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Abstract. In February 2006, a disastrous rockslide-debris avalanche occurred in tropical mountain terrain, on Leyte Island, Central Philippines. Over 1100 people perished when the village of Guinsaugon was overwhelmed directly in the path of the landslide. The landslide was initiated by the failure of a 450 m high rock slope within the damage zone of the Philippine Fault where the rock mass consisted of sheared and brecciated volcanic, sedimentary and volcaniclastic rocks. Tectonic weakening of the failed rock mass had resulted from active strike-slip movements along the Philippine Fault which have been estimated by other workers at 2.5 cm/year. The landslide involved a total volume of 15 Mm^3, including significant entrainment from its path, and ran out a horizontal distance of 3800 m over a vertical distance of 810 m, equivalent to a fahrböschung of 12°. Run-out distance was enhanced by friction reduction due to undrained loading when the debris encountered flooded paddy fields in the valley bottom at a path distance of 2600 m. A simulation of the event using the dynamic analysis model DAN indicated a mean velocity of 35 m/s and demonstrated the contribution of the paddy field effect to total run-out distance. There was no direct trigger for the landslide but the landslide did follow a period of very heavy rainfall with a lag time of four days. The rockslide-debris avalanche is one of several disastrous landslides to have occurred in the Philippines in the last twenty years. In terms of loss of life, the Guinsaugon event is the most devastating single-event landslide to have occurred worldwide since the Casita Volcano rock avalanche-debris flow which was triggered by Hurricane Mitch in Nicaragua in 1998.

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1 Introduction

On 17 February 2006 a disastrous landslide occurred in Southern Leyte Province, Leyte Island, the Philippines (Lagmay et al., 2006; Fig. 1). It originated on a steep 450 m high, heavily-forested rockslope and swept down into the densely-populated Himbungao River valley. The landslide overwhelmed the village of Guinsaugon resulting in the loss of over 1100 people, including 250 schoolchildren who were attending morning classes at the Guinsaugon School.

The landslide is one of the largest to have occurred in tropical mountain terrain in recent years. The event originated within the damage zone of the Philippine Fault, one of the major geological structures of the western Pacific region. Geological factors were thus major contributors to the catastrophic failure.

In this paper we summarise the main characteristics of the landslide, discuss its geological, tectonic, and climatic setting, present a first-approximation to a simulation of its motion, examine its destructiveness in a global and historical context, and review the implications of its occurrence for landslide hazard assessment on Leyte Island. The report is based on data obtained from the analysis of space-borne optical imagery, orbitally-aquired digital terrain data, and field investigations at the landslide site in March 2006 (see Appendix A).

2 Tectonic, geologic and climatic setting of Leyte Island, Philippine archipelago

Leyte Island is located in the central part of the Philippine islands (Fig. 2). The archipelago is located in one of the most active geologic settings on earth. Three major tectonic elements characterize this complex oblique convergence environment; the Philippine Sea Plate, the Eurasian Plate and the Philippine Fault (Fig. 2). The westward moving

Fig. 1. **(A)** Oblique aerial view (to the northwest) of the Guinsaugon landslide taken on 19 February 2006. (U.S. Navy photograph by M. D. Kennedy). The Himbungao River flows from right to left. **(B)** View of debris toward the source area of the rockslide-debris avalanche (Photograph taken 12 March 2006).

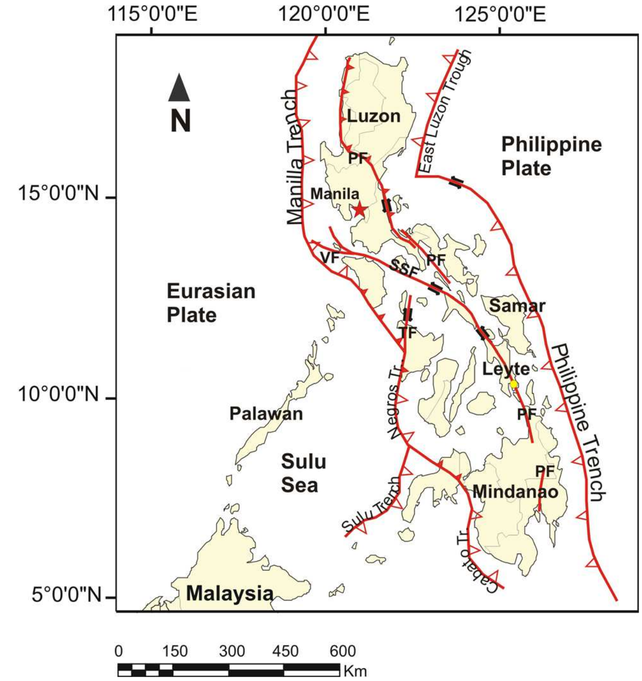

Fig. 2. Map of the Philippine archipelago showing plate tectonic setting, trace of the Philippine Fault (PF), other main active faults (the Sibuyan Sea Fault (SSF), the Verde Passage Fault (VF), Tablas Fault (TF)), and the location of Leyte Island (modified after Barrier et al., 1991).

Philippine Sea Plate collides obliquely with the eastward moving Eurasian Plate. The result of this collision is a double subduction zone marked on the east by the Philippine Trench and on the west by the Manila Trench and its extension, the Sulu Trench (Fig. 2). Rates of subduction have been estimated at 6–8 cm/yr (Aurelio, 2000). The Philippine Archipelago is bisected by a major strike-slip transform structure, the Philippine Fault (Allen, 1962; Barrier et al., 1991), which roughly parallels the plate boundaries that border the islands (Fig. 2). Although the precise interaction between the subduction zones and the strike slip faulting is not fully understood, the 1300 km long Philippine Fault appears to have formed in direct response to the oblique collision (Aurelio, 2000).

The geology of Leyte Island consists of a number of Pliocene-Quaternary volcanic cones, generally andesitic in nature, Tertiary sediments and thick successions of Tertiary volcanic and volcaniclastic rocks (Fig. 3a; Aurelio, 1992; Sajona et al., 1997). The dominant structure is the Philippine Fault (Allen, 1962; Aurelio, 1992) which bisects the island (Fig. 3). In the vicinity of Ormoc, the fault has offset the northeast and southwest sectors of the ancestral Mount Bao volcano in the northern part of Leyte Island by a distance of 8 km over a period of 450 000 years (Figs. 3a, b; Duquesnoy et al., 1994; Lagmay et al., 2000).

