The 15/Oct/2013 M7.1 Bohol Earthquake (Philippines)

Stéphane Baize (stephane.baize@irsn.fr), Marc Cushing, Sébastien Hok
Institut de Radioprotection et Sûreté Nucléaire, France
Updated 24.10.2013

A strong (M_w7.1) and damaging (I_{MMI}=VIII) earthquake occurred on the 15th of October, 2013, at 0:12:32 UTC, in a region of active tectonics between the Negros and Philippine trenches, 100 km west of the active Philippine strike-slip fault (figure 1). This earthquake was generated by the activation of a previously unknown reverse fault, running along the northern coast of the Bohol Island.

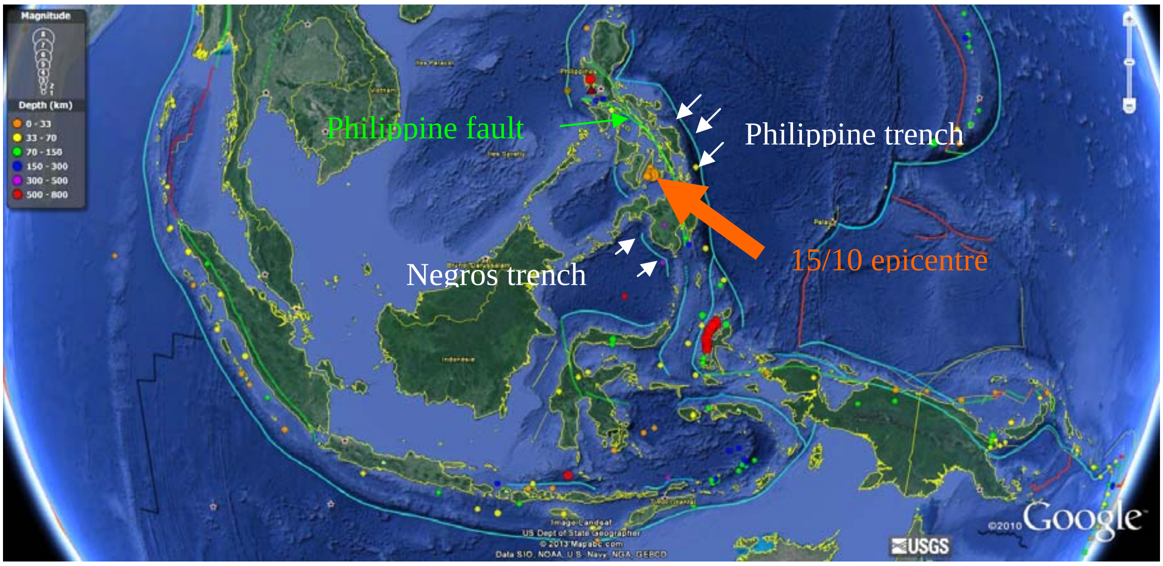


Figure 1: Geodynamic context of the Bohol earthquake (plate boundaries: source EARTHREF)

1. Geodynamics, seismotectonic context and seismic hazard

1.1 Structural and geological background

The Bohol island basement is composed of oceanic terranes (mainly Cretaceous in age) that were accreted during the Tertiary. These terranes are separated by main thrust faults (Figure 2), one of them could have been activated during the October 15th earthquake; however, field observations show that the earthquake may rather have occurred on an antithetic fault (see hereafter).

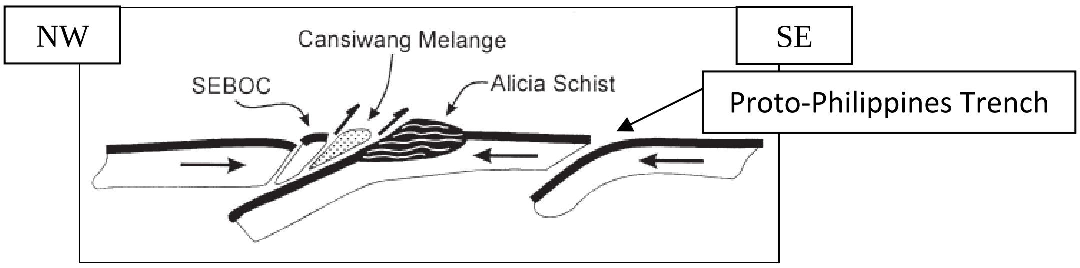


Figure 2: Sketch of the Bohol Island structure. SEBOC : Southeast Bohol Ophiolitic Complex ; Cansiwang Melange : prisme d'acrétion ; Alicia Schist : massif amphibolitique (From Barretto et al. 2000)

The basement rocks are emblematic of an ancient oceanic crust with harzburgites, ophiolites, gabbros and basalts (SEBOC formation). These basement rocks crop out in the north-eastern island part (Figure 3). An assemblage of basic magmatic rocks and deep marine sediments is also recognized in the Cansiwang Melange. The Alicia Schist Group is made up with metamorphic schists (protoliths are sedimentary rocks). The Bohol stratigraphy is completed by young sedimentary carbonates (Neogene to Quaternary) (Figure 3). The Maribojoc formation, the most recent, is formed by recifal limestones (Upper Pliocene – Lower Pleistocene). The meteoric erosion of these limestones led to the cone-shaped « Chocolate Hills ». According to their cartographic extension and their relative elevation, we suggest that these recent limestones have been uplifted by the cumulated activity of the NE-SW thrust system (see hereafter).

