# Potential paleo-tsunami records around the eastern Taiwan area

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USGS
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U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

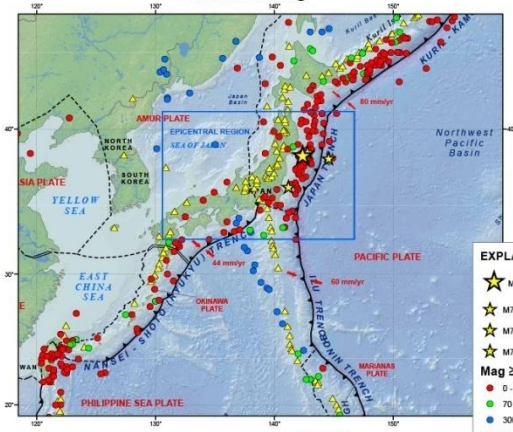
EARTHQUAKE SUMMARY MAP XXX

*Prepared in cooperation with the Global Seismographic Network*

GSN

# The M9.0 Great Tohoku Earthquake (northeast Honshu, Japan) of March 11, 2011

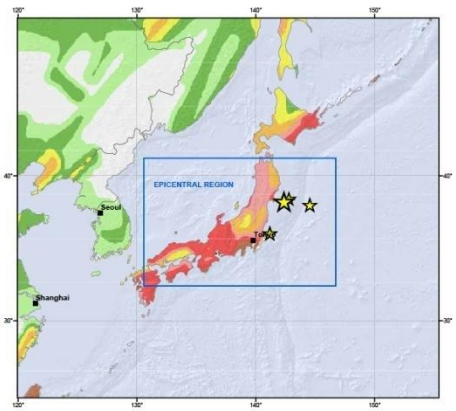
## Tectonic Setting




RELATIVE PLATE MOTIONS

The red vectors represents the motion of the Pacific Plate relative to the Philippine Plate, and the Philippine Plate relative to the Eurasia Plate in the region. The motion of the Pacific Plate is generally 80 mm/yr north westward with respect to the Philippine Plate. The motion of the Philippine Plate is generally 44 mm/yr north westward with respect to the Eurasia Plate.

## Seismic Hazard

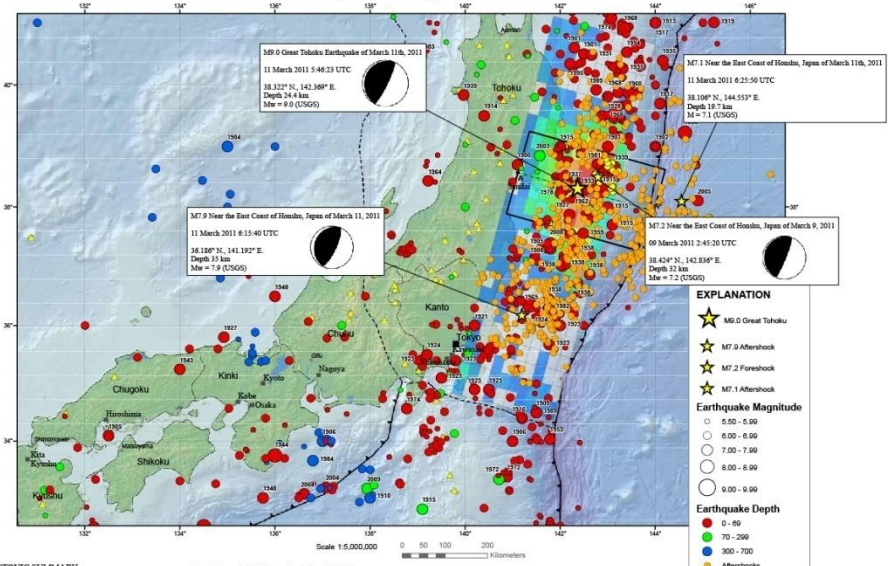



Seismic hazard is expressed as peak ground acceleration (PGA) on firm rock, in meters/sec², expected to be exceeded in a 50-yr period with a probability of 10 percent.

Peak Ground Acceleration in m/sec**2

.2 .4 .8 1.6 2.4 3.2 4.0 4.8

## Epicentral Region




EXPLANATION

- M9.0 Great Tohoku
- M7.9 Aftershock
- M7.2 Foreshock
- M7.1 Aftershock

Mag ≥ 7.0

- 0 - 69 km
- 70 - 299
- 300 - 600

Plate Boundaries

- Subduction
- Transform
- Divergent
- Others

EXPLANATION

- M9.0 Great Tohoku
- M7.9 Aftershock
- M7.2 Foreshock
- M7.1 Aftershock

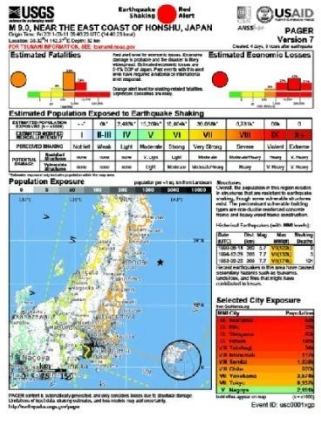
Earthquake Magnitude

- 5.50 - 5.99
- 6.00 - 6.99
- 7.00 - 7.99
- 8.00 - 8.99
- 9.00 - 9.99

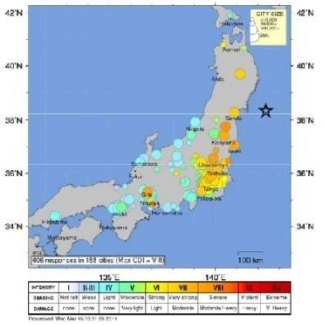
Earthquake Depth

- 0 - 69
- 70 - 299
- 300 - 700
- Aftershocks
- Foreshocks

## PAGER




## Did You Feel It?




## M9.0 GREAT TOHOKU TECTONIC SUMMARY

The magnitude 9.0 Tohoku earthquake on March 11, 2011, which occurred near the northeast coast of Honshu, Japan, resulted from thrust faulting on or near the subduction zone plate boundary between the Pacific and North America plates. At the latitude of this earthquake, the Pacific plate moves approximately westwards with respect to the North America plate at a rate of 83 mm/yr, and begins its westward descent beneath Japan at the Japan Trench. Note that some authors divide this region into several microplates that together define the relative motions between the larger Pacific, North America and Eurasia plates; these include the Okhotsk and Amur microplates that are respectively part of North America and Eurasia.

The March 11 earthquake was preceded by a series of large foreshocks over the previous two days, beginning on March 9th with a M 7.2 event approximately 40 km from the epicenter of the March 11 earthquake, and continuing with another three earthquakes greater than M 6 on the same day.

The Japan Trench subduction zone has hosted nine events of magnitude 7 or greater since 1973. The largest of these, a M 7.8 earthquake approximately 260 km to the north of the March 11 epicenter, caused 3 fatalities and almost 700 injuries in December 1994. In June of 1978, a M 7.7 earthquake 35 km to the southwest of the March 11 epicenter caused 22 fatalities and over 400 injuries. Large offshore earthquakes have occurred in the same subduction zone in 1611, 1896 and 1933 that each produced devastating tsunami waves on the Sanriku coast of Pacific NE Japan. That coastline is particularly vulnerable to tsunami waves because it has many deep coastal embayments that amplify tsunami waves and cause great wave inundations. The M 7.6 subduction earthquake of 1896 created tsunami waves as high 38 m and a reported death toll of 22,000. The M 8.6 earthquake of March 2, 1933 produced tsunami waves as high as 29 m on the Sanriku coast and caused more than 3000 fatalities.

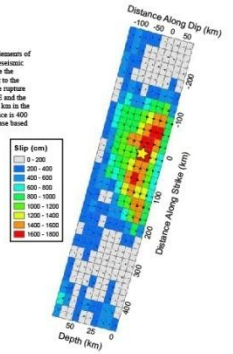
The March 11, 2011 earthquake was an infrequent catastrophe. It far surpassed other earthquakes in the southern Japan Trench of the 20th century, none of which attained M8. A predecessor may have occurred on July 13, 869, when the Sendai area was swept by a large tsunami that Japanese scientists have identified from written records and a sand sheet.

## Significant Earthquakes Mag >= 7.5

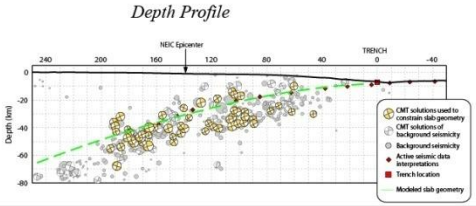
| Year | Mon | Day | Time | Lat | Long | Dep | Mag |
|---|---|---|---|---|---|---|---|
| 1901 | 08 | 09 | 1833 | 40.600 | 142.300 | 35 | 7.5 |
| 1906 | 01 | 21 | 1949 | 34.000 | 137.000 | 350 | 7.7 |
| 1909 | 03 | 13 | 1429 | 34.500 | 141.500 | 35 | 7.6 |
| 1915 | 11 | 01 | 0724 | 38.300 | 142.900 | 35 | 7.5 |
| 1923 | 09 | 01 | 0250 | 35.405 | 139.084 | 35 | 7.9 |
| 1923 | 09 | 02 | 0246 | 34.900 | 140.200 | 35 | 7.6 |
| 1927 | 03 | 07 | 0927 | 35.802 | 134.924 | 9.6 | 7.6 |
| 1931 | 03 | 09 | 0348 | 40.484 | 142.664 | 35 | 7.7 |
| 1933 | 03 | 02 | 1731 | 39.224 | 144.622 | 35 | 8.4 |
| 1938 | 05 | 23 | 0718 | 36.488 | 141.785 | 35 | 7.7 |
| 1938 | 11 | 05 | 0843 | 37.009 | 142.045 | 35 | 7.9 |
| 1938 | 11 | 05 | 1050 | 37.108 | 142.081 | 35 | 7.8 |
| 1938 | 11 | 06 | 0853 | 37.287 | 142.283 | 35 | 7.7 |
| 1944 | 12 | 07 | 0435 | 33.750 | 136.000 | 0 | 8.1 |
| 1953 | 11 | 25 | 1748 | 34.034 | 141.786 | 35 | 7.9 |
| 1960 | 03 | 20 | 1707 | 39.871 | 143.435 | 2.1 | 7.8 |
| 1964 | 06 | 16 | 0401 | 38.434 | 139.226 | 13.1 | 7.5 |
| 1968 | 05 | 16 | 0049 | 40.903 | 143.346 | 25.8 | 8.3 |
| 1972 | 02 | 29 | 0923 | 33.377 | 140.881 | 58.8 | 7.5 |
| 1978 | 06 | 12 | 0814 | 38.224 | 142.009 | 59.3 | 7.7 |
| 1983 | 05 | 26 | 0300 | 40.468 | 139.080 | 20 | 7.7 |
| 1994 | 12 | 28 | 1219 | 40.530 | 143.403 | 29.2 | 7.8 |
| 2011 | 03 | 11 | 0646 | 38.322 | 142.369 | 24.4 | 8.9 |

## Finite Fault Model

Distribution of the amplitude and direction of slip for subfault elements of the fault rupture model are determined from the inversion of teleseismic body waveforms and long period surface waves. Arrows indicate the amplitude and direction of slip (of the hanging wall with respect to the foot wall); the slip is also colored by magnitude. The view of the rupture plane is from above. The strike of the fault rupture plane is S19E and the dip is 14 NNW. The dimensions of the subfault elements are 30 km in the strike direction and 20 km in the dip direction. The rupture surface is 400 km along strike and 150 km downdip. The seismic moment release based upon this plane is 4.04e+29 dyne.cm.




## Depth Profile




DISCLAIMER

Base map data, such as place names and political boundaries, are the best available but may not be current or may contain inaccuracies and therefore should not be regarded as having official significance.

DATA SOURCES

EARTHQUAKES AND SEISMIC HAZARD
USGS, National Earthquake Information Center
NOAA, National Geophysical Data Center
IASPEI, Centennial Catalog (1900 - 1999) and extensions (Engdahl and Villaseñor, 2002)
HDF (unpublished earthquake catalog) (Engdahl, 2003)
Global Seismic Hazard Assessment Program

PLATE TECTONICS AND FAULT MODEL
PB2002 (Bird, 2003)
Finite Fault Model, Gavin Hayes, USGS (2011)

BASE MAP
NIMA and ESRI, Digital Chart of the World
USGS, EROS Data Center
NOAA GEBCO and GLOBE Elevation Models

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Bird, P., 2003, An updated digital model of plate boundaries: Geochem. Geophys. Geosyst., v. 4, no. 3, pp. 1027- 80.