Creep movement along the fault in the Leyte area has been measured at about 2.5 cm/year (Aurelio et al., 1997; Barrier et al., 1991; Duquesnoy et al., 1994). In Leyte Island the creep is largely aseismic. An analysis of the shear partitioning along the fault suggests that oblique convergence is decomposed into a component perpendicular to the Philippine Trench and another parallel to the Trench and thus parallel to the Philippine Fault (Aurelio, 2000). GPS measurements in the central Philippines (Duquesnoy et al., 1994; Aurelio, 2000), suggest left-lateral displacement although an extensional component perpendicular to the strike of the fault was also detected which may represent non-brittle deformation of surface rocks, perhaps in response to slope movement. The topographic expression of the fault includes fault line scarps, side-hill ridges, pressure ridges parallel to the fault and associated narrow elongate depressions (Allen, 1962; Duquesnoy et al., 1994; Fig. 3b).

The Philippine Fault has been seismically active in historical times, notably in the 1990 Luzon Earthquake (M_w=7.7) which resulted in the deaths of about 1600 people in the northern part of the Philippines (Velasco et al., 1996).

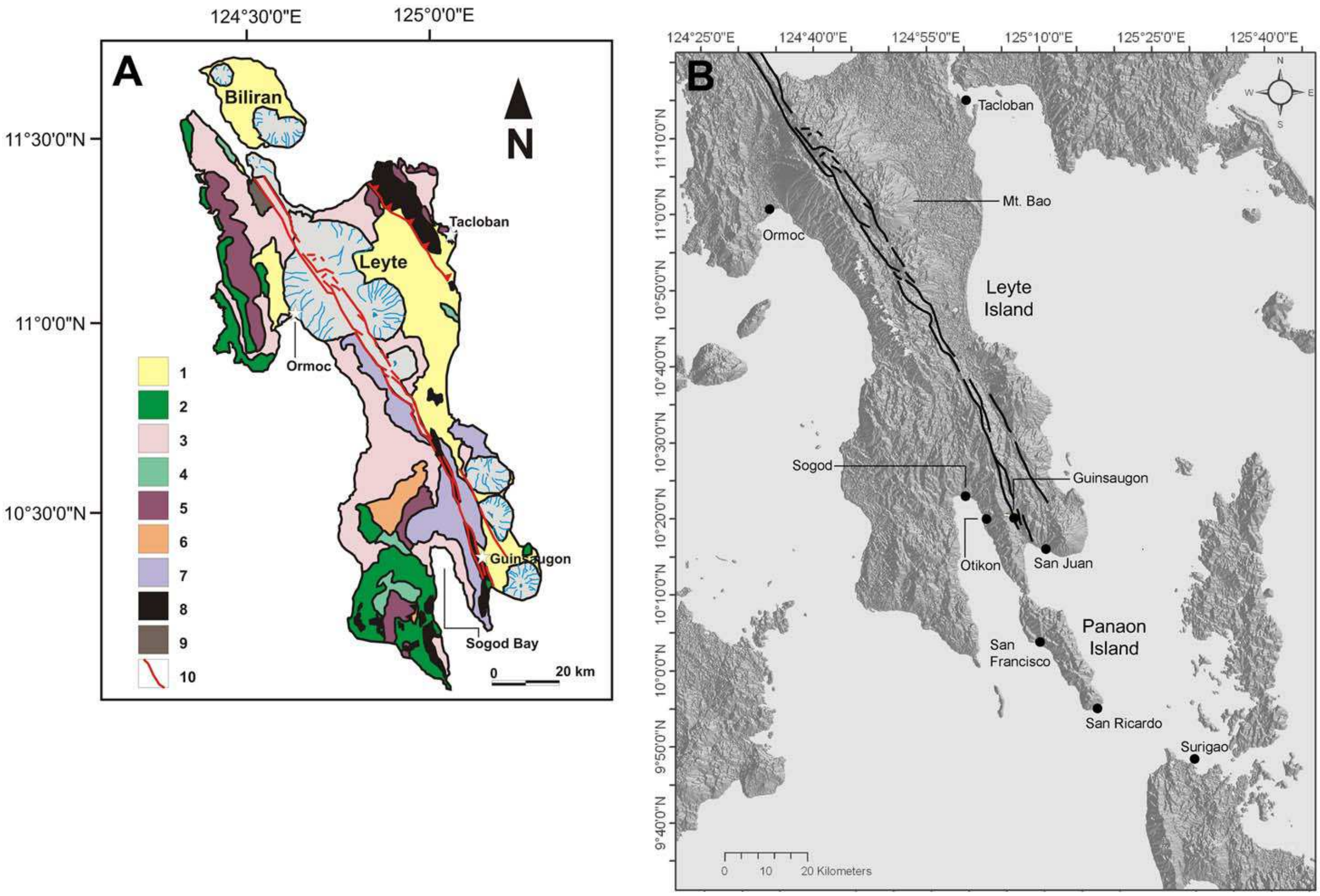

Fig. 3. **(A)** Geology of Leyte Island (modified from Aurelio, 1992). Key to geological units: 1 – alluvium; 2 – Pleistocene limestone; 3 – Late Miocene to Early Pliocene sediments; 4 – Middle Miocene Limestone; 5 – Late Oligocene to Early Miocene sediments; 6 – Eocene volcaniclastics; 7 – undifferentiated volcanics; 8 – ophiolite; 9 – marshland; 10 – Trace of Philippine Fault that bisects Leyte Island. **(B)** Shaded relief map (based on SRTM data – for technical details see Appendix)) of Leyte Island showing the location of 17 February Guinsaugon landslide and the trace of the Philippine Fault (thick black lines). Locations of communities mentioned in the text are also shown.

However, the seismicity of the fault is marked by spatial variation in the occurrence of large earthquakes. In the Leyte area no large historical earthquake has been reported since the 17th century and seismicity appears to be dominated by shallow (<10 km in depth) small magnitude earthquakes (Inter-Agency Committee, 2006). This pattern of seismicity is consistent with the idea that the Philippine Fault in Leyte Island is creeping slowly rather than accumulating strain (Duquesnoy et al., 1994).