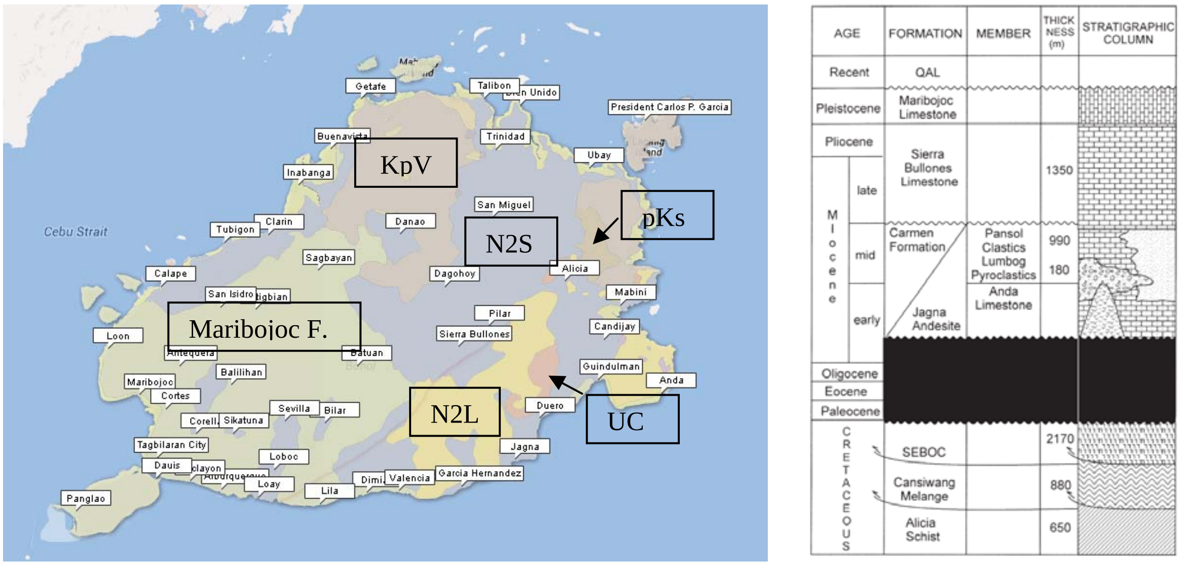


Figure 3: Simplified geological map (source: PPDOBOHOL) and stratigraphic log of the Bohol Island (from Barretto et al., 2000). N2L : Sierra Bullones formation ; N2S : Carmen formation; KpV: basement volcanic rocks; pKs: Alicia Schist; UC: Ophiolites (SEBOC).

1.2 Seismotectonics in the Bohol Island region

In the current geodynamic context, the Bohol island is part of the Visayas block as defined by Rangin et al. (1999), between the Philippine fault and the Negros trench (Figure 4). According to the GPS data analyzed by these last authors, the Visayas block accomodates a NW-SE shortening at a rate of 13 mm/y.

Regional seismicity is obviously mainly associated with the Philippine subduction interface that accomodates a relative displacement of ≈ 50 mm/y. The region is also characterized by the Philippine strike-slip fault (slip rate≈2-4 cm/y), which generated in 1990 a large earthquake in the Luzon Island (M≈7.6) and significant surface faulting.

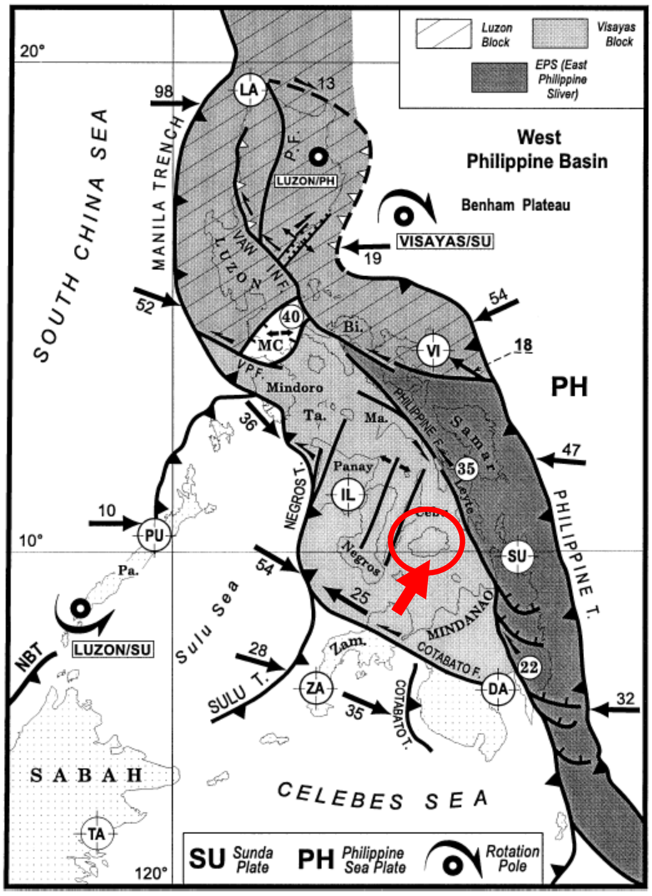


Figure 4: Geodynamics in the Philippines Archipelago (Rangin et al. 1999). Red arrows indicates the Bohol Island.

With respect to some parts of the country, the Bohol Island is not a very active area with large earthquakes. Apart several deep events related to the subducted Philippine sea slab, several significant crustal earthquakes were nonetheless reported in the Bohol Island area before 2013 (Figure 5).

On the February 8th 1990, a strong crustal earthquake (Mw=6.7; depth=16 km) occurred several km off the southeastern coast (Figure 5), with a similar focal solution as the 15.10.2013 event (source: CMT). A tsunami was generated and flooded the coastal cities and villages (max. tsunami height: 2 m at Anda; see Figure 4 for location) (Besana-Ostman et al., 2011).

In 1996 (May, 25th), the epicentral area of the 15/10/2013 earthquake was already shaken by a Ms=5.6 which caused minor damages in Cebu and along the Bohol northern coast (Figure 6).

Finally, in 2012 (February, 6th), a strong earthquake (Mw=6.7) struck the Cebu Island causing heavy damages, landslides and fatalities. This earthquake was caused by a NNE-SSW thrust fault. Its epicentre was located offshore, at 70-80 km to the west of the Bohol Island coast (Figure 7).

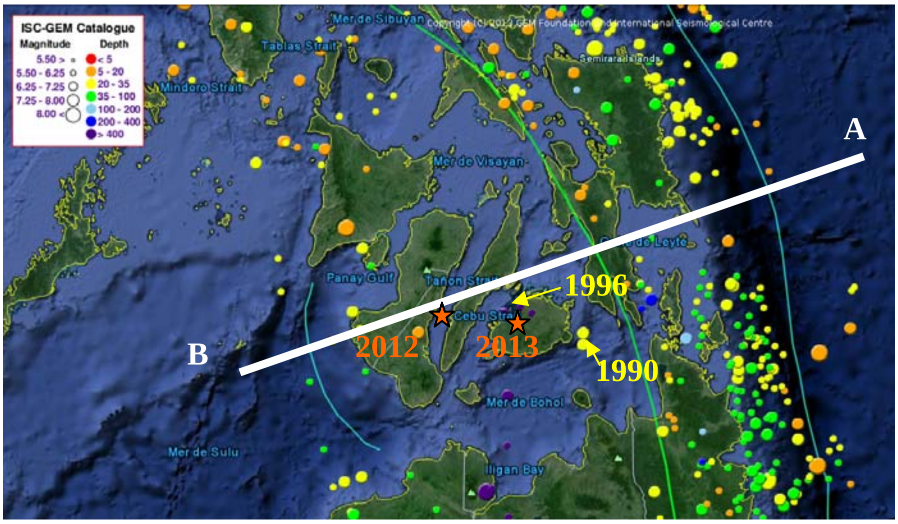


Figure 5: Instrumental and historical earthquakes in the Philippine area (source: GEM catalogue 1900-2009). The A-B section is shown in Figure 11.