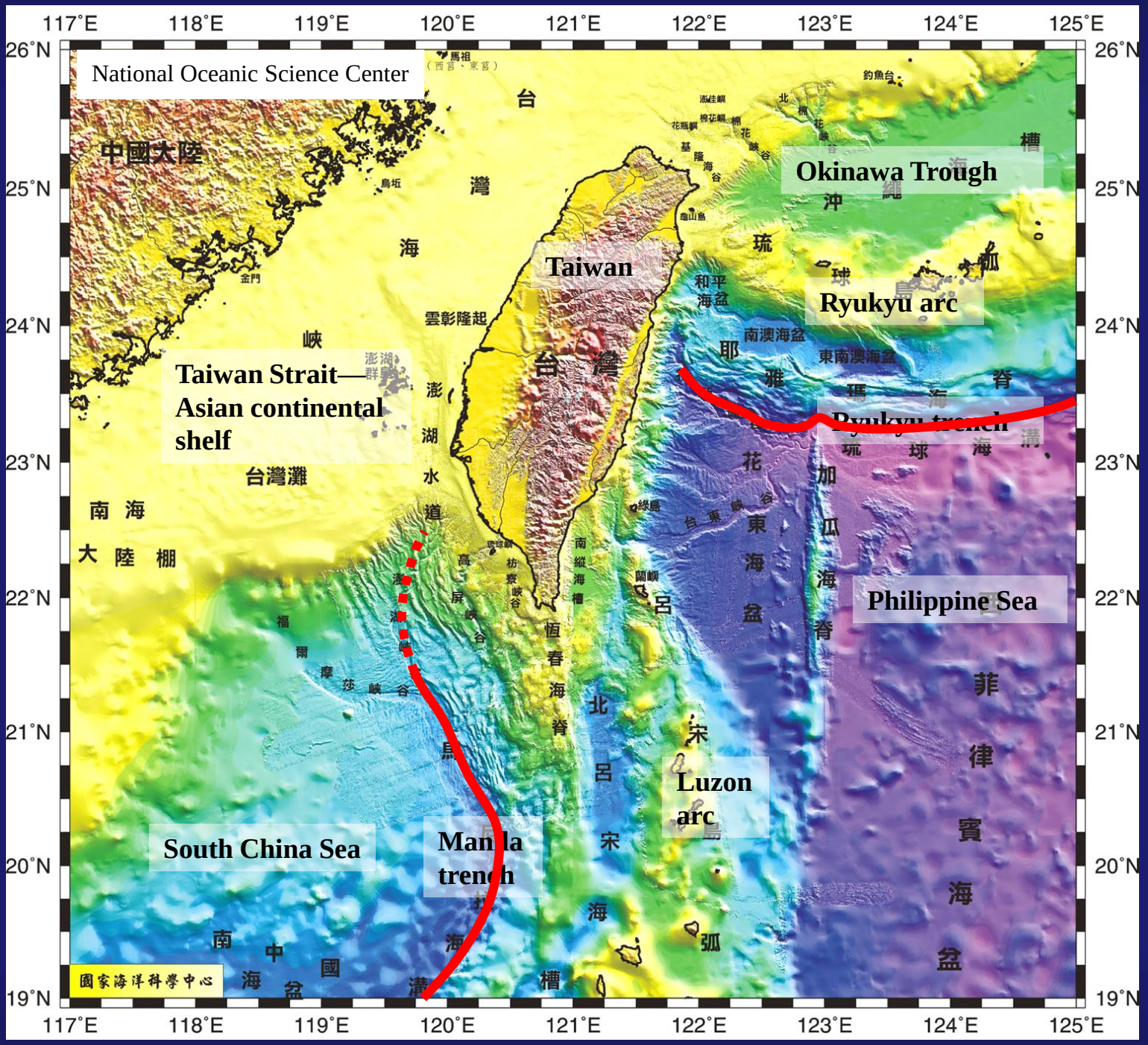
Engdahl, E.R. and Villaseñor, A., 2002, Global Seismicity: 1900 - 1999, chap. 41 of Lee, W.H.K., and others, eds., International Earthquake and Engineering Seismology, Part A: New York, N.Y., Elsevier Academic Press, 932 p.

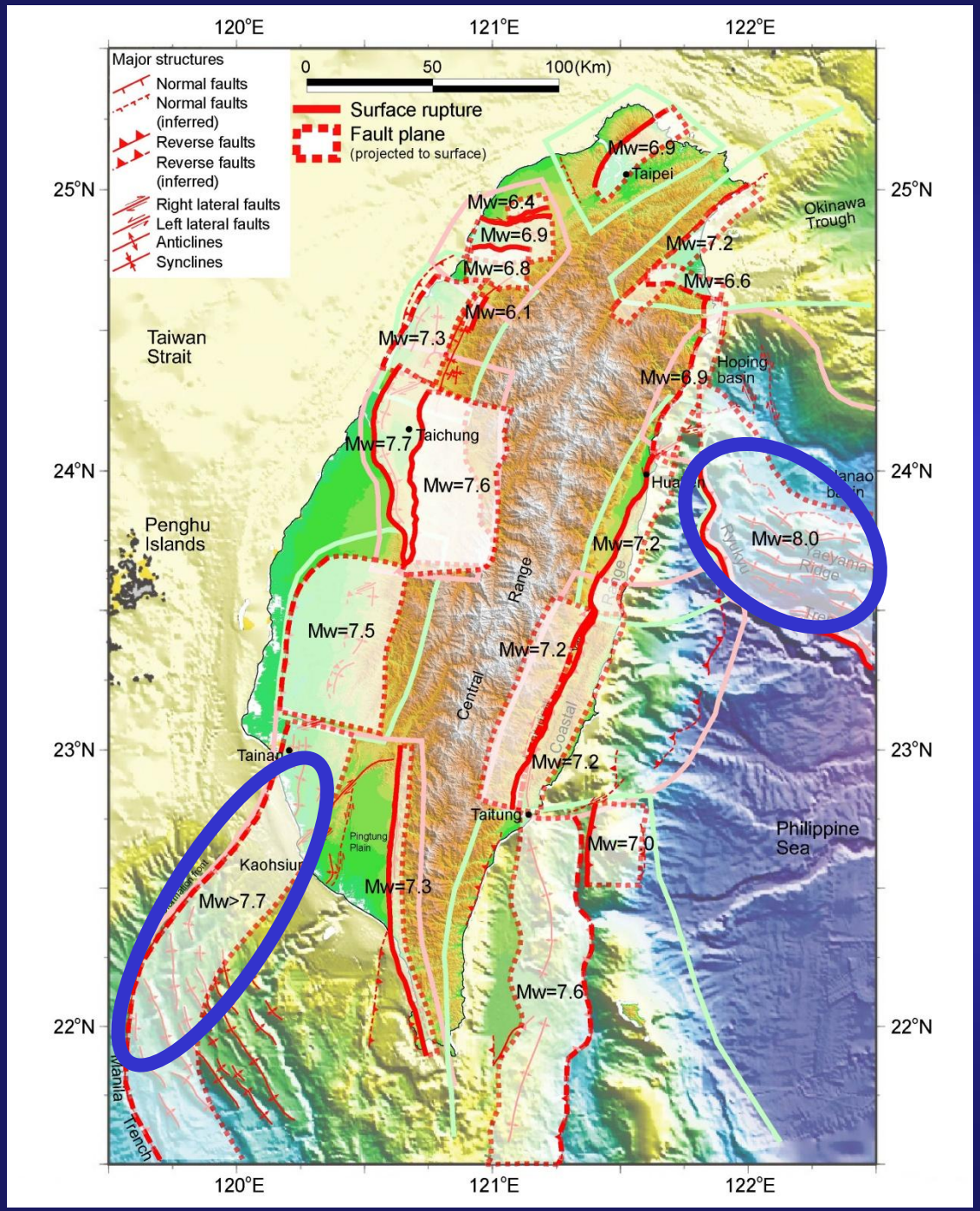
Engdahl, E.R., Van der Hilst, R.D., and Buland, R.P., 1998, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination: Bull. Seism. Soc. Amer., v. 88, p. 722-743.

The GEBCO_08 Grid, version 20090202, http://www.gebco.net


Map prepared by U.S. Geological Survey
National Earthquake Information Center
14 March 2011
Map not approved for release by Director USGS

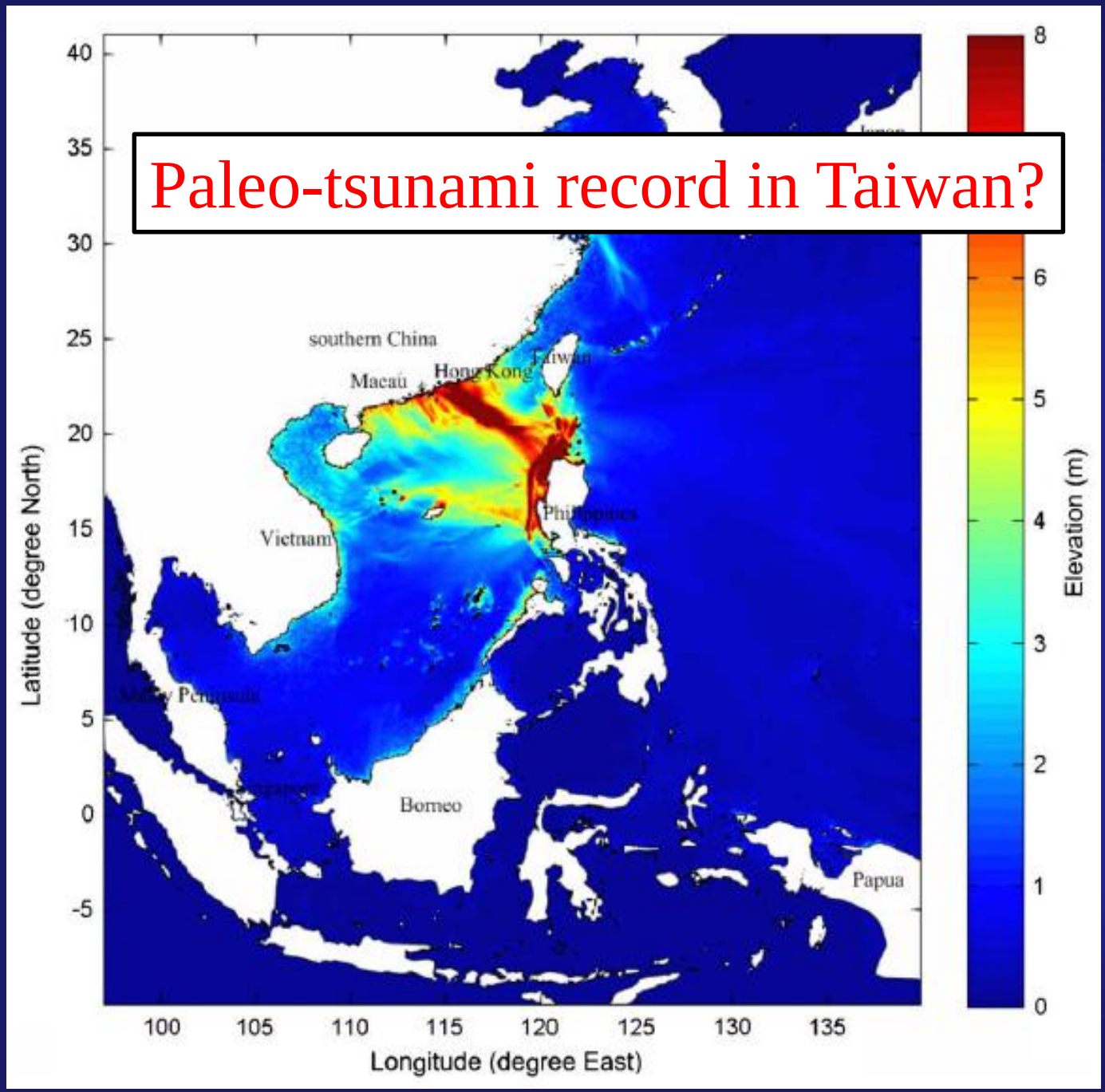
http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2011/20110311.php