The climate of Leyte Island is characterized by high total annual rainfall, episodic very heavy rains associated with tropical cyclones and almost constant warm temperatures (Fig. 4). Southeastern Leyte is characterized by Type II climate under the Philippine Climate Classification (the Coronas Classification), i.e., no dry season and a very pronounced maximum rainfall from November to January (Fig. 4). Climate data for the period 1902–2005 were obtained for Surigao, located within the same Type 2 zone at the northern tip of Mindanao (Fig. 3b). Climate data from this station is believed to be representative of the southeastern part of Leyte Island, at least in broad outline. The total annual precipitation is in the order of 3640 mm. The combination of warm temperatures and high rainfall results in widespread deep tropical weathering and the extensive development of residual soils throughout the Philippines (e.g., Hart et al., 2002).

3 The 17 February 2006 Guinsaugon landslide

3.1 Overview

The landslide (Figs. 1, 5) occurred between 10:30 a.m. and 10:45 a.m. on the morning of 17 February 2006. An eyewitness interviewed during field work said that the landslide started with a shaking of the ground, followed by the sound

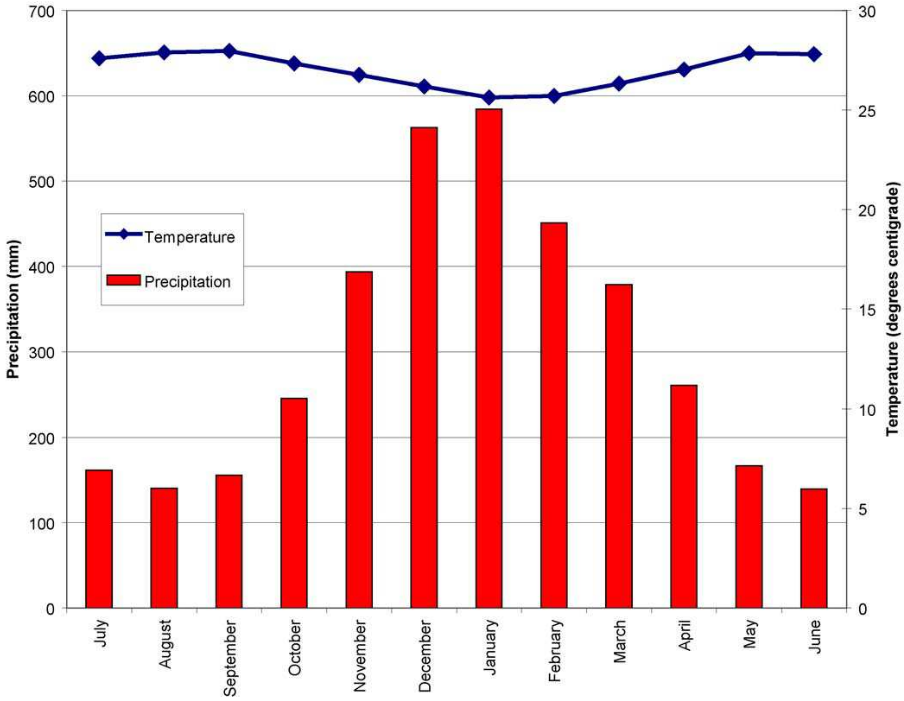

Fig. 4. Climatic data (mean monthly precipitation and mean monthly temperature) typical of Philippine Climate Zone Type II from Surigao, Mindanao (located on Fig. 3b). Data is summarized for the period 1902–2005 (Data obtained from Global Historical National Climate Network).

of an explosion which was in turn followed by a deafening noise similar to that of a jet engine. Initial media reports suggested that the landslide was a mudslide, debris flow, or debris avalanche. However, based on field observations, the landslide is best classified as a rockslide-debris avalanche, as defined by Hungr et al. (2001) and Hungr and Evans (2004), in which a landslide begins with a failure of a rockslope and proceeds to entrain large quantities of debris (in this case colluvium at the base of the source slope). Hungr and Evans (2004) further propose the term to describe landslides in which the Entrainment Ratio, defined by Hungr and Evans (2004) as the ratio between the volume of debris entrained from the landslide path and the bulked volume of rock fragments produced by the initial rock slope failure, exceeds 0.25 (see below). A rockslide-debris avalanche also involves extremely rapid, massive, flow-like motion (Hungr et al., 2001) (Figs. 5a, b). Estimates of velocity by eyewitnesses suggest a mean velocity for the Guinsaugon event to be in the order of 27–38 m/s (Lagmay et al., 2006).

The topographic map generated from SRTM data (see Appendix A) for this paper (Fig. 6) indicates that the rockslide-debris avalanche traveled a horizontal distance (L) of about 3.8 km (Figs. 6, 7) over a vertical height difference (H) of about 810 m (Fig. 6). This yields a fahrböschung of 12°, a value that is identical to the field measurement of 12°. Based on field estimates of debris depth and an analysis of digital terrain data (Fig. 6) the volume of the landslide debris is about 15 Mm^3. On a mobility plot of H/L vs. volume, these data for the landslide plot within the 95% confidence limit calculated by Corominas (1996).

3.2 Initial failure

Detailed large-scale geological mapping has not been carried out in Southern Leyte Province. However, the 1:1 000 000 scale Geological Map of the Philippines indicates that the landslide involved initial failure of a rock slope developed in a succession of Upper Miocene-Pliocene interbedded sedimentary (mainly marine clastics), volcanic (mainly andesite and dacite flow rocks), and volcaniclastic rocks (tuffs and tuffites) (Philippine Bureau of Mines, 1963) that appear to dip at about 20° to the west (Fig. 6). The direction of landslide movement is toward the east (Fig. 6) and thus involved the failure of the escarpment face across the bedding.