Figure 6: Isoseismal map of the 1990 Bohol earthquake (source: PHIVOLCS)

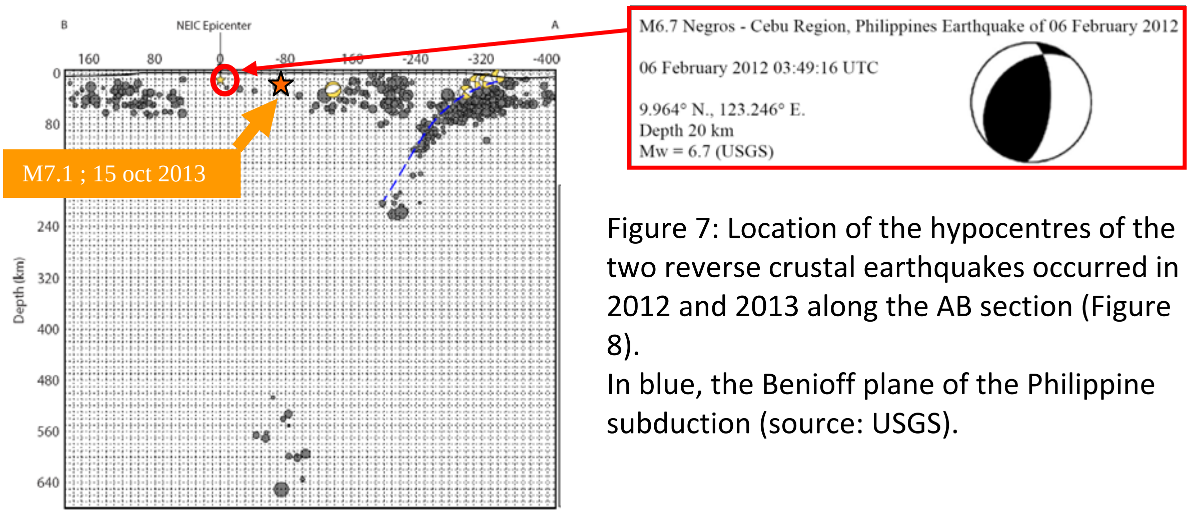


Figure 7: Location of the hypocentres of the two reverse crustal earthquakes occurred in 2012 and 2013 along the AB section (Figure 8).
In blue, the Benioff plane of the Philippine subduction (source: USGS).

1.3 Seismic hazard

According to the available hazard map (GSHAP) (Figure 8), the Bohol Island is not one of the most hazardous part of the Philippines. A probability of exceedance of 10% in 50 years is there estimated for peak ground acceleration of 0.25 to 0.3 g, whereas the same probability of exceedance is estimated for PGA around 0.5 g in the most active areas (e.g. along the Philippine fault).

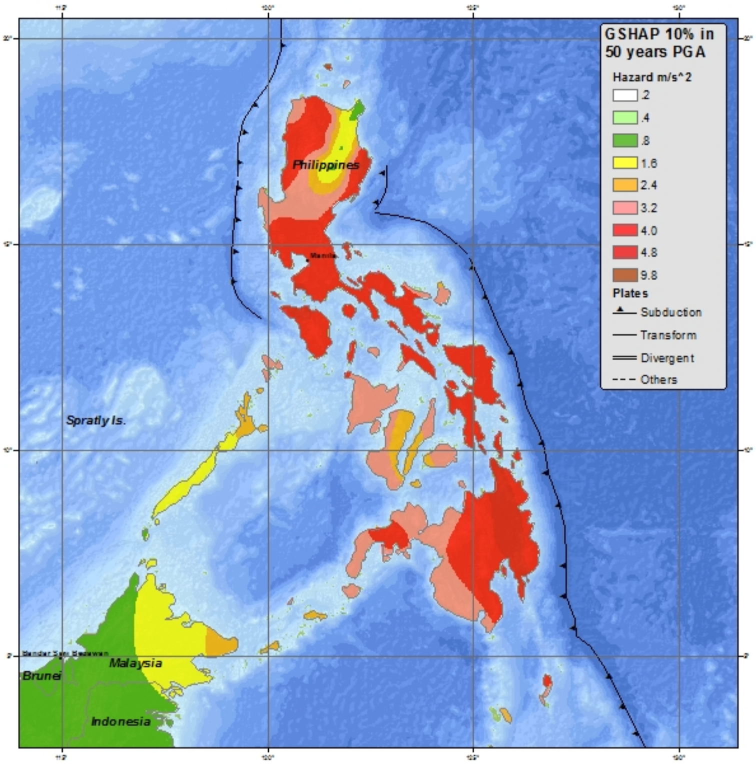


Figure 8: Seismic hazard map of the Philippines (GSHAP; source USGS)

2. The 15/10/2013 earthquake and its effects

2.1 Mainshock and aftershocks

The mainshock magnitude is Mw=7.1 and focal depth is 20 km according to the USGS. The Philippines Institute of Volcanology and Seismology (PHIVOLCS) evaluates a shallower depth (12 km). The epicentre locations given by USGS and PHIVOLCS are very close.
Other institutes give similar values of magnitude, as well as similar focal mechanisms (Figure 9). The earthquake is a reverse event, along a N°40E fault plane that is dipping of about 45°, either westward or eastward. The earthquake was followed by numerous aftershocks, of which about fifteen ranging from Mw=5 to 5.9 within the first 30 hours.
The mainshock and the aftershocks are located within a broad WSW-ENE band. The aftershocks show similar fault plane solutions as the mainshock, with dominant reverse faulting solutions and a series of strike-slip mechanisms at the north-eastern tip of the area (Figure 10).

