-term uplift rate. This estimation is similar to the recurrence interval inferred from coral age and elevation at southwestern corner of Cheduba Island.

To estimate the plausible seismic parameters of 1762 earthquake, we conduct a simple homogeneous elastic half-space dislocation model with least-square optimization approach. The aim of this modeling is to test whether the simplest fault geometry can reproduce the net-uplift pattern, as well as the general interseismic deformations observed at Cheduba and Ramree Island. If the model can explain the majority of our observations, it implies the motion on the megathrust plays the major role to the coastal deformations, rather than the upper plate structures. However, if this model failed to explain the deformation pattern, it suggests the action of upper-plate structure is not ignorable from the active deformations.

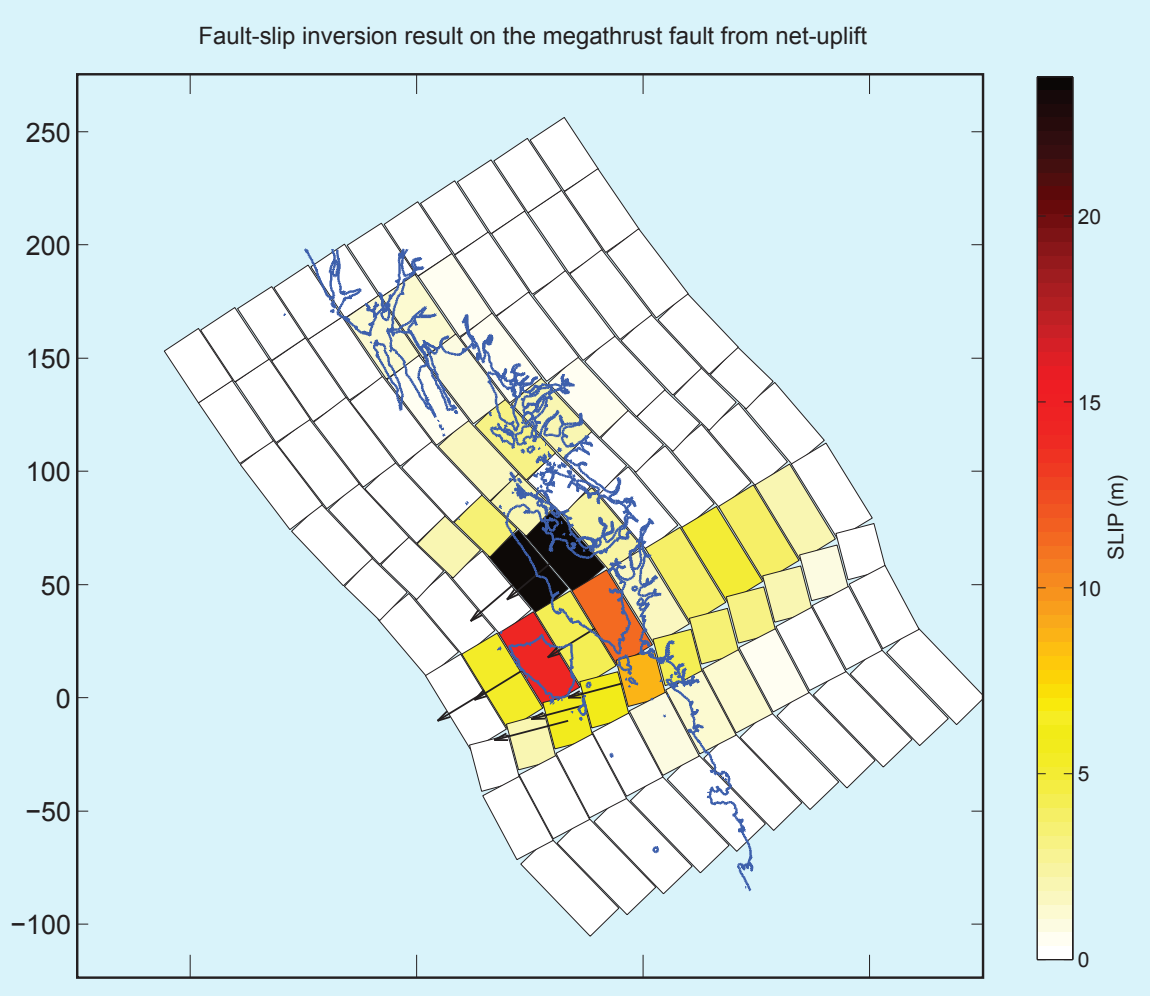
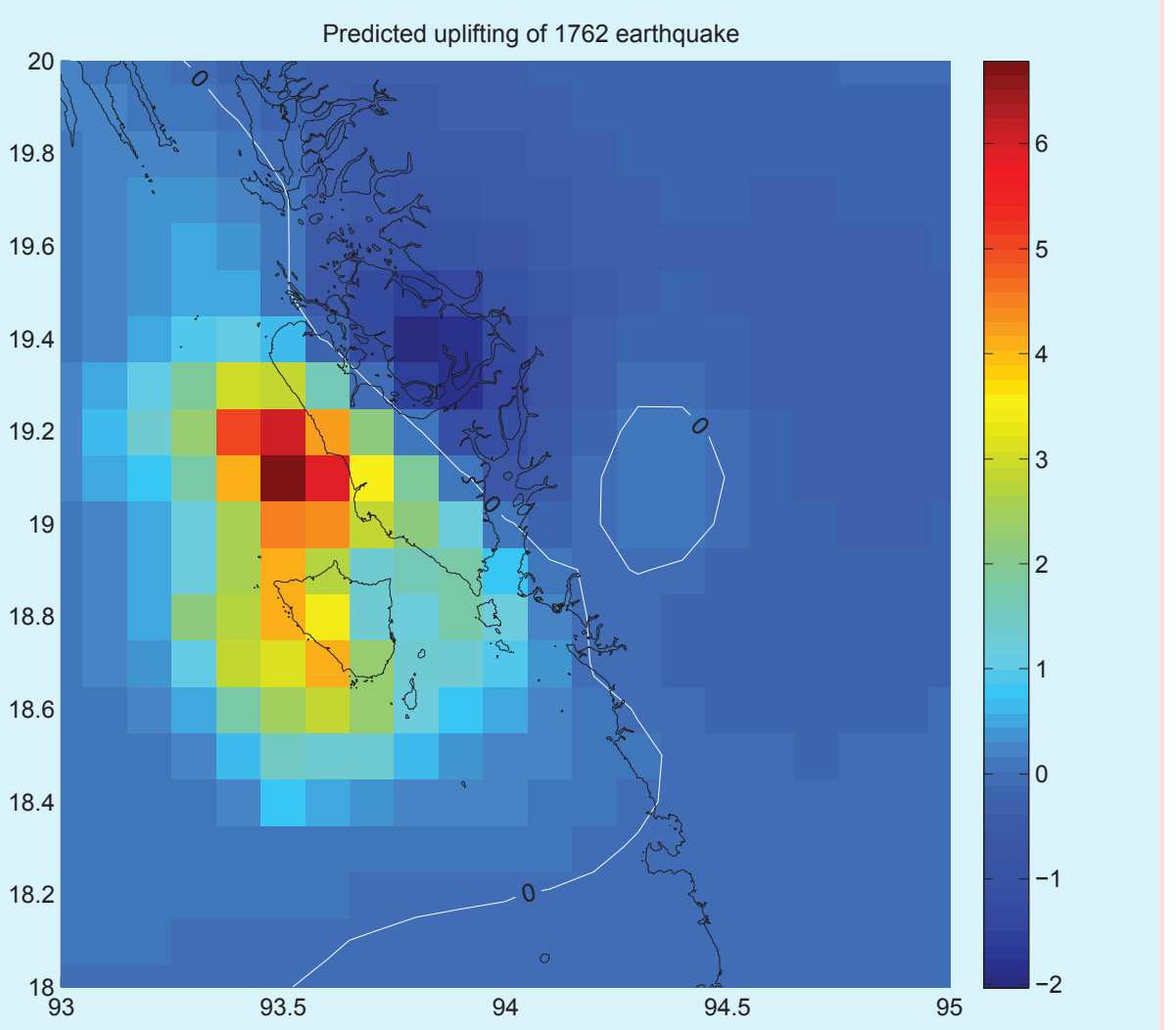


Figure 19.
The inversion result from the net-uplift data yields a high-slip patch beneath the Ramree and Cheduba Island. In order to fit the high uplift at Central Ramree Island, maximum slip beneath the Ramree Island is about 20 m, whereas under the Cheduba Island is nearly 15m. The fault slips are concentrated between the depths of 5 to 25 km along the interface.

Figure 20.
The prediction of surface uplift from our fault slip model. Based on this inversion model, the maximum surface uplift occurred west of the Ramree Island, creating more than 6 m uplift on the sea floor. The total moment of the fault slip is equivalent to Mw 8.7. This generally fit the pattern of our net-uplift data.



Result: The predicted recurrence interval from this simple dislocation model mismatches the recurrence interval inferred from the long-term uplift rate. By dividing the 20 m maximum slip by the 2 cm/yr plate convergence rate, we obtain the recurrence interval of about 1000 years. Since this dislocation model is inverted from the net-uplift, the true coseismic slip must be greater then what we have derived. This implies if coseismic slip associated with the 1762 earthquake occurred only on the megathrust, its recurrence-interval must be even longer than 1000 years.