As noted above the initial failure involved a steep (48°) forested rock slope that forms the east facing slope of a NNW-SSE trending ridge (Figs. 7, 8). Satellite imagery and helicopter observations indicate that this sharp-crested ridge has undergone notable slope displacements (Figs. 7, 8). This is manifested in slipped masses and tension cracks along the crest of the ridge (Fig. 8). The source of the rockslide-debris avalanche is located within the damage zone (Kim et al., 2004) of the Philippine Fault; the site of the landslide is traversed by the main trace of the Philippine Fault (Figs. 6, 7,

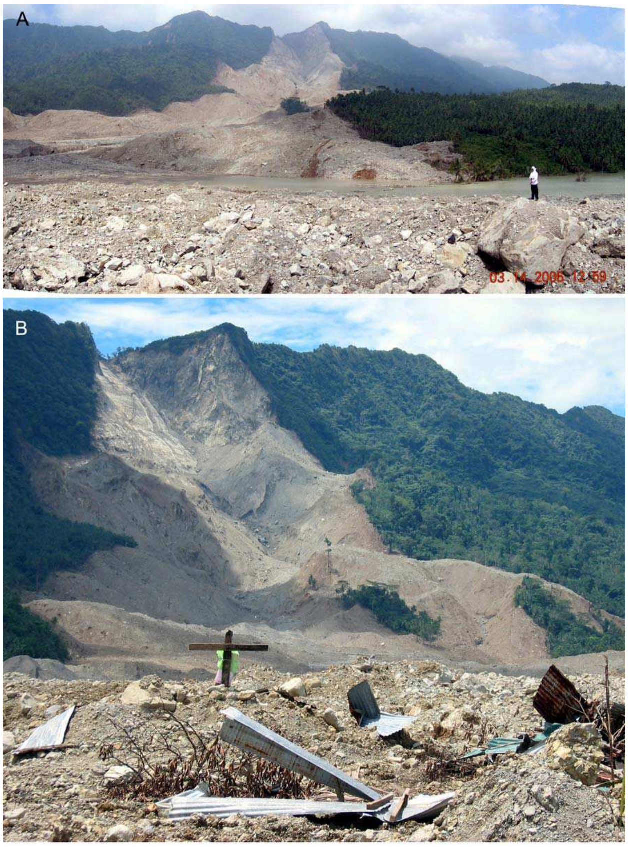

Fig. 5. **(A)** View to the west toward the source area from northern boundary of landslide of debris. **(B)** View from the surface of the debris toward the source area of the rockslide-debris avalanche. Characteristics of the source area are well illustrated. Particularly evident is the planar sliding surface that corresponds to a splay of the Philippine Fault. Note wreckage of buildings in foreground and the nature of the debris.

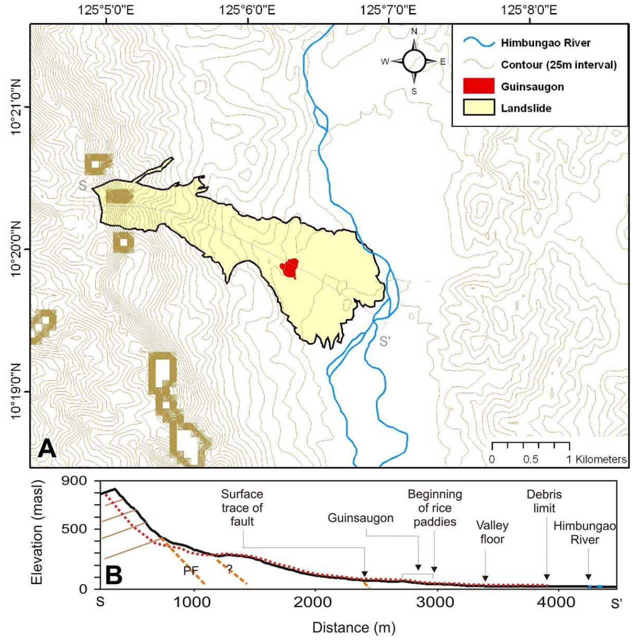

Fig. 6. **(A)** Map of area of Guinsaugon landslide based on SRTM data. Holes are apparent in the digital terrain data along the ridge line (see Appendix for discussion). Outline of the landslide is based on interpretation of ASTER image collected on 1 March 2006 and GPS-controlled field traverses in March 2006. **(B)** Profile of rockslide-debris avalanche based on SRTM data and field measurements in March 2006. Line of profile is marked in Fig. 6b (S-S′).

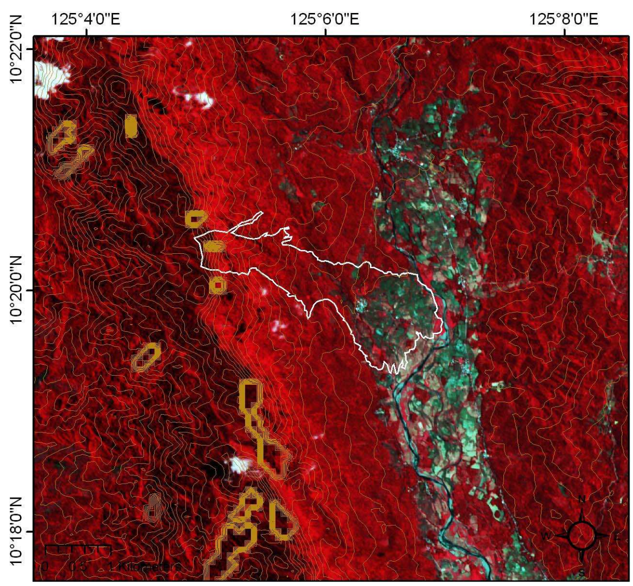

Fig. 7. Satellite image of the landslide site (SPOT image, June 2003) with outline of the rockslide-debris avalanche (from Fig. 6a) showing pre-event conditions on the source slope and in the Himbungao river valley.

8) and it appears that a splay of the fault formed the steep sliding surface of the initial rock slope failure (Figs. 5b, 8).

Movement in the Philippine Fault zone has led to the development of thick clay-rich gouge zones in the slope, which are also noted at other locations along the Philippine Fault (Hart et al., 2002), resulting in poor rock mass quality. The rock mass in the hanging wall is visibly sheared, crushed and fragmented (Figs. 5b, 8). Thus the source area of the rockslide-debris avalanche consisted of a rock mass that had undergone active tectonic displacement of up to 2.5 cm/year which resulted in loosening, shearing, and the reduction of rock mass strength, a process described by Korup (2004) as tectonic weakening. The process contributed to the high degree of disintegration of the failed rock mass and to the high percentage of silt to clay sized particles in the rockslide-debris avalanche debris. Grain size analyses on two samples of the rockslide-debris avalanche matrix (particles <20 mm in size) indicated that they consisted of 45% and 70% fines (silt and clay-sized material) respectively.

Fig. 8. Aerial view of the sliding surface showing horizontal striations consistent with strike-slip fault movement. Note also rock mass characteristics on the right of the source area resulting from movement of Philippine Fault (Photograph courtesy of Mines and Geosciences Bureau, Government of the Phillippines).