National Oceanic Science Center
Taiwan
Okinawa Trough
Ryukyu arc
Taiwan Strait—Asian continental shelf
Ryukyu trench
Philippine Sea
Luzon arc
South China Sea
Manila trench
國家海洋科學中心
117°E
118°E
119°E
120°E
121°E
122°E
123°E
124°E
125°E
26°N
25°N
24°N
23°N
22°N
21°N
20°N
19°N




A rudimentary map of potential sources of large earthquakes in and around Taiwan

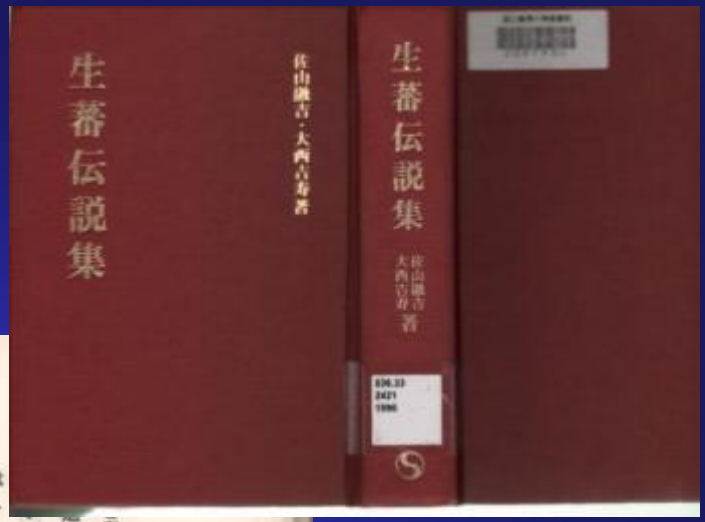
(Shyu et al., 2005, JGR)

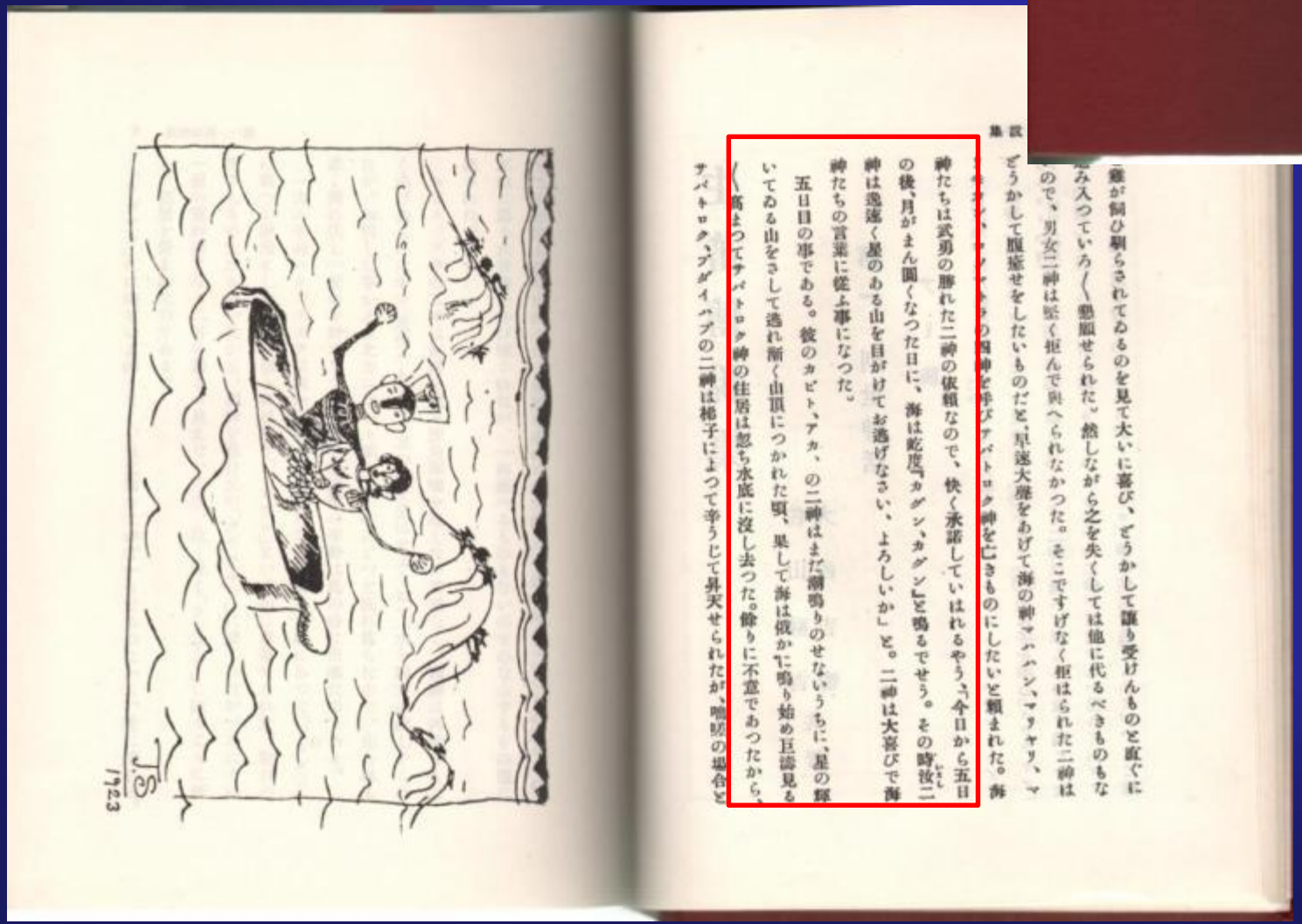



(Megawati et al., 2009)

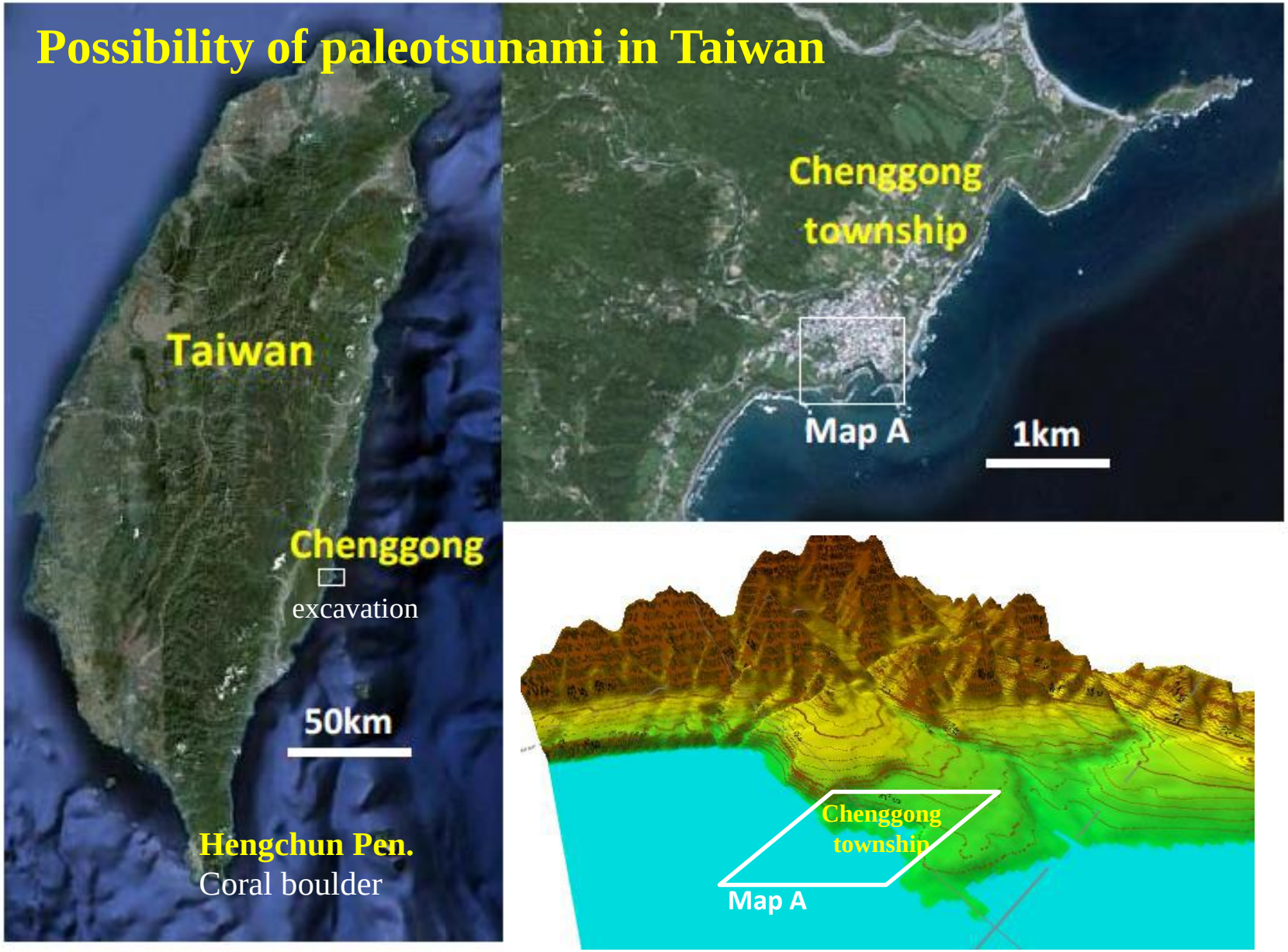

1866?
1867
1792
1721?
1661?
1781
How about pre-historic event?
How about eastern Taiwan?
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
©2010 Cnes/ Spot Image
Image ©2010 TerraMetrics
Data ©2010 MIRC/JHA
22° 09'41.76" N 121° 39'08.89" E 標高 -2600 メートル
©2009 Google
高度 1124.53 キロメートル

# Legends from the Amis tribe, eastern Taiwan



# Possibility of paleotsunami in Taiwan

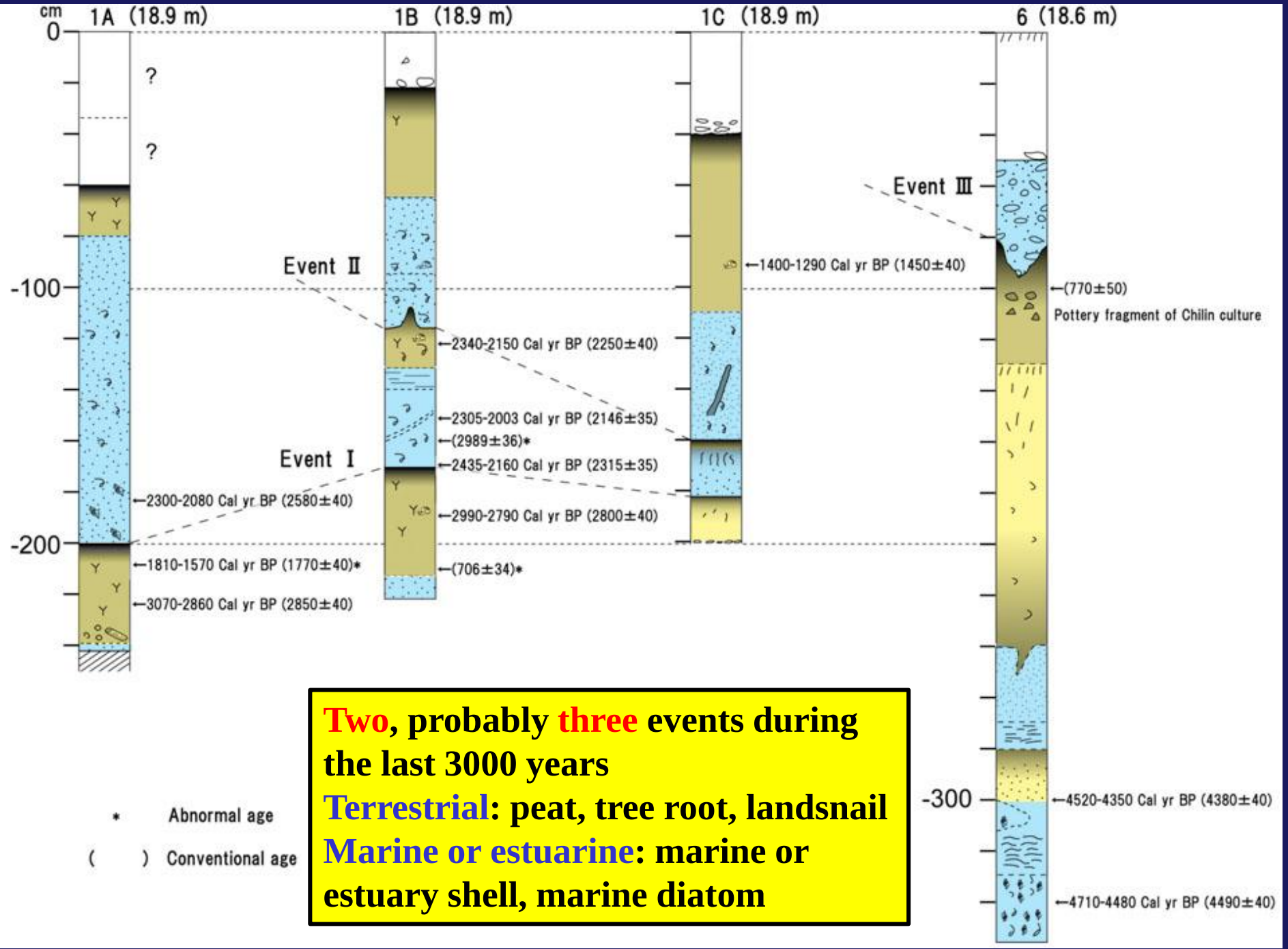



The Chenggong coast is fringed by a series of Holocene marine terraces. Excavation sites are located on the terrace at ca. 15-20 m asl.