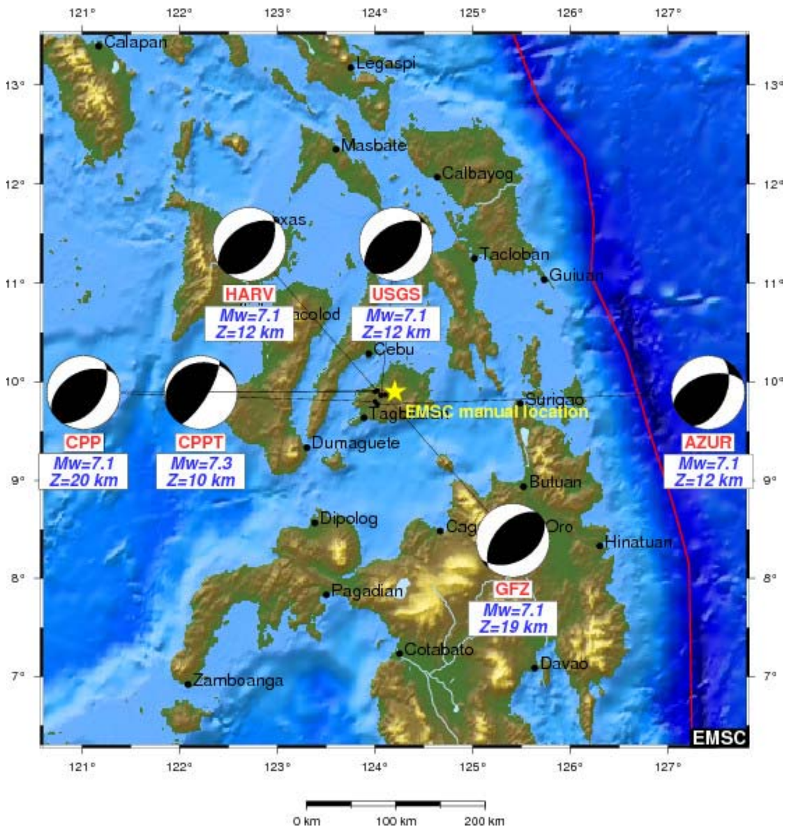


Figure 9 : Various solutions of the mainshock focal mechanism (source: EMSC)

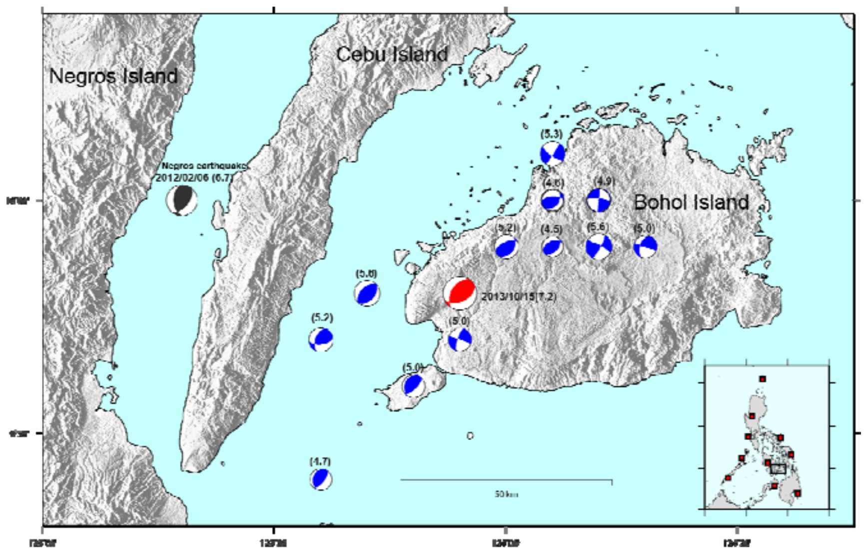
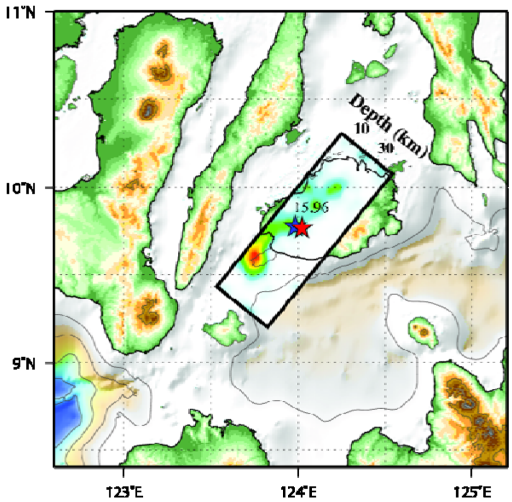


Figure 10: CMT solutions of the mainshock and its aftershocks (source: ISN)

A preliminary estimation of the slip distribution is provided by the USGS (Figure 11). By comparing with the few geological data that are available, the following is mentioned:

1. The maximum slip patch is located to the southwestern portion of the fault.
2. The maximum slip estimated at depth from seismological data (1.2 m) is much lower than the slip observed at the surface (3 m) close to a fault tip (see below).



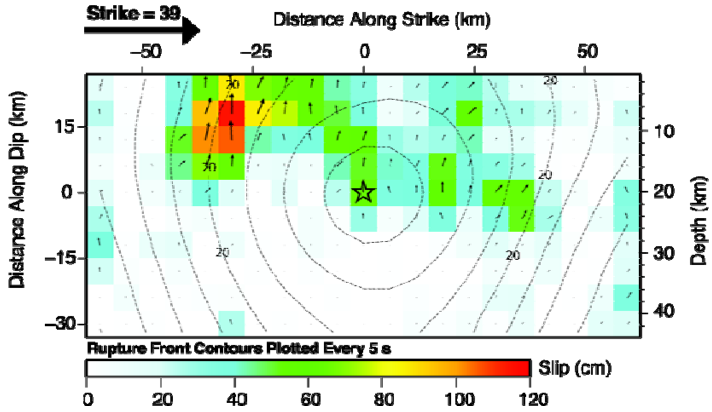


Figure 11: Slip distribution for the solution with a southeast dipping fault plane (the one consistent with geological observation of surface faulting; see hereafter) (update, 22/10/13) (source USGS)

The fault plane defined by the slip distribution (length: 75 km; depth: 20 km) is rather consistent with the aftershock map. The "seismological" fault plane at depth (75x20 km², dip 45°) would lead to a magnitude of Mw=7.3 according to the scaling relation for reverse faults of Leonard (2010). According to the same author, this would give a 60 km long fault at the surface, a maximum displacement of 5.5-6 m and an average displacement of 1.8 m.