Initial failure appears to have involved a steep promontory that previously existed on the slope. The failure surface is a crude asymmetrical wedge and involved a rock slope about 450 m in height, between el. 830 and 380 m a.s.l. (Fig. 5b). The wedge was formed by the intersection of two surfaces; the steep east dipping planar fault surface and east-west trending sub-vertical fractures. It is not clear if the line of intersection of the wedge daylighted in the slope. It is probable that the failure surface broke through a wedge of colluvium at the base of the rock slope, between el. 380 and 280 m a.s.l. (Figs. 5b, 6b, and 9). The headscarp area was inaccessible by both foot and air because it is located in territory held by New People's Army (NPA) rebels.

3.3 Post-failure behaviour and debris characteristics

The initial rock mass slid down the steep escarpment and began to disintegrate almost immediately. This is indicated by debris tongues that are diverted away from the main path very high up in the source area as the debris collided with a series of side-hill ridges that mark the Philippine Fault Zone (Figs. 5 and 9). From field evidence (e.g., Fig. 5b), the mass entrained a significant volume of material from the base of the source slope beginning at el. 380 m down to just below 280 m a.s.l. We estimate this entrained volume to be in the order of about 4 M m^3. If this is the case, then 11 M m^3 of debris originated from the initial rock slope failure, that before bulking (which we assume, after Pierson, 1998, to be 20%), had an initial in-situ volume of about 9.2 M m^3. These estimates suggest an Entrainment Ratio (Hungr and Evans, 2004) of 0.36, above the suggested threshold of 0.25 necessary for the landslide to be described as a rockslide-debris avalanche (Hungr and Evans, 2004).

The debris began to be deposited as it traveled over rolling hummocky topography below el. 300 m a.s.l. which, on the basis of roadcut exposures immediately adjacent to the landslide, is interpreted to represent the surface of a previous landslide deposit (cf. Fig. 1a). The thickest part of the deposit occurs between el. 200 and el. 50 m a.s.l. (Fig. 6b). In this part of the debris, which averages 10 m in thickness, the material appears to be predominantly block-supported in nature with matrix material being less dominant than in the distal part of the debris (Fig. 5a).

At a path distance of 2600 m, the rockslide-debris avalanche debris encountered flooded paddy fields on the flat valley floor in the vicinity of Guinsaugon (Fig. 7b). This had two effects; a) the debris spread out on the valley floor and thinned to a mean thickness of about 2–3 m (Figs. 1a, 9, 10) b) the undrained loading of the paddy fields led to an enhanced travel distance of 1.3 km over an almost horizontal surface consisting of flooded paddy fields on the valley floor (Fig. 6b). A prominent break in slope in the debris at about 2.6 km indicates considerable deposition as the debris accumulated on the slope leading to the valley floor (Fig. 6b).

Debris deposited on the valley floor is dominated by finer grain sizes which forms a matrix-supported deposit (Figs. 9, 10), despite the fact that large boulders are present (Fig. 11a). This may reflect the entrainment of finer-grained colluvium by the leading edge of the rockslide-debris avalanche from the base of the source slope and/or the mixing of the rockslide-debris avalanche debris with the saturated sediments from paddy fields on the valley floor. The distal limit of the debris consists of series of irregular lobes on the flat valley floor, (Figs. 10a, b) which are rimmed by a zone of dark mud. This represents the fine muds ejected from beneath the moving debris sheet during the final part of its travel over the paddy fields. In some places we noted that trees and buildings were destroyed by the ejected mud beyond the limit of the coarser debris (Fig. 11b).

The debris contains large boulders up to 5 m in diameter, transported in some cases to the distal limit of the debris (Figs. 1b, 11a). As noted above, a significant part of the debris is made up of a fine-grained matrix including significant amounts of silty sand, sandy silt, and low plasticity clay (Liquid Limit = 48 and Plasticity Index = 22), reflecting the composition of the sheared source rock mass and the colluvium entrained form the base of the rock slope.

The village of Guinsaugon (el. 35 m a.s.l.) was overwhelmed at a path distance of 2.6 km (Fig. 6b, 7).

3.4 The trigger for the 17 February landslide

No direct trigger exists for the Guinsaugon landslide. The rockslide-debris avalanche was preceded, however, by excessive rainfall during the period 8–12 February 2006 (Fig. 12). Rainfall was measured at Otikon, Libagon, on the western (lee) side of the mountain ridge (for location see Fig. 3b) affected by the landslide. At this station, in the 5 day period

Fig. 9. View from near the distal limit of the debris toward the source area. Note matrix supported nature of the debris at this distal location and flat surface, corresponding to rice paddy fields, over which the debris ran in the distal part of its path. Debris thickness here is about 2 m.

between 8 February and 12 February 2006 cumulative rainfall reached 571.2 mm, with an average of 114 mm per day (Fig. 13). This exceeds the monthly average rainfall measured both at Libagon (by a factor of two) and Surigao (by a factor of 1.2). There was, therefore, a lag time of four days between the end of the 5 day period of heavy rainfall and the occurrence of the landslide of 17 February. No analysis of the frequency of the February rainfall magnitude has been carried out but rainfalls of this magnitude and intensity are not uncommon in the Philippines, especially those related to tropical storms (typhoons) (Hart et al., 2002).

It is also noted that two small earthquakes were recorded in Southern Leyte on the day of the landslide. The first event (M 2.3), occurred 10 km northwest of the rockslide-debris avalanche at 06:07 a.m. local time, and the second, (M 2.7) occurred at 10:36 a.m., 23 km west of the rockslide-debris avalanche (Inter-Agency Committee, 2006), a time that corresponds closely with the rockslide-debris avalanche event. These magnitudes are, however, well below those associated with the occurrence of earthquake-triggered landslides (cf. Keefer, 1984).

4 Two-dimensional dynamic analysis – a first approximation

A two-dimensional hindcast dynamic analysis of the 17 February rockslide-debris avalanche was carried out using the numerical model DAN (Hungr, 1995). DAN has been used to successfully simulate the behaviour (run-out distance, velocity and debris thickness) of over 25 well-documented rock avalanches and rockslide-debris avalanches (Hungr and Evans, 1996, 2004; Evans et al., 2001). In the model, the basal resistance of the moving mass is approximated by the selection of one of eight rheologies as outlined by Hungr (1995).