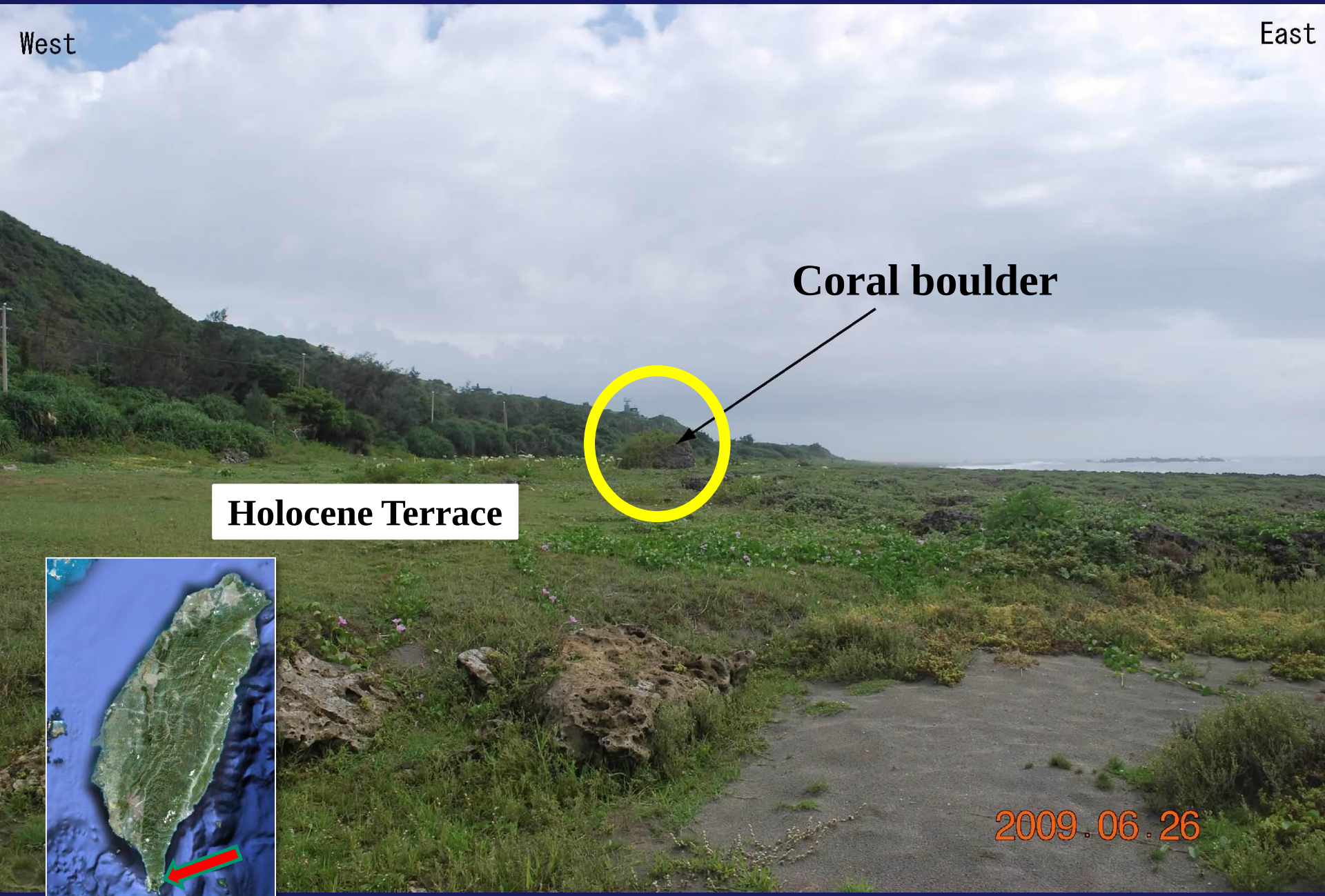


**Continuous section using Geoslicer in areas with limited space or gravel rich sediments**

# Core obtained by Geoslicer


cm
1A (18.9 m)
1B (18.9 m)
1C (18.9 m)
6 (18.6 m)
0
-100
-200
-300
?
?
Event Ⅱ
Event Ⅰ
Event Ⅲ
←1400-1290 Cal yr BP (1450±40)
←(770±50)
Pottery fragment of Chilin culture
←2340-2150 Cal yr BP (2250±40)
←2305-2003 Cal yr BP (2146±35)
←(2989±36)*
←2435-2160 Cal yr BP (2315±35)
←2990-2790 Cal yr BP (2800±40)
←2300-2080 Cal yr BP (2580±40)
←(706±34)*
←1810-1570 Cal yr BP (1770±40)*
←3070-2860 Cal yr BP (2850±40)
←4520-4350 Cal yr BP (4380±40)
←4710-4480 Cal yr BP (4490±40)
* Abnormal age
( ) Conventional age
Two, probably three events during the last 3000 years
Terrestrial: peat, tree root, landsnail
Marine or estuarine: marine or estuary shell, marine diatom

# Coral boulder on Holocene marine coral terrace



# Three coral boulders on Holocene coral terrace




**Tsunami? Timing?**

(Matta et al., 2013)

# Radiocarbon ages from the coral terrace and boulders

| Sample occurrence | Sample no. | Lab no. | 14C age yr BP | Cal yr BP |
|---|---|---|---|---|
| **in situ coral** | 20051015-4 | NTU-4457 | 5270 ± 50 | **5320-5220** |
| **in situ coral** | 950702-08 | NTU-4575 | 5160 ± 49 | **5220-5120** |
| **coral boulder (B1)** | J-1 | NTU-5331 | 4530 ± 50 | **4860-4570** |
| **coral boulder (B2)** | J-2 | NTU-5365 | 5000 ± 50 | **5490-5250** |
| **coral boulder (B2)** | J-3 | NTU-5338 | 4570 ± 50 | **4910-4620** |

Pros:

The size of boulders are likely only movable during extreme events

All boulders are coral reef blocks

Only few boulders along the stretch of coast

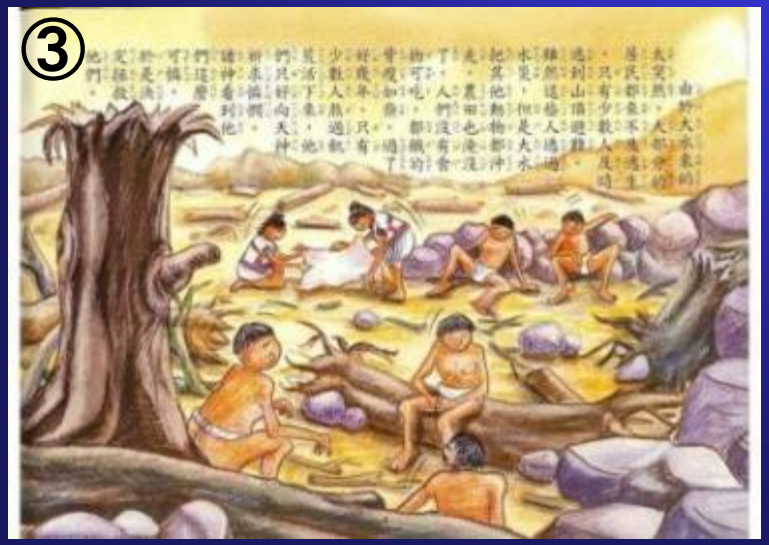
Cons:

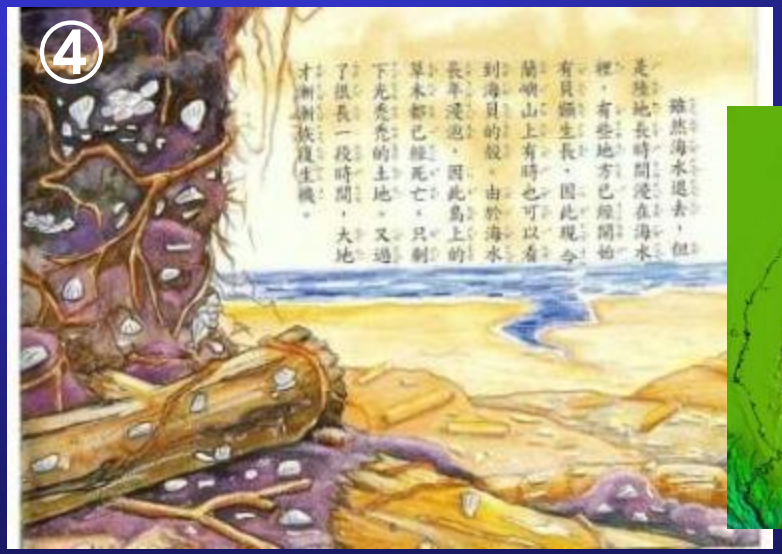
The age of boulders only shows that they are blocks of the Mid-Holocene coral terrace

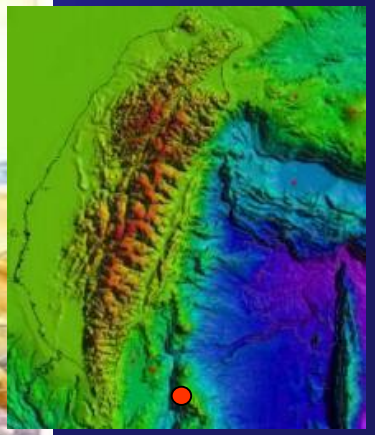
Very difficult to confirmably exclude the possibility of storms