2.2 Ground shaking, damages and other effects

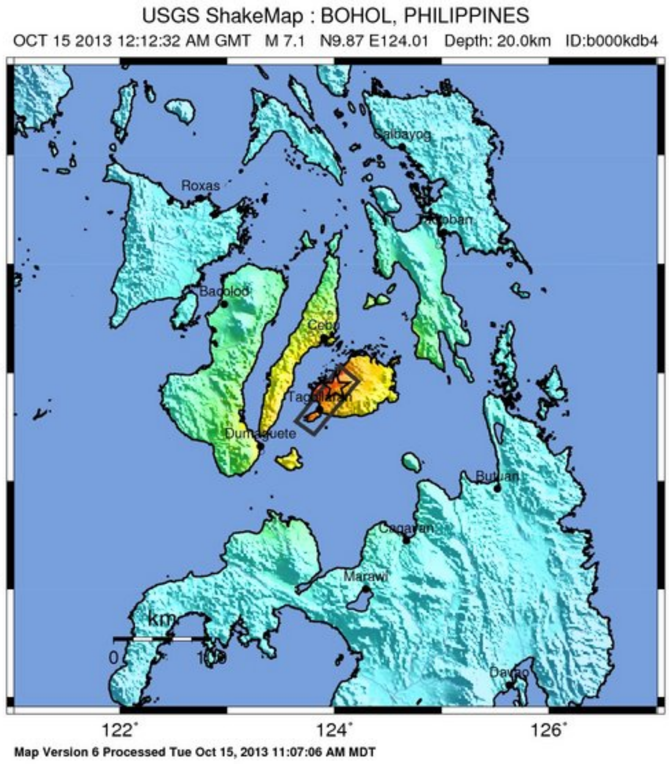
Up to now (October, 22nd), instrumental records of shaking are not available for the epicentral area. Estimation of acceleration and intensities are provided by the USGS. Acceleration and intensity may have reached respectively 0.4 g and VIII in the epicentral area (Figure 12). This calculated intensity is quite consistent with the reported damages.

Environmental effects

Surface faulting has been observed along the northern coastline of the island, at Anonang and Danahao, in the northern part of the aftershocks' box (Figures 13 and 14). According to the PHIVOLCS geologists (Press reports), the vertical separation across the fault reaches 3 m and the fault uplifted the southern block. In addition, they indicate that the fault trace was tracked over at least 5 km. Another direct environmental effect of coseismic faulting is the off-fault uplift and subsidence of some parts of the island. According to the Earthquake Report site (witness reporting), the Batasan Island (7 km off the coast of Inabanga; Figure 4) is experiencing subsidence, whereas the coast between Loon and Maribojoc is retreating (uplift).

Secondary effects are also reported. The Mw=7.2 earthquake triggered many superficial landslides and block falls all over the Bohol and Cebu islands, especially affecting the cone-shaped Chocolate Hills. As illustrated on Figure 15, some of the landslides are deep-seated in the Chocolate Hills' rock and involve relatively large volumes. Liquefaction has also been described (Figure 16), with a limited extent as indicated on the susceptibility map (see

hereafter, Figure 18). Other effects like settlement, lateral spreading or maybe sinkhole collapse have occurred (Figure 16).
The Bohol Island is made up of carbonate rocks and is a highly karstified region with large caves (sometimes called “cave country”), these last being prone to have recorded the past and current shaking events (e.g. broken speleothems).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Figure 12: Estimation of the peak ground acceleration and intensities (source: USGS)

Effects on population, buildings and infrastructures

According to Earthquake-Report and the *National Disaster Risk Reduction and Management Council* (NDRRMC), 209 people were killed, 12 are missing, and 651 individuals were injured (updated 24th Oct). Economic damage is estimated around 4 billion PHP and the reconstruction would cost 7 billion PHP. According to the NDRRMC, the affected population almost reaches 3 million. Among them, 345,000 were displaced.
Many houses (more than 50,000), schools, hospitals and churches were affected or collapsed all over the Bohol Island and the region of Cebu (Figure 17). Airports and seaports of Bohol and Cebu islands also collapsed or were partly damaged. Many roads and bridges were affected, in particular by the numerous landslides. Some of the roads and bridges then became not passable.