In the Guinsaugon case, we analysed the travel path in Fig. 6b. The initial failure geometry was specified as indicated in Fig. 6b and we assumed the immediate disintegration of the initial failure mass. This assumption was based on the brecciated nature of the source rock mass in the damage zone of the Philippine Fault and the field evidence of flowage high up in the source area as mentioned above (Fig. 6a). This assumption enabled the simulation to be carried out with a single rheology from initiation to el. 72 m a.s.l. where the debris encountered flooded paddy fields. At this point the rheology determining basal resistance was changed to simulate the undrained loading of the paddy field mud by the debris sheet.

As noted above, the volume of the initial failure mass was augmented by entrainment between elevations 380 m and 280 m. Our field estimate of the entrainment volume in this part of the path (4 M m^3) suggests an erosion depth of 22 m equivalent to a yield rate of 13 000 m^3/m along this part of the travel path. These values were input into the DAN simulation. Further, as suggested by Hungr and Evans (1996, 2004), a Voellmy rheology (Hungr, 1995) was selected to characterize the rockslide-debris avalanche behaviour from initiation to el. 72 where the flooded paddy fields were encountered; for the simulation of this part of the path values for the friction coefficient (f) in the range of 0.05–0.15 together with a range of values for the turbulence coefficient (ξ) of 400–500 m/s^2 were used. It is noted that these values for the Voellmy parameters are within the range of those found to best simulate the run-out distance and velocity of the majority of rock avalanche/rockslide-debris avalanche case histories analysed by Hungr and Evans (1996, 2004). At the

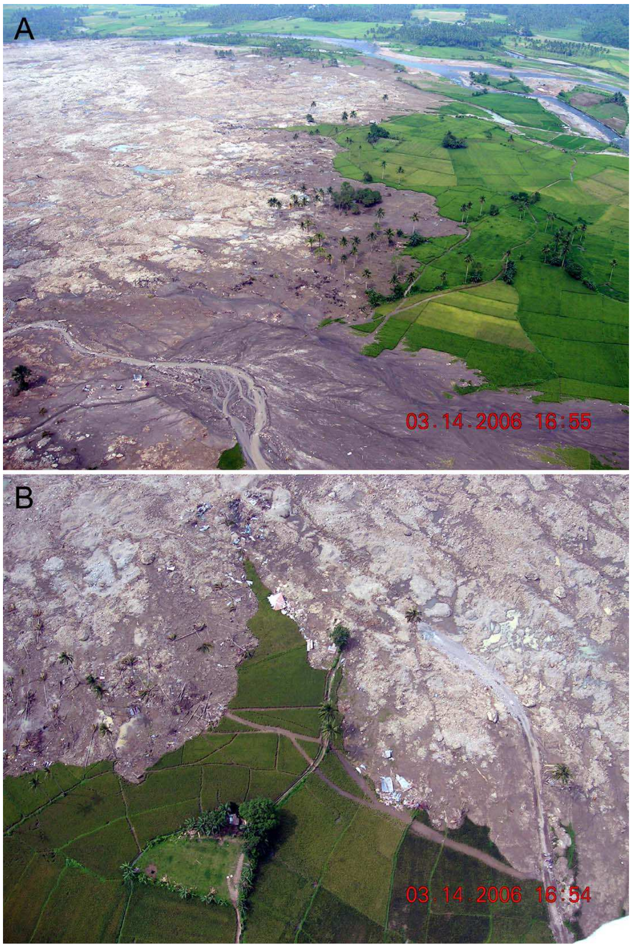

Fig. 10. Aerial views of distal limit of debris. **(A)** View east along southern edge of debris showing muddy lobes extending out from main debris deposit onto the paddy fields on the valley floor. **(B)** Close-up view of distal limit of debris and wreckage of buildings. Note paddy fields. (Photograph taken on 14 March 2006).

point where the avalanche encountered flooded paddy fields, the rheology was changed from Voellmy to frictional flow (ϕ=30°), with pore pressure. We explored pore water pressure conditions beneath the debris sheet for this section of the landslide path, equivalent to a range in pore pressure ratio (r_u) of 0.5 to 0.8, to simulate the frictional loss at the base of the debris sheet arising from the undrained loading of the paddy field mud. These values were then used in a series of simulation runs to obtain the best match for the observed characteristics of the Guinsaugon rockslide-debris avalanche.

The results of the DAN simulation are seen in Fig. 14. The run-out is precisely duplicated with Voellmy parameters of f=0.12, and ξ=400 m/s^2 and with a value of r_u of 0.8 for the materials in the paddy field section of the path. The maximum frontal velocity (58 m/s) occurred at a path distance of 942 m (Fig. 14). The duration of the movement is estimated at 102 s for a mean velocity of 35 m/s. This compares with estimates of velocity estimates in the range 27–38 m/s noted by Lagmay et al. (2006) based on eyewitness accounts. Further, the length of the deposit, the location of maximum thickness, and the distal thinning of the debris are simulated quite well, the pattern of deposition corresponding generally to that observed in the field (Fig. 14). It is noted, however, that the maximum debris thickness obtained in the simulation is 37 m at a path distance of 1670 m (Fig. 14b). This is in considerable excess of the field estimate. The DAN simulation clearly overestimates the deposit thickness at the beginning of deposition in the path, possibly a model response to the effect of irregularities in the surface profile (Fig. 6b). However, further downslope, the depth of burial of Guinsaugon is estimated to be 4–7 m, which corresponds to field estimates. It is also noted that the simulation indicates that the centre of gravity of the deposit is quite high up in the path (Fig. 14b), reflecting the spreading and thinning of the distal part of the debris as it encountered the flooded paddy fields.

Fig. 11. Distal limit of rockslide-debris avalanche. **(A)** characteristics of debris, including large boulder **(B)**: damage to trees and houses by fine mud ejected from base of debris sheet, the limit of which is seen at left.

The fact that the run-out was best predicted using an r_u of 0.8 suggests that the development of excess pore-pressure by the loading of the paddy field mud by the debris sheet was a key factor in the mobility of the rockslide-debris avalanche.