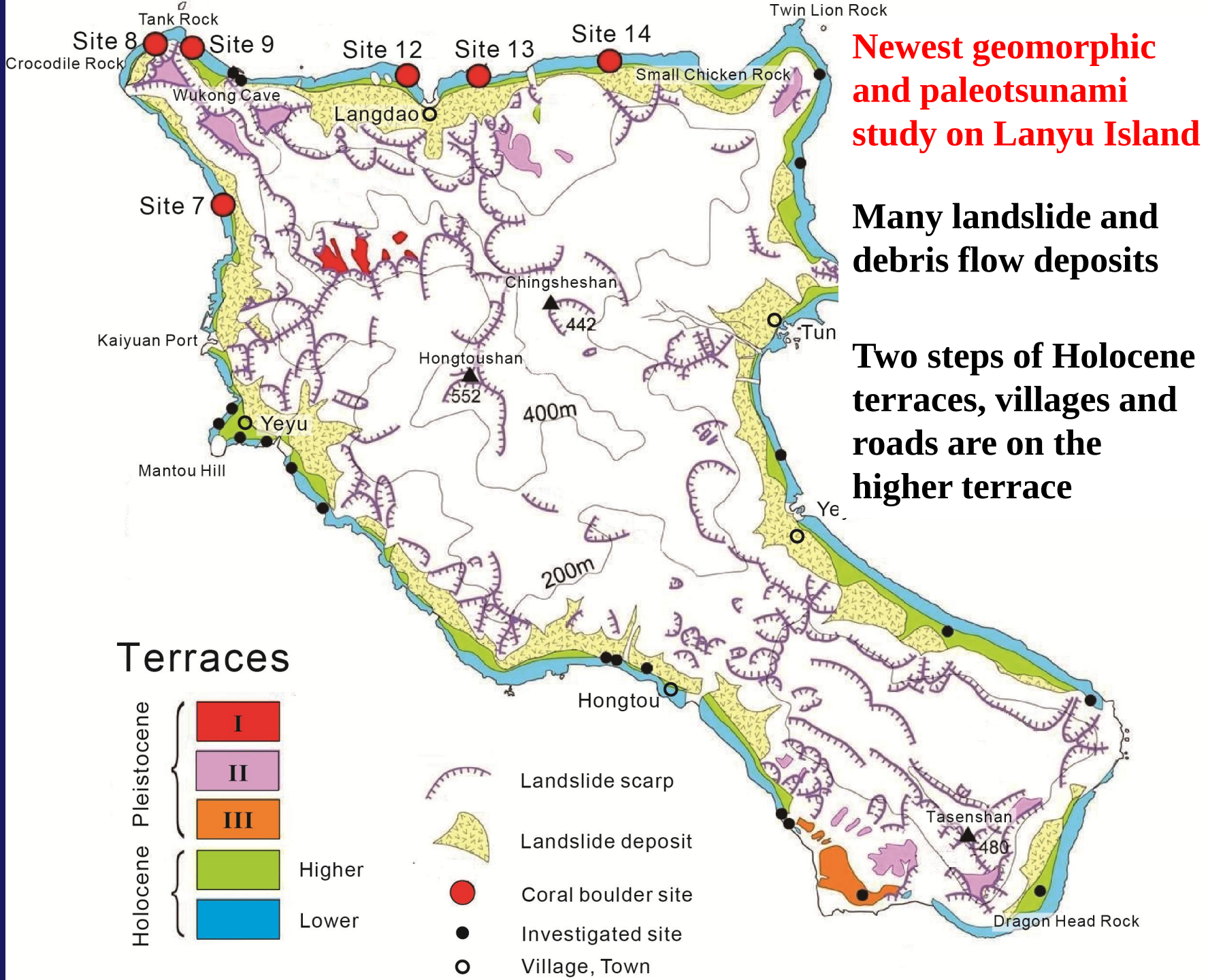
# An even more noteworthy legend from the Tao tribe, on Lanyu Island, southeastern Taiwan







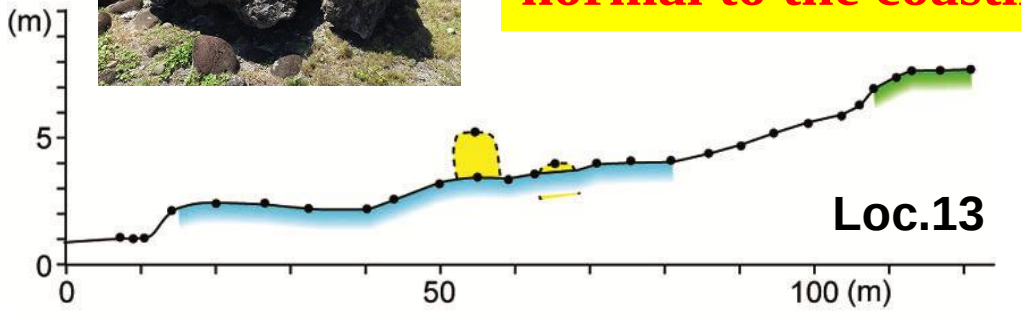

**Newest geomorphic and paleotsunami study on Lanyu Island**

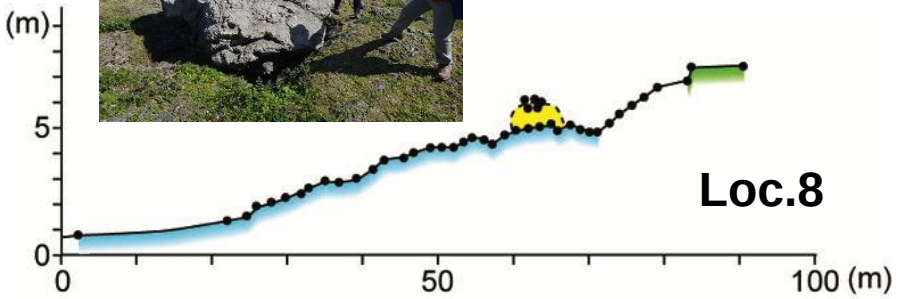
**Many landslide and debris flow deposits**

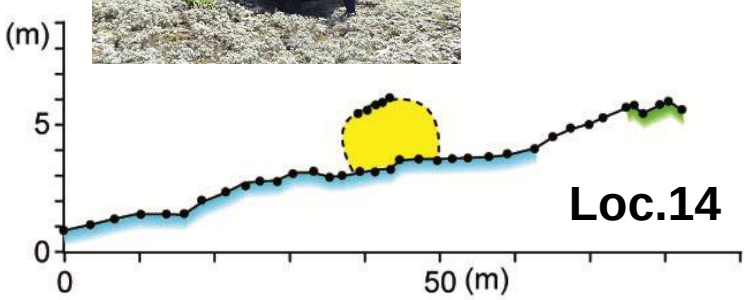
**Two steps of Holocene terraces, villages and roads are on the higher terrace**

**Potential tsunami boulders and profiles normal to the coastline**



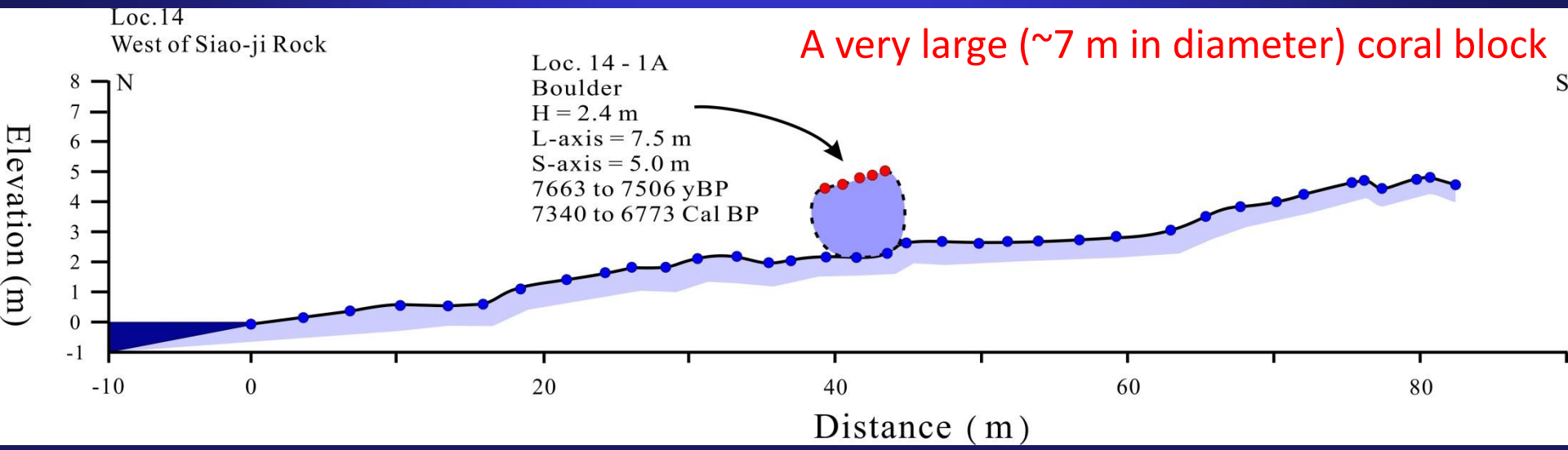




Lower Holocene terrace
Higher Holocene terrace
Coral boulders

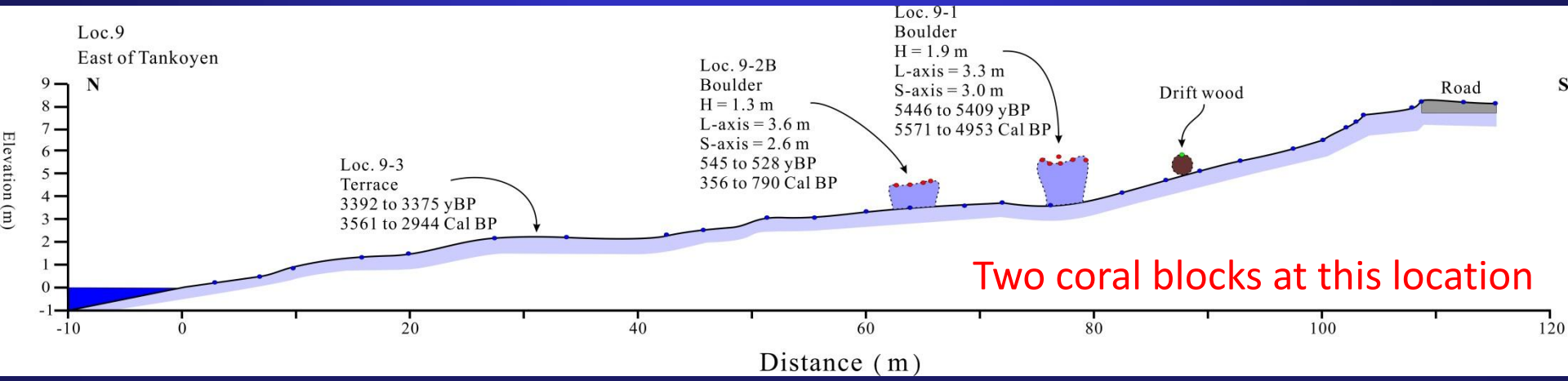
**Coral boulders are on the lower terrace**

# Site 14, northern Lanyu



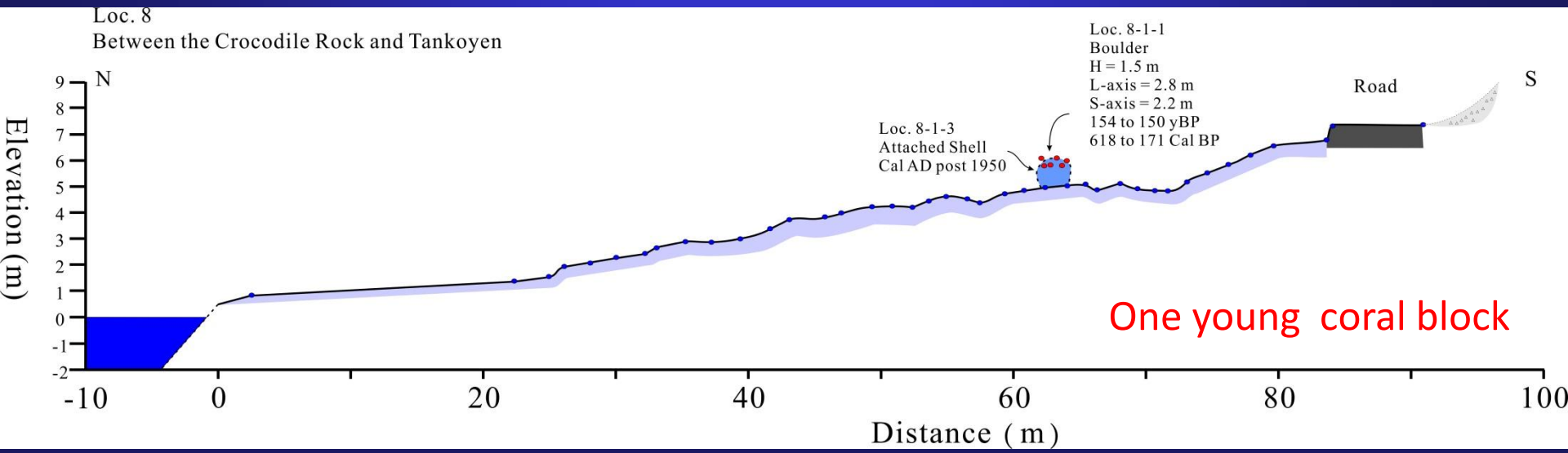

A very large (~7 m in diameter) coral block

# Site 9, northern Lanyu



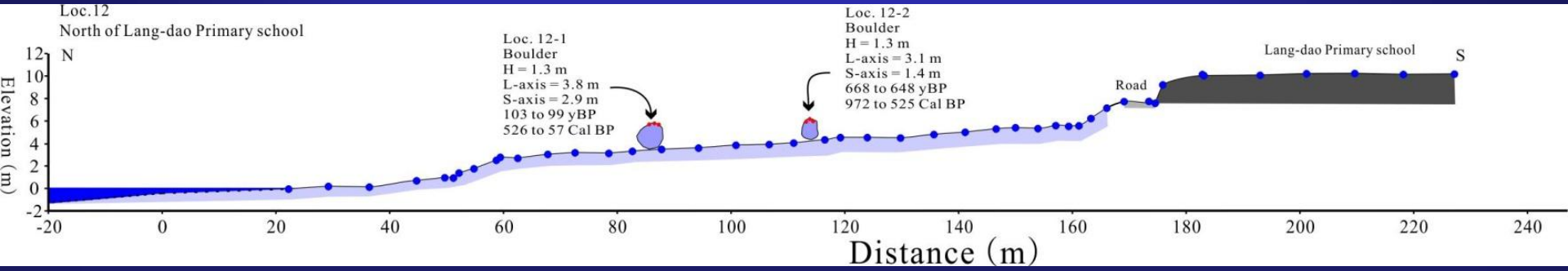

Two coral blocks at this location

# Site 8, northwestern Lanyu



# Site 12, northern Lanyu

One large (~4 m in diameter) and one smaller (~3 m in diameter) coral blocks



Site 7, northwestern Lanyu

One large (~5 m in diameter) coral block, but it is quite likely transported from a nearby source