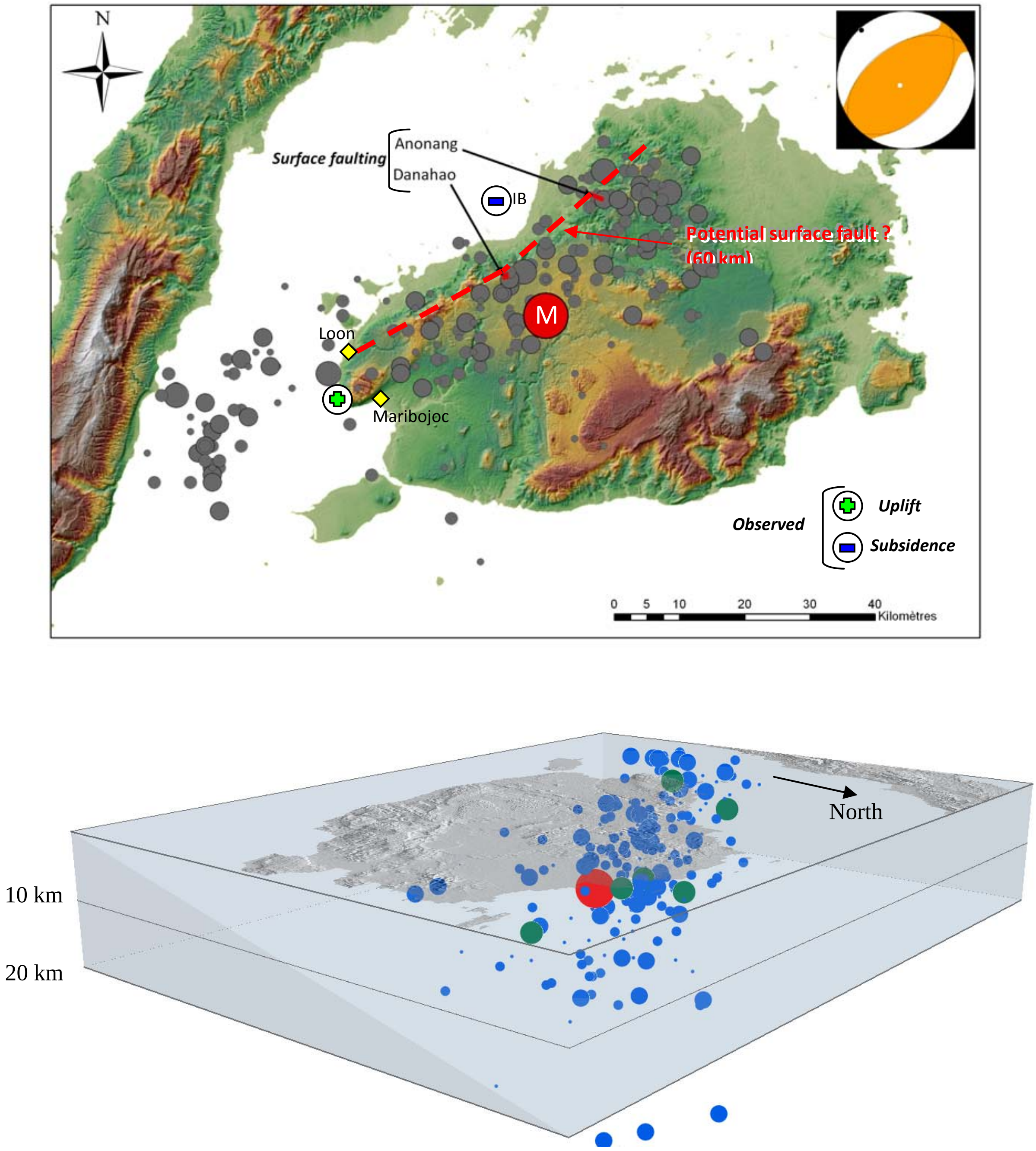


Figure 13: Map and 3D diagram (1:1 scale) illustrating the mainshock (M) and its aftershocks (in green, with Mw>5), based on the PHIVOLCS catalogue (updated Oct 21th). The location of surface faulting evidences (Anonang and Danahao; pictures in Figure 14) and vertical displacement markers are also shown (uplift between Loon and Maribojoc; subsidence at Island of Batasan, IB). On the 3D diagram, the hypocentres are scattered within a steeply southward-dipping block. Focal solution comes from the USGS. Source: this paper.

Figure 14: Several pictures of the surface deformations in the Bohol Island (location of sites on Figure 13).

At Anonang and Danahao, the fault scarp was observed by PHIVOLCS geologists. Note the anthropic terrace risers that could help in estimating the horizontal component of slip.
Between Loon and Maribojoc, the shoreline retreated, exposing the marine platform.

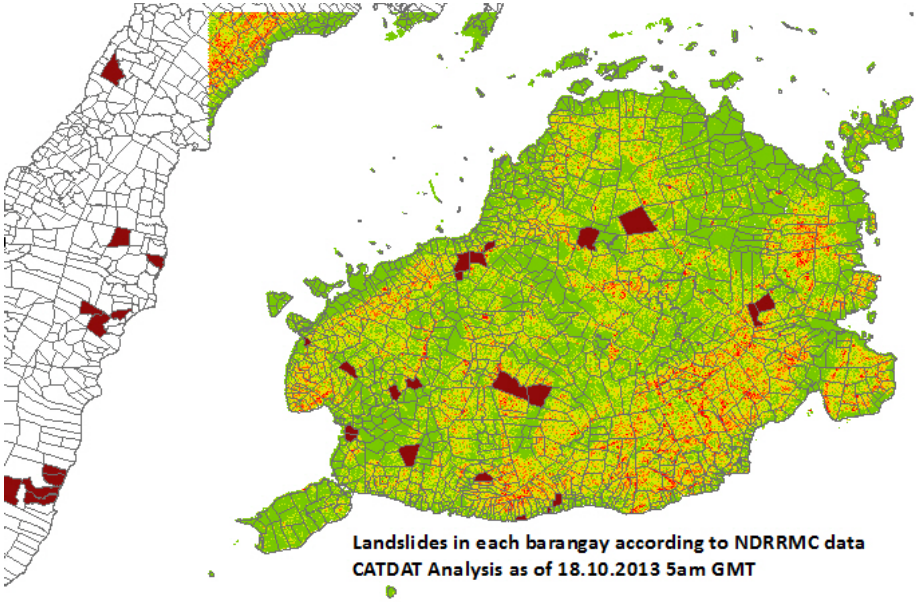
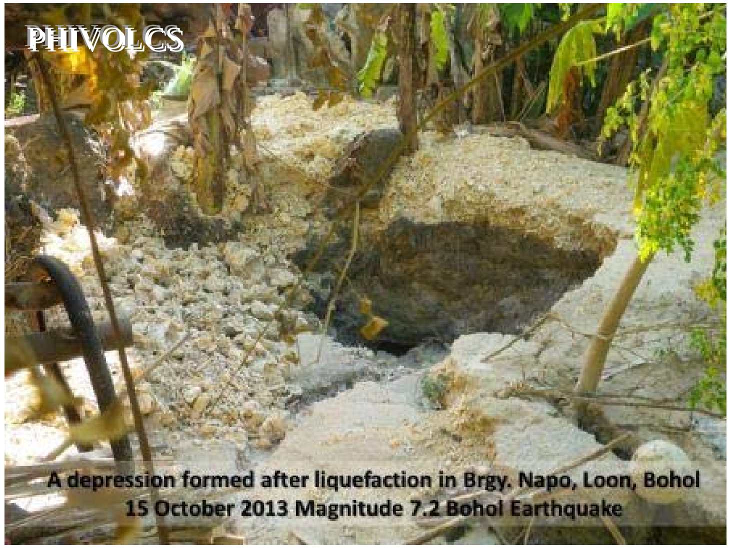


Figure 15: Map of landslides (source: Erathquake report, according to NDRRMC data) and examples of rock falls (top) and deep-seated landslide in the Chocolate Hills (bottom).

Figure 16: Some other secondary effects (liquefaction, settlement, lateral spreading or sinkhole collapse?)



Damaged Hunan Bridge 2.6 meters vertical displacement
(ground settlement) in Buenavista, Bohol
15 October 2013 Magnitude 7.2 Bohol Earthquake

Figure 17: Collapsed church (17th century) in Bohol Island (Loboc) and buildings in Cebu

3. A short and preliminary analysis of crustal active fault(s) in the Bohol Island

The PHIVOLCS describes an active fault along the southeastern coastline of the Bohol Island, the East Bohol Fault (Figure 18). Detailed data on this fault are unfortunately not available.