In summary, the first approximation to a dynamic analysis of the Guinsaugon rockslide-debris avalanche suggests that the run-out behaviour was conditioned by a) entrainment and b) the flooded paddy field effect which reduced the friction at the base of the debris sheet in its distal parts. This is shown by two additional simulations using the same rheological parameters as above. The result of a simulation without entrainment, but including the paddy field effect,

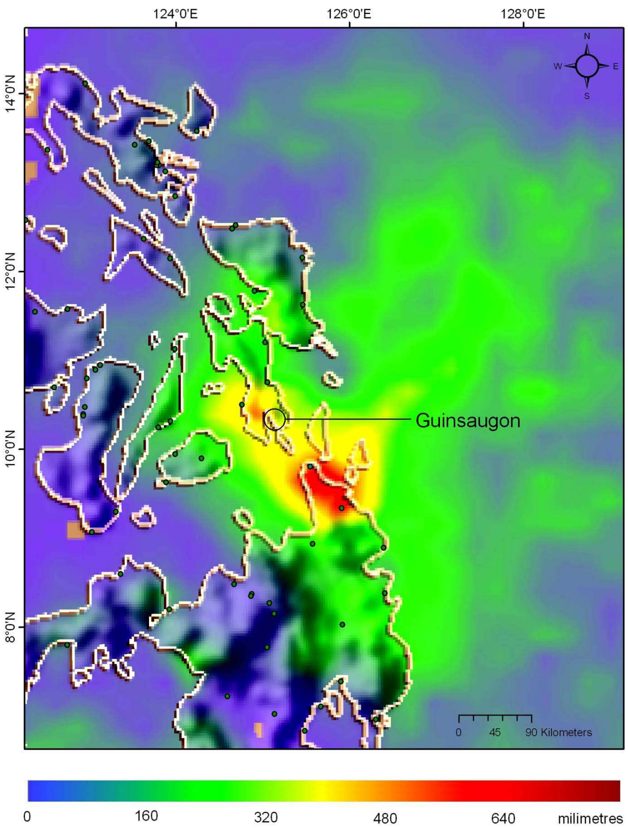

Fig. 12. Tropical Rainfall Measuring Mission (TRMM) data showing accumulation of rainfall between 4 February and 17 February 2006 in the Central Philippines. (Image based on data supplied by NASA). Rainfall in Southern Leyte during this time is seen to exceed 500 mm.

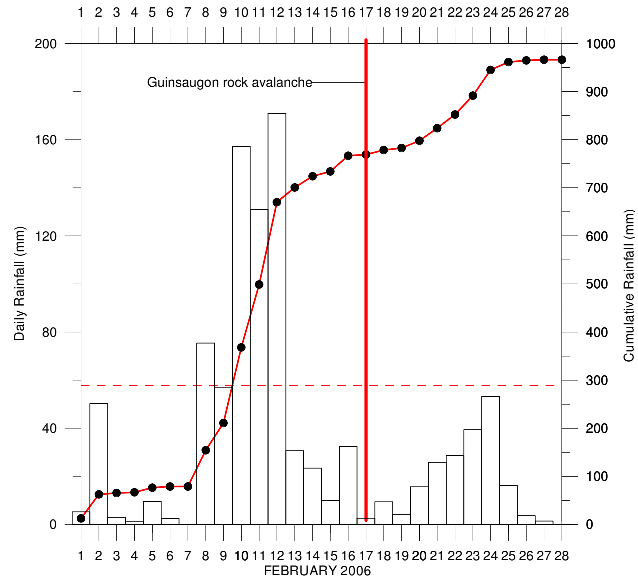

Fig. 13. Daily rainfall and cumulative rainfall measured at Otikon, Liagon (for location see Fig. 3b) for the period 1–28 February 2006. Horizontal dashed line is monthly mean rainfall. Data courtesy of Philippine Atmospheric, Geophysical, and Astronomical Services Administration.

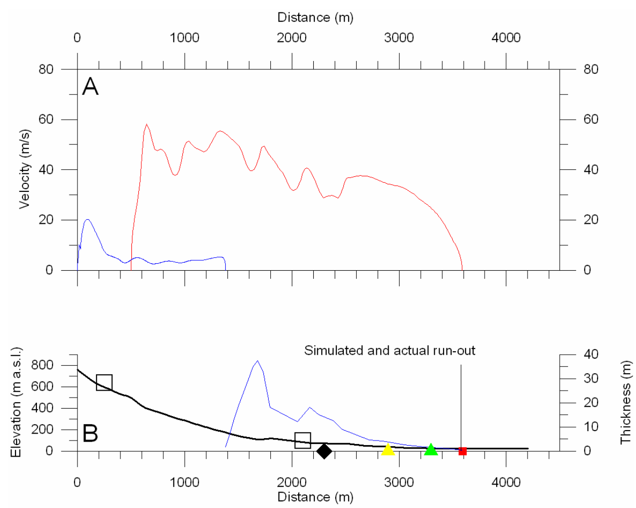

Fig. 14. Results of dynamic analysis using DAN simulation model. **(A)** Plot of velocity along the path showing the velocity of the front (red) and rear (blue) of the moving mass. **(B)** Profile is shown in black. Squares are the centres of gravity of the initial slide mass (pre-event) and of the deposit (post-event). Thickness of deposit is shown in blue. Simulated run-out distances without presence of paddy field (yellow triangle) and without entrainment (green triangle) are also shown. The location of the beginning of the paddy fields is shown with a black diamond corresponding to the point where the basal resistance of the moving mass is changed from a Voellmy rheology (f=0.12; ξ=400 m/s^2) to a frictional one (ϕ=30°) with pore pressure (r_u=0.8) (for discussion see text).

gave a runout distance 291 m less than the observed case (Fig. 14b), a reduction of 8%. A second DAN simulation, using a Voellmy rheology for the entire path (i.e., without the presence of the flooded paddy field), but including entrainment as specified above, indicated a run-out 692 m shorter than the real case, a run-out reduction of about 20% (Fig. 14b). We suggest that these simulation results demonstrate the importance of the flooded rice paddy fields as a major contributor to the enhanced run-out of the Guinsaugon rockslide-debris avalanche.