Site 13, northern Lanyu

Two coral boulders; they are relatively smaller (~3 m) and may have possible nearby sources

# Criteria for identification of possible tsunami boulders:

Primary criteria (for identifying target sites):

- Size of boulders (comparing with recent storm events)
- Rock type of boulders (not from local landslides)

Secondary criteria (for ranking of tsunami possibilities):

- Shape of boulders (round or stick-shaped vs. disk-shaped)
- Possibility of nearby sources

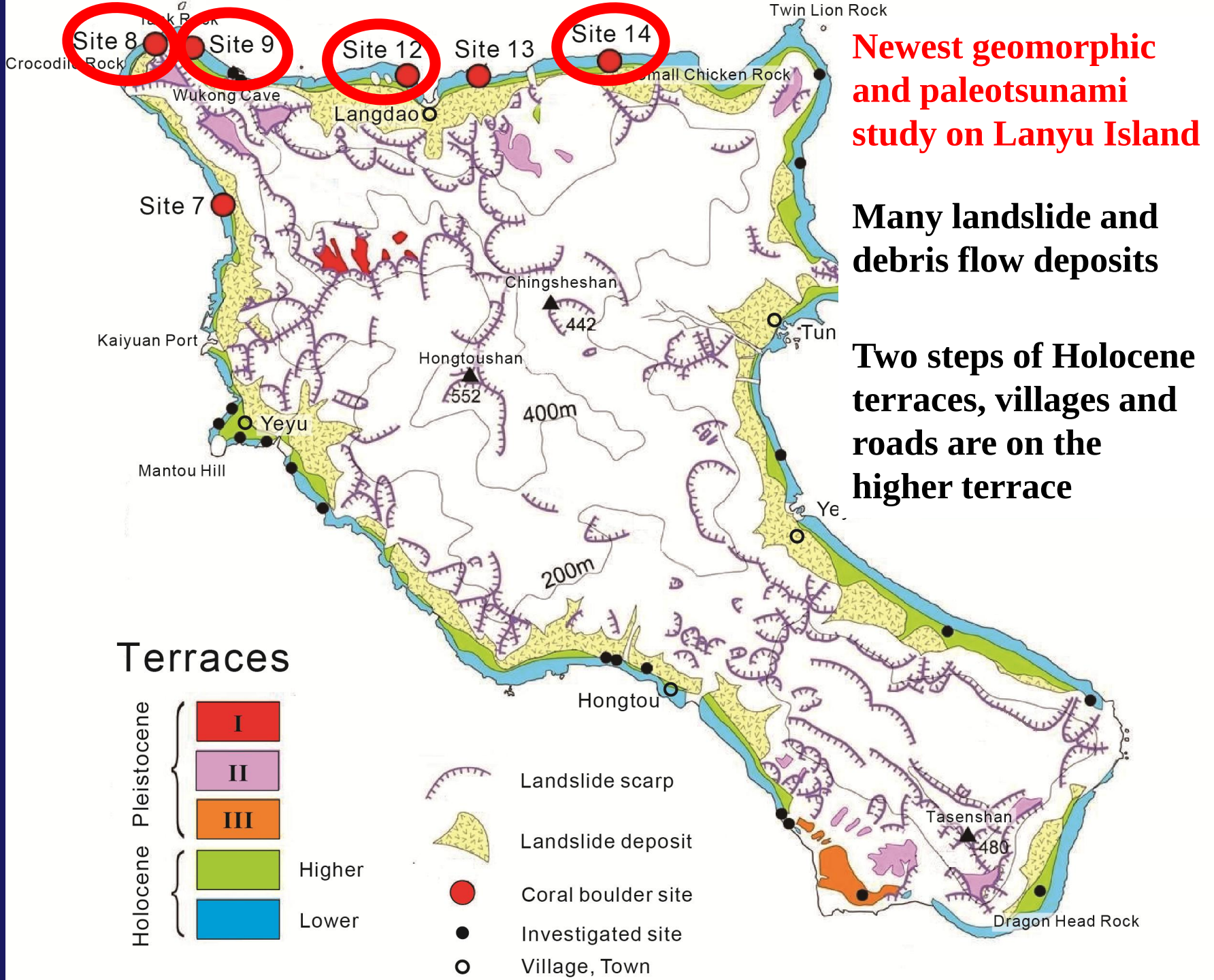
# Combined age results of coral boulders from Lanyu Island

| Sample | Material | Boulder size (m) | | | Volume ($m^3$) | Weight (kg) | Radiocarbon Age (cal BP)[a,b] | | | $^{230}$Th Age (yBP)[c] | Remark |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | L | S | H | | | Delta R = 119±31 | Delta R = 73±17 | Delta R = -218±118 | | |
| 7-1 | Coral | | | | | | 5440 – 5650 | 5490 – 5700 | 5630 – 6200 | 5950 - 5978 | Terrace |
| 7-2 | Coral | 5.3 | 3.5 | 3.0 | 55.65 | 145000 | 4400 – 4680 | 4440 – 4760 | 4640 – 5290 | 5111 – 5143 | |
| 8-1-1 | Coral | 2.8 | 2.2 | 1.5 | 9.24 | 24000 | Post 1950 | 0 – 230 | 150 – 620 | 150 – 154 | |
| 8-1-2 | Coral | | | | | | 0 – 230 | 0 – 240 | 150 – 640 | 127 – 161 | |
| 8-1-3 | Shell | | | | | | Post 1950 | Post 1950 | 0 – 490 | | |
| 8-1-4 | Shell | | | | | | Post 1950 | Post 1950 | 0 – 530 | | |
| 8-1-5 | Coral | | | | | | Post 1950 | Post 1950 | 0 – 500 | | |
| 9-1 | Coral | 3.3 | 3.0 | 1.9 | 18.81 | 49000 | 4720 – 4970 | 4810 – 4990 | 4950 – 5570 | 5408 – 5446 | |
| 9-2B | Coral | 3.6 | 2.6 | 1.3 | 12.17 | 32000 | 150 – 420 | 270 – 430 | 340 – 790 | | |
| 9-3 | Coral | | | | | | 2740 – 2950 | 2780 – 3000 | 2940 – 3560 | 3375 – 3392 | Terrace |
| 9-4 | Coral | | | | | | 2990 – 3290 | 3090 – 3330 | 3250 – 3860 | | Terrace |
| 12-1 | Coral | 3.8 | 2.9 | 1.3 | 14.33 | 37000 | Post 1950 | Post 1950 | 0 – 530 | 100 – 103 | |
| 12-1-3 | Coral | | | | | | 2850 – 3120 | 2920 – 3160 | 3080 – 3700 | | Terrace |
| 12-1-4 | Coral | | | | | | 2670 – 2840 | 2710 – 2860 | 2820 – 3420 | 3253 – 3275 | Terrace |
| 12-2 | Coral | 3.1 | 1.4 | 1.3 | 5.64 | 15000 | 340 – 560 | 450 – 600 | 530 – 970 | 655 – 661 | |
| 13-1 | Coral | 3.2 | 2.0 | 1.8 | 11.52 | 30000 | 700 – 900 | 750 – 920 | 900 – 1380 | 947 – 958 | |
| 13-2 | Coral | 2.9 | 2.4 | 1.1 | 7.66 | 20000 | 1520 – 1750 | 1580 – 1800 | 1750 – 2320 | 1851 – 1869 | |
| 14-1 | Coral | 7.5 | 5.0 | 2.4 | 90.00 | 234000 | 6550 – 6790 | 6640 – 6830 | 6780 – 7330 | 7533 – 7637 | |

[a] Calibrated with 2σ. Marine13 data set (Reimer et al., 2013) was used.

[b] Delta R values were averaged value of -218 ± 118 for eastern Taiwan (Yamaguchi et al., 2004), 119 ± 31 for Ishigaki Island, and 73 ± 17 for the Kuroshio Current area (Yoneda et al., 2007).

[c] The yBP is the age recalculated to before 1950.