In the first days after the earthquake, this fault was thought to be a reliable candidate as a source because

1. The focal mechanism is consistent with the trend and kinematics of this fault.
2. The fault trace is located at almost 25 km south of the epicentre (Figure 19). Considering the depth of the focus between 12 to 20 km (depending of the institute) and the dip of the nodal plane solution (45°), this hypothesis was reasonable and was initially supported by the PHIVOLCS.
3. The map of the aftershock sequence shows an outstanding NE-SW plane as long as 75-80 km and 15 km wide (projected on the horizontal plane).

However, the aftershocks tend to extend from the epicentre towards the north, not towards the south and the East Bohol fault. The post-seismic field observations indicate that a previously unknown fault is the source of the event, running inland all along the NW coastline (Figures 13 and 14).

The island morphology suggests that the East Bohol Fault is an active and morphogenic structure. In its western portion (profile 1; Figure 19), one can distinguish a cumulative scarp of about 400 m that could be associated with the uplift of the hanging wall of the fault. To the east, this cumulative scarp increases up to 600 m (profiles 2 and 3).
Several points are also interesting to be emphasized:

1. A smaller (cumulative) scarp also appears to the north of the 3 profiles. Its separation is around 200 m.
2. In between the coastal scarps, the young (lower Pleistocene) Maribojoc Formation is uplifted of about 100 to 200 m.

This suggests that, besides the southeast-verging Eastern Bohol fault, a northwest-verging "northern" structure may cause vertical displacement and uplift of the Quaternary Maribojoc sediments. This morphogenic structure might be the continuation to the SW of the surface rupture observed in Anonang. It could be considered as a back-thrust related to the major East Bohol fault.
Assuming that the Maribojoc formation is 2 Ma old, the general uplift rate of the central part of the island, that could be associated with the thrust system activity, would be of 0.05-0.1 mm/a.

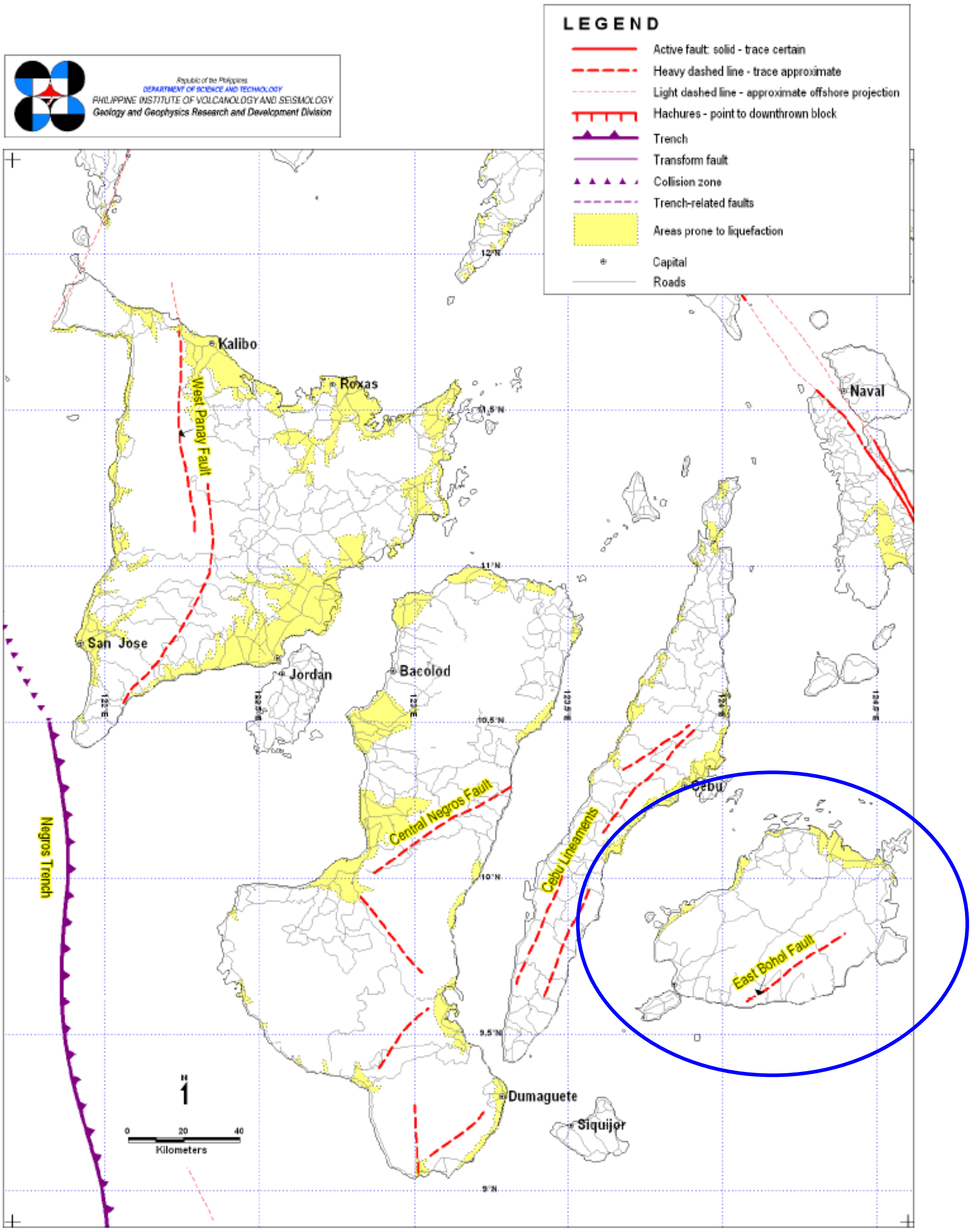


Figure 18: Active faults of the VII-VIII region of the Philippines, according to PHIVOLCS.