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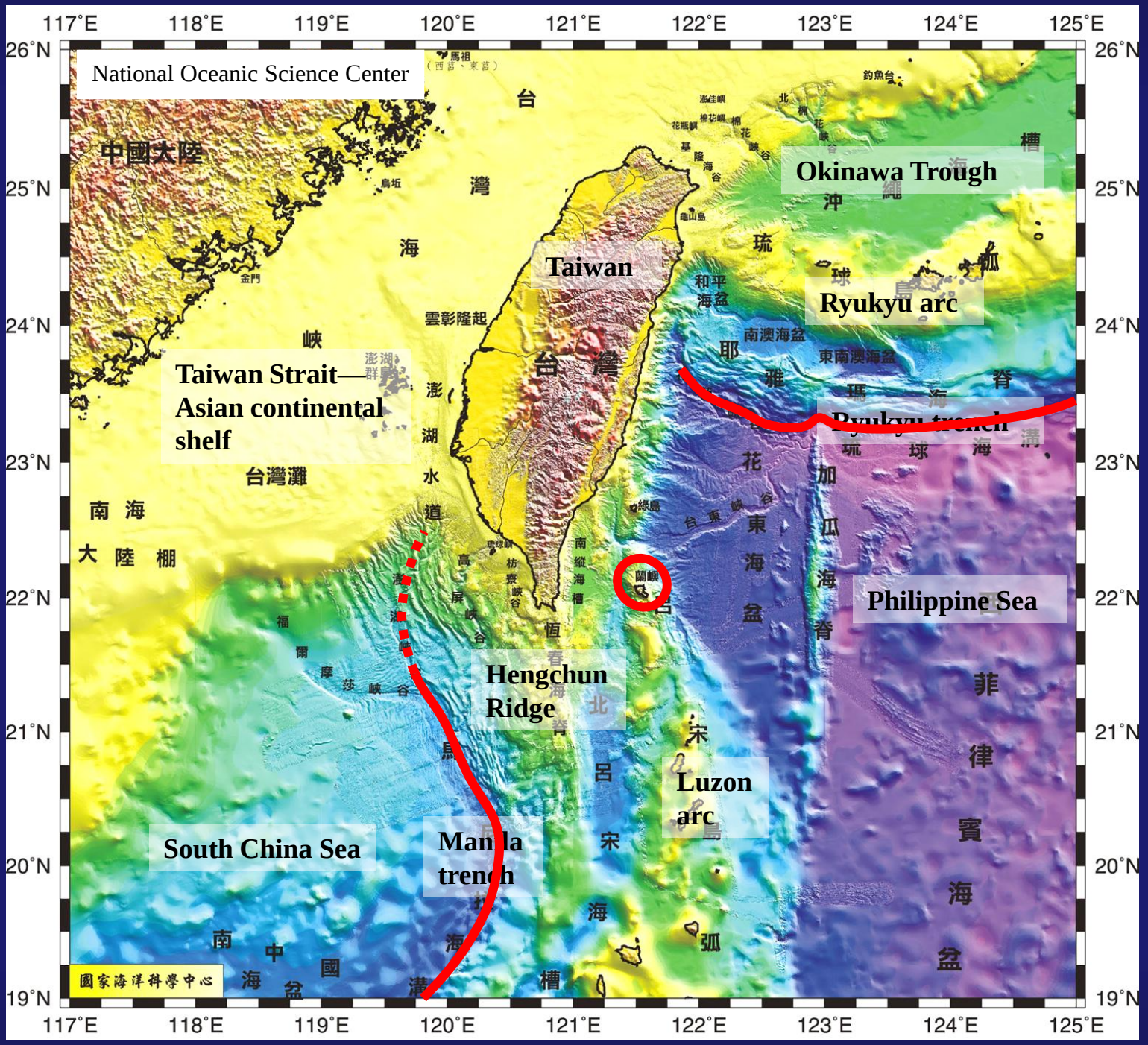
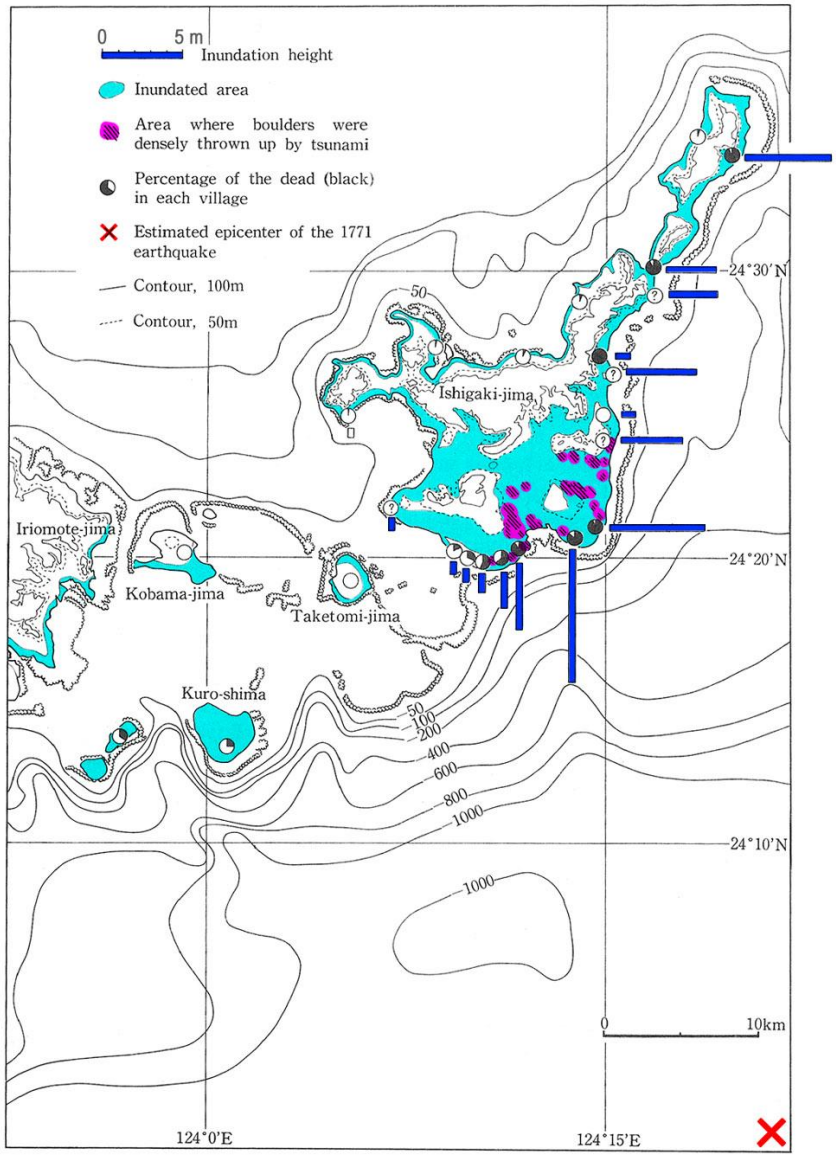

National Oceanic Science Center
Taiwan
Okinawa Trough
Ryukyu arc
Taiwan Strait—Asian continental shelf
Ryukyu trench
Philippine Sea
Hengchun Ridge
Luzon arc
South China Sea
Manila trench
國家海洋科學中心

# Paleo tsunami in the South Ryukyu

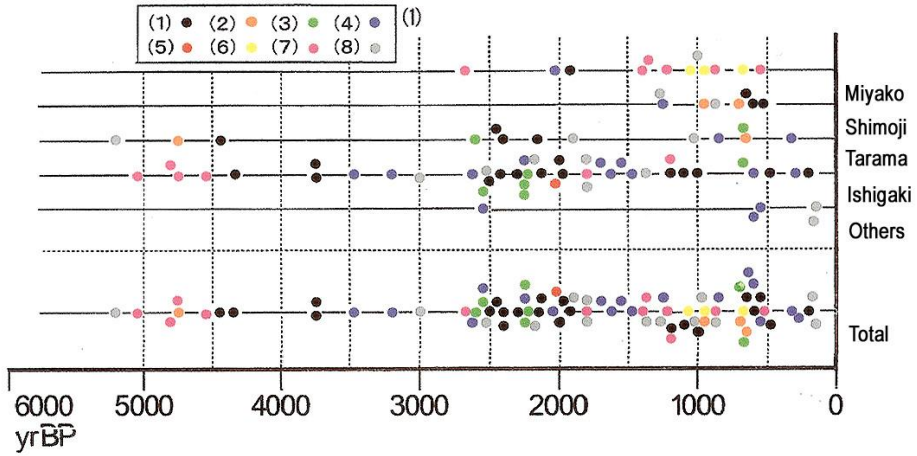



Tsunami by the 1771 Eq. (Makino 1968)

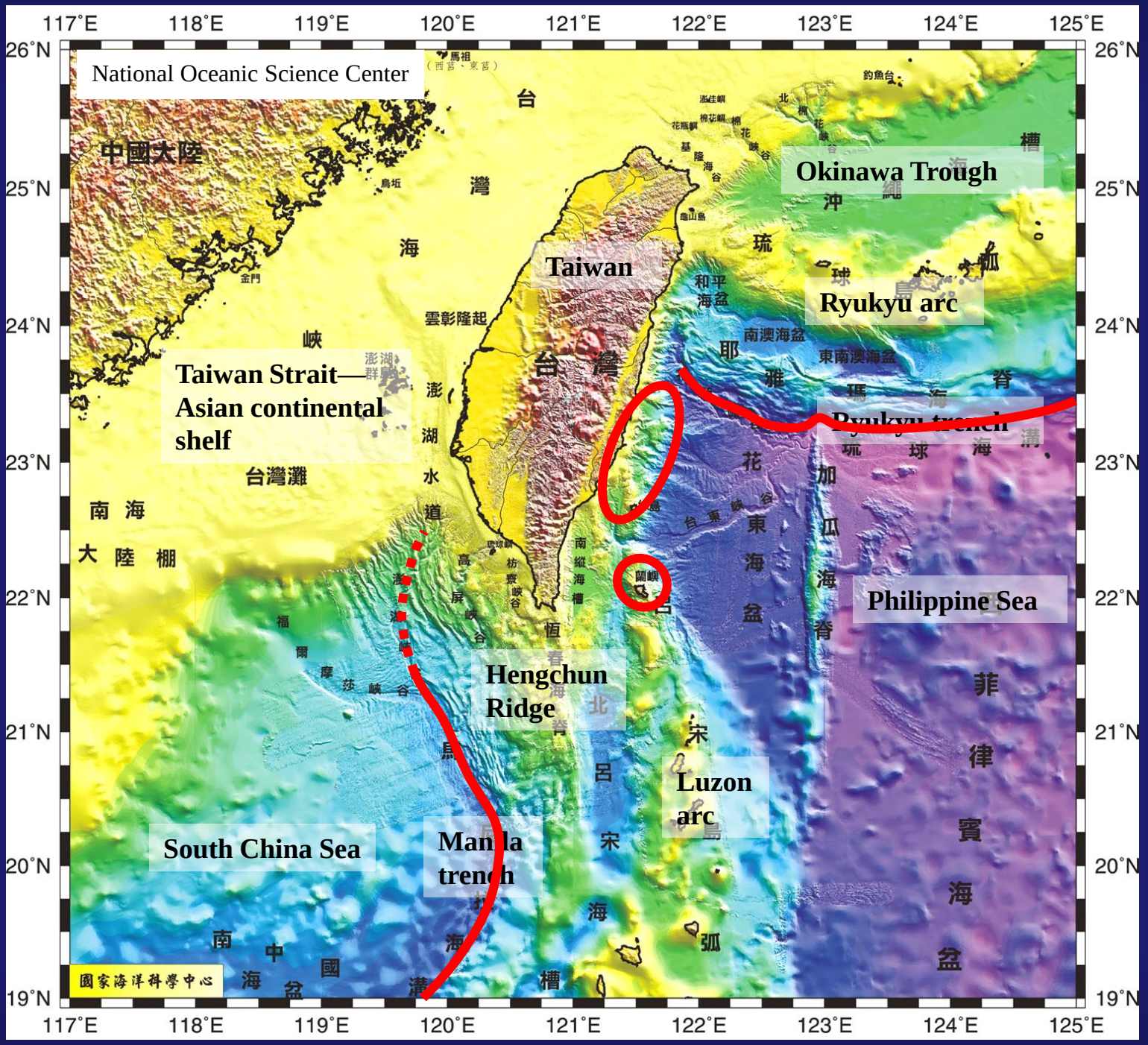
A

Tsunami boulder at Tarama Is. (Kawana)

B




Radiocarbon ages of tsunami boulders
(Kawana & Nakata 2001 )


National Oceanic Science Center
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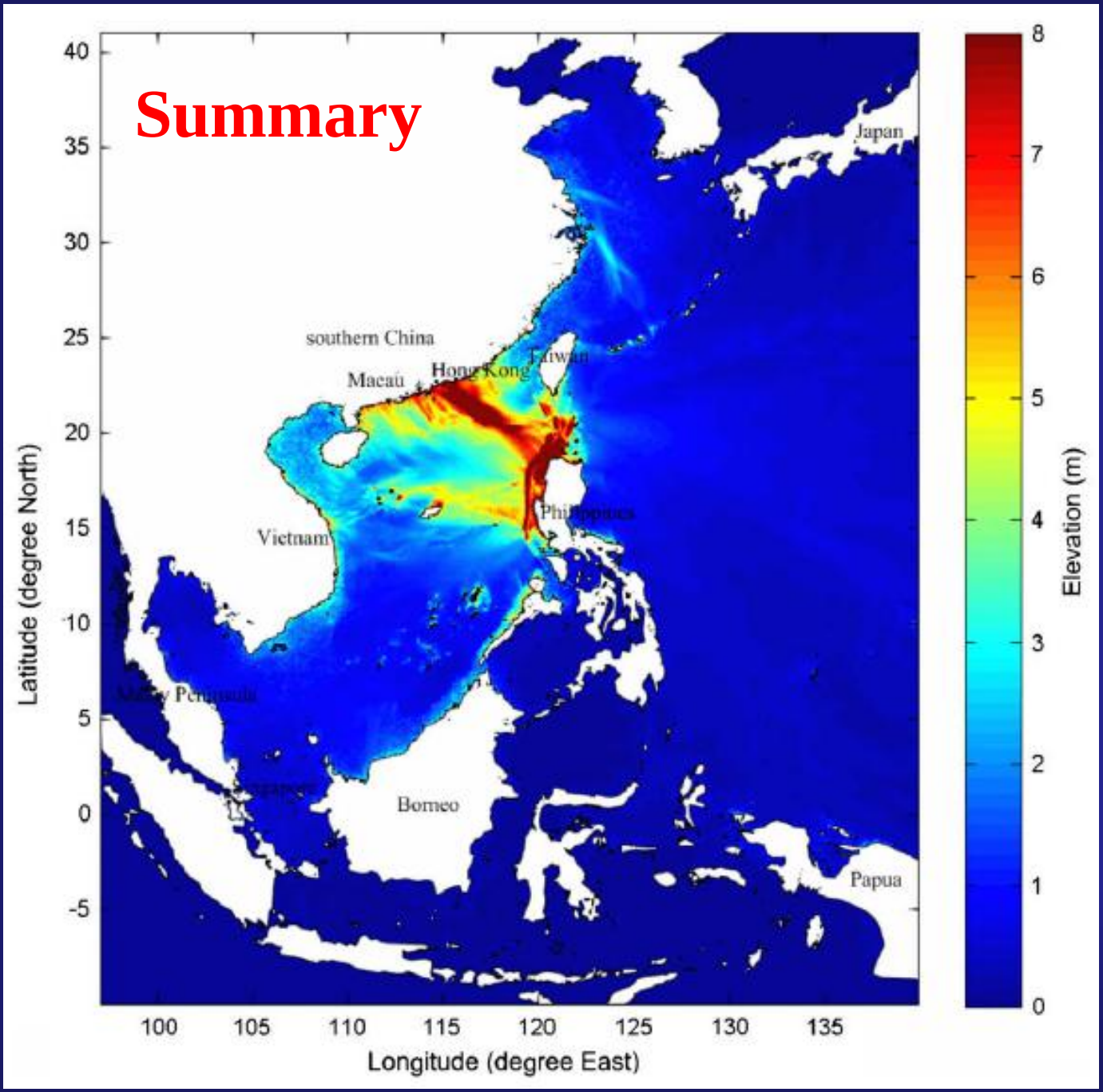
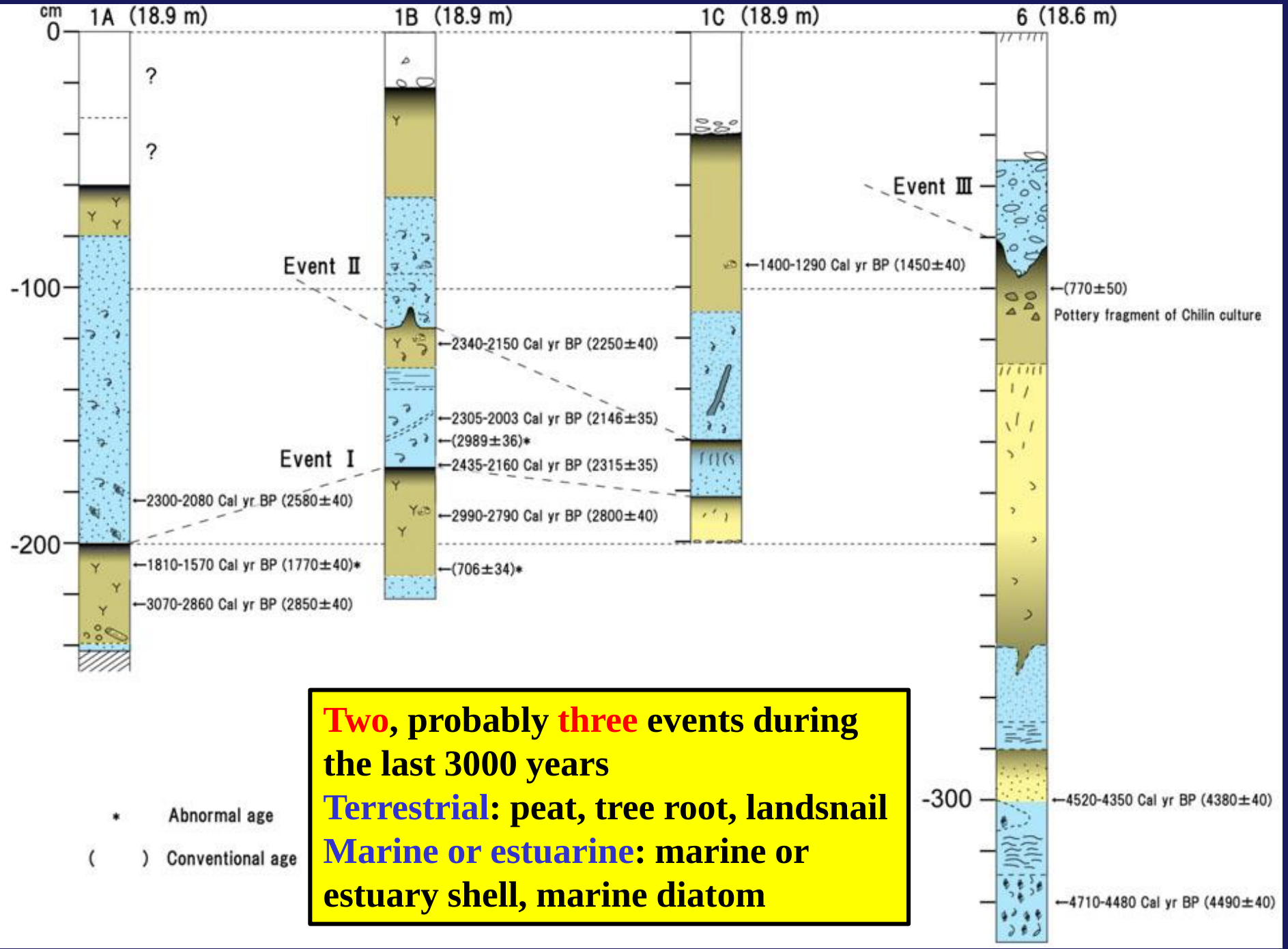
# Summary

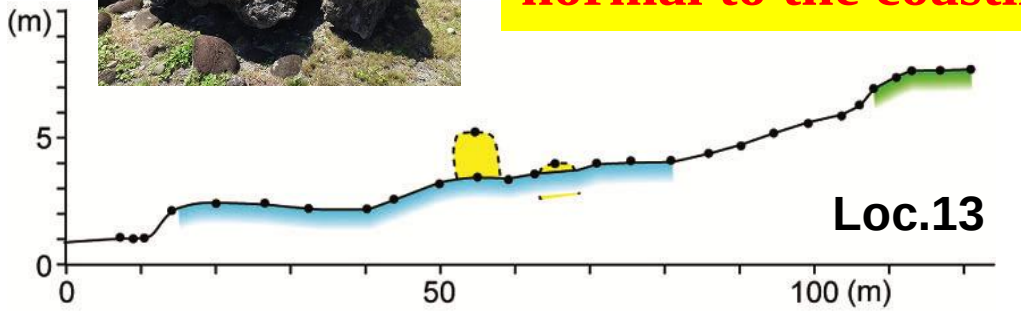


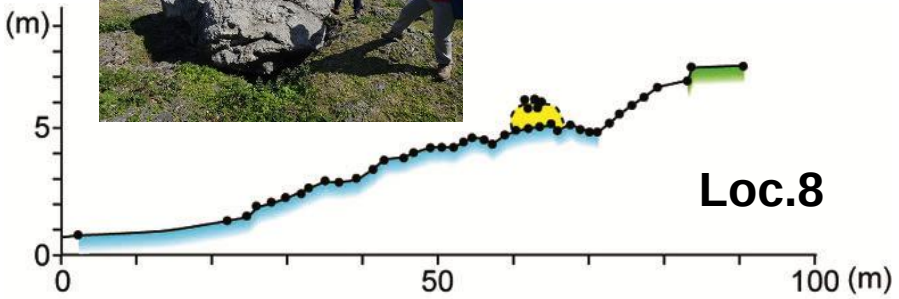

(Megawati et al., 2009)

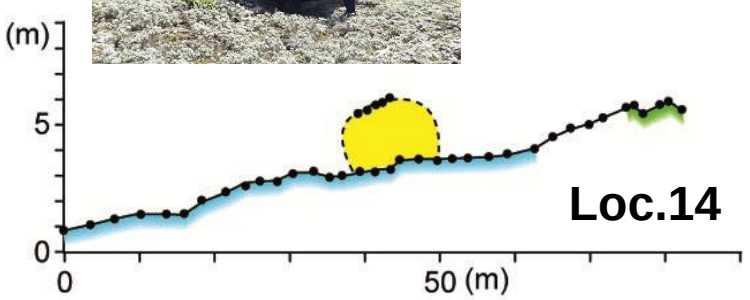

cm
1A (18.9 m)
1B (18.9 m)
1C (18.9 m)
6 (18.6 m)
0
-100
-200
-300
?
?
Event Ⅱ
Event Ⅰ
Event Ⅲ
←1400-1290 Cal yr BP (1450±40)
←(770±50)
Pottery fragment of Chilin culture
←2340-2150 Cal yr BP (2250±40)
←2305-2003 Cal yr BP (2146±35)
←(2989±36)*
←2435-2160 Cal yr BP (2315±35)
←2990-2790 Cal yr BP (2800±40)
←2300-2080 Cal yr BP (2580±40)
←(706±34)*
←1810-1570 Cal yr BP (1770±40)*
←3070-2860 Cal yr BP (2850±40)
←4520-4350 Cal yr BP (4380±40)
←4710-4480 Cal yr BP (4490±40)
* Abnormal age
( ) Conventional age
Two, probably three events during the last 3000 years
Terrestrial: peat, tree root, landsnail
Marine or estuarine: marine or estuary shell, marine diatom

**Potential tsunami boulders and profiles normal to the coastline**



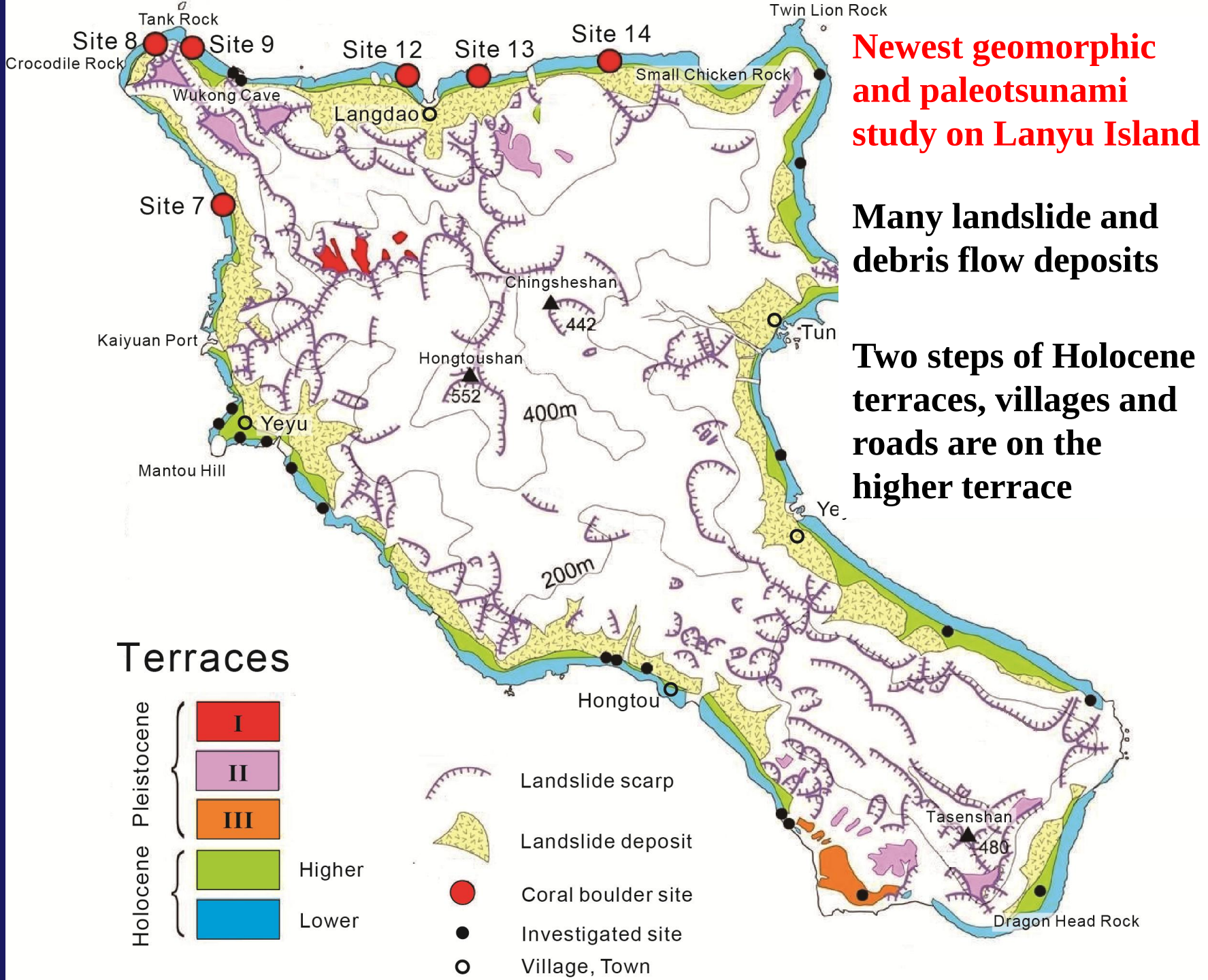







Lower Holocene terrace
Higher Holocene terrace
Coral boulders

**Coral boulders are on the lower terrace**

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