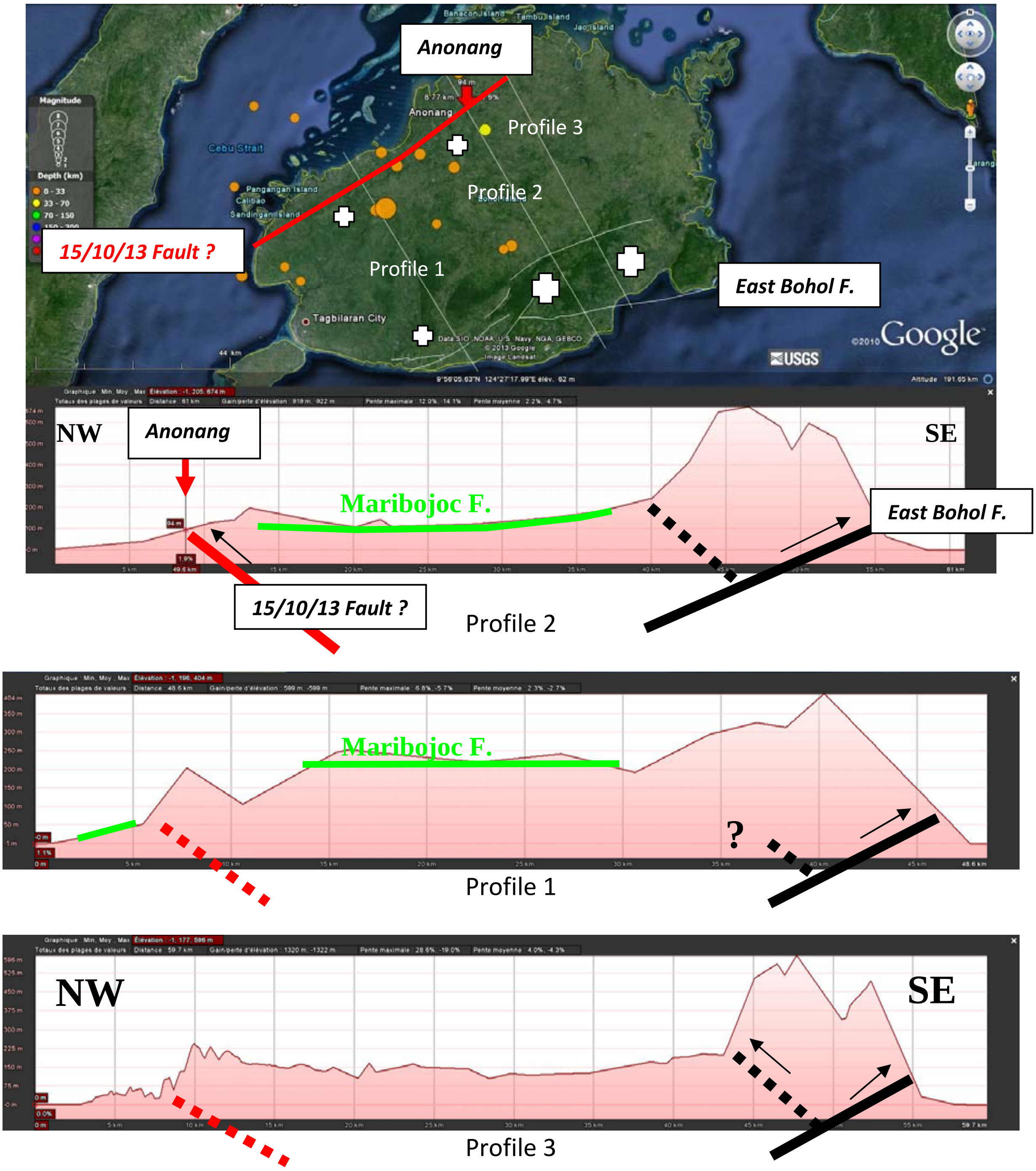


Figure 19: Morphological sections of the Bohol Island (source of topographic data: Google Earth Pro) and provisional interpretation of the potential active and morphogenic faults (source: this paper).

4. Conclusion

The following points are emphasized:

- The Bohol earthquake is a severe event with significant damages on buildings and infrastructures;
- Such a high magnitude earthquake has never been reported in this area of the Philippines archipelago;
- The fault that ruptured during the earthquake was previously unknown;
- According to the aftershock extension and slip distribution estimated from seismology, the fault may be as long as 75-80 km at depth;
- Primary faulting has been recognized at the surface and surface offset appears significant (3 m);
- Secondary effects are widespread, with landslides and rock falls;
- The large repartition and homogeneity of the cone-shaped Chocolate hills, over the epicentral area, may provide meaningful statistics on landslide triggering.

Considering these points, a comprehensive study should be conducted to map and characterize the surface fault, as well as other Earthquake Environmental Effects (EEE). To our knowledge, secondary faulting and off-fault environmental effects, such as speleothem breaks, were not discovered yet but, considering the high magnitude, the strong shaking and the large surface offset along the main fault, these shoud be searched. Such a study should be completed through field survey and remote sensing analyses (INSAR).

This study should also increase the EEE database (http://www.eeecatalog.sinanet.apat.it/). This earthquake might also be an interesting case study to feed the worldwide database dedicated to Probabilistic Fault Displacement Hazard Assessments (e.g. Moss & Ross, 2011) and to calibrate the Environmental Seismic Intensity scale, a potential useful tool to evaluate the earthquake source potentiality for ground shaking assessments (Michetti et al., 2007).

With respect to the regional seismic hazard assessment, a paleoseismological survey (morphotectonics, trenching) should also give a time history of this newly found fault and evaluate its potentiality.

References

Barretto et al. (2000). Gravity variations along the Southeast Bohol Ophiolite Complex (SEBOC), Central Philippines: Implications on Ophiolite Emplacement. The Island Arc, 9, 575–583.

Besana-Ostman et al. (2011). The 1990 Bohol earthquake: tsunami observations and effects at Bohol Island, Philippines. Science of Tsunami Hazards, Vol. 30, No. 2, 78-93.

CMT: http://www.globalcmt.org/

Earthquake-Report: http://earthquake-report.com/

EARTHREF: http://earthref.org/ERDA/1372/

EMSC: http://www.emsc-csem.org/

GEM: http://www.isc.ac.uk/iscgem/

ISN: http://www.isn.bosai.go.jp/

Leonard (2010). Earthquake fault scaling: self-consistent relating of rupture length, width, average displacement, and moment release. Bull. Seismol. Soc. Am. 100, 1971-1988.

Michetti et al. (2007). Intensity Scale ESI 2007. In. Guerrieri L. & Vittori E. (Eds.): Mem. Descr. Carta Geol. d'Italia., vol. 74, Servizio Geologico d'Italia – Dipartimento Difesa del Suolo, APAT, Rome, Italy.

Moss & Ross (2011). Probabilistic Fault Displacement Hazard Analysis for Reverse Faults. Bulletin of the Seismological Society of America, 101, 1542–1553.

NDRRMC: http://www.ndrrmc.gov.ph/

PHIVOLCS: http://www.phivolcs.dost.gov.ph/

PPDOBOHOL: http://www.ppdobohol.lgu.ph/

Rangin et al. (1999). Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary: the Philippines and eastern Indonesia. Geophys. J. Int., 139, 296–316.

USGS: http://earthquake.usgs.gov/