5 Implications for landslide hazard assessment

5.1 Regional and global significance

Because of heavy rainfall, active tectonics, frequent earthquakes and extensive tropical weathering the rugged topography of the Philippine archipelago is particularly prone to catastrophic landslides. The Leyte Island rockslide-debris avalanche is the latest in a succession of landslide disasters to have affected the Philippines since 1945 (e.g. Punong-

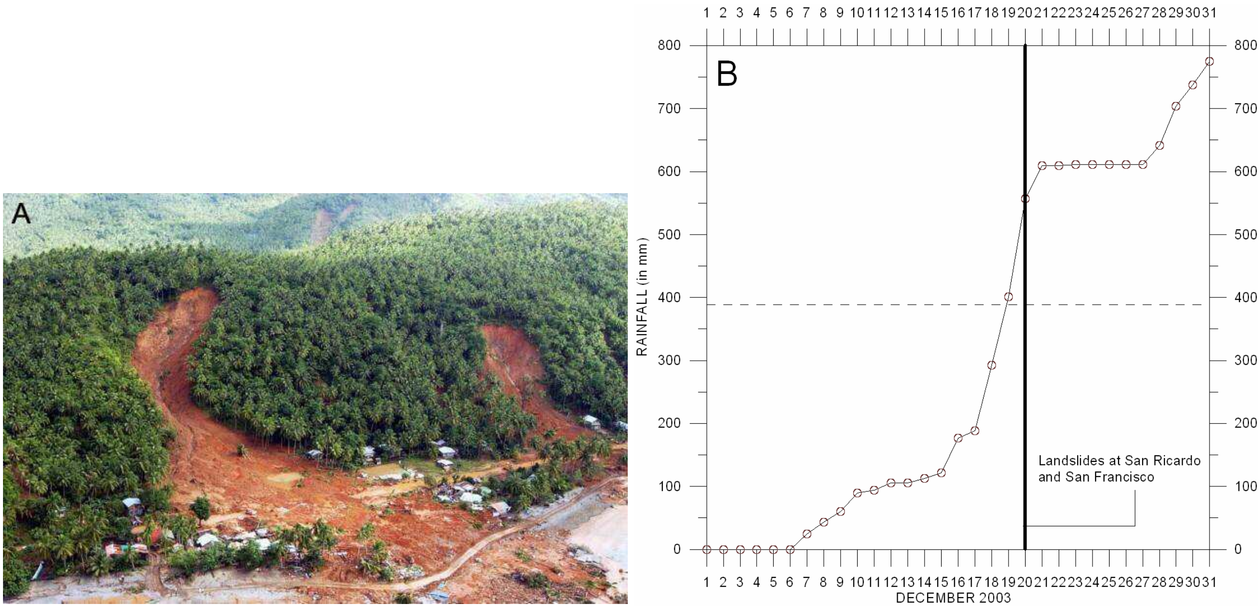

Fig. 15. **(A)** Rainfall-triggered debris avalanche in residual soils that destroyed the village of Pinut-an, Township of San Ricardo, Panoan Island, Southern Leyte Province (For location see Fig. 3b) on 23 December 2003. 209 people lost their lives in the landslide (Photograph courtesy of PCPO/PNS). **(B)** Cumulative rainfall for December 2003 landslide disaster in Southern Leyte Province. Rainfall measured at Otikon, Liagon (for location see Fig. 3b). Horizontal dashed line is monthly mean rainfall. Data courtesy of Philippine Atmospheric, Geophysical, and Astronomical Services Administration).

bayan et al., 2000). Major disasters struck Leyte Island in 1991 and 2003 in which over 5000 people died in rainfall-triggered landslides at Ormoc (1991) and on Panaon Island (2003; for location see Fig. 3b). In the 2003 disaster, over 350 people lost their lives in three major landslide events on Panaon Island (Figs. 3b and 15a) in the period 17–20 December 2003. These landslides were triggered by very heavy rainfall; 369 mm of rain fell in just three days (18–20 December, 2003), almost equal to the mean monthly rainfall of 389 mm (Fig. 15b). In addition, infrastructure in the Philippines is also constantly under threat from landslides resulting in high risk to lifeline facilities (e.g., Hart et al., 2002; Leynes et al., 2005).

The February 2006 rockslide-debris avalanche indicates the potential for large scale landslides (>10 Mm^3) in tropical mountain terrain in the western Pacific region. Other examples have been reported from the mountains of Papua New Guinea, at Bairaman (est. vol. 200 M m^3; 1986; King et al., 1989) which was triggered by an earthquake, and at Kaiapit (est. vol. 1.5 B m^3; 1988) which had no discernible trigger (Peart, 1991). However, the magnitude and frequency of these types of landslides in the tropical environment is not well understood, neither are the geological controls on their spatial occurrence.

At a global scale, in terms of lives lost, the 2006 Leyte Island rockslide-debris avalanche is the most destructive single-event landslide disaster to have occurred in the world since the 1998 Casita Volcano landslide, Nicaragua, triggered by the heavy rains of Hurricane Mitch. The death toll of the Casita event has been estimated at 2500 (Scott et al. 2005). With reference to the global record of single event destructive landslides in which over a thousand people have lost their lives, the landslide is the 15th to have occurred worldwide since 1900 (Evans, 2006, and unpublished data).

5.2 Landslide hazard assessment on Leyte Island

Landslide hazard assessment on Leyte Island has at least three elements which need to be considered in a hazard assessment strategy;

(i) Localisation of source area; The source area of the 2006 rockslide-debris avalanche consisted of rocks from the damage zone of the Philippine Fault, an active strike slip fault that is moving at 2.5 cm/yr. In fact the sliding surface was a splay in the fault. Field evidence indicated the presence of other rockslide-debris avalanche deposits in the Humbungao valley (Fig. 1a). The combination of high steep slopes consisting of rock masses that are subject to active tectonic shearing (tectonic weakening) suggests a high potential for large scale rock slope failure along the damage zone of the Philippine Fault.

(ii) Post-failure behaviour; The February 2006 rockslide-debris avalanche also indicates that the presence of flooded paddy fields in valley bottoms may enhance the travel

distance of flow-type landslides through decreased frictional resistance at the base of the debris sheet by undrained loading.

(iii) Trigger and warning; The rockslide-debris avalanche occurred as a delayed response to a 5 day period of unusually heavy rains. The lag time has implications for landslide warnings based on expected rainfall occurrence and intensity. The heavy rains were part of the 2005–2006 La Nina phenomenon and thus the occurrence of the rockslide-debris avalanchemay be viewed as a local response to a sub-global climatic phenomenon (ENSO).

6 Conclusions

The occurrence and behaviour of the disastrous Guinsaugon rockslide-debris avalanche was determined by the intersection of geological/tectonic, climatic and cultural factors.

With reference to geological/tectonic elements, the rockslide-debris avalanche originated in rocks within the damage zone of the Philippine Fault, an active strike-slip fault that shows a rate of movement of about 2.5 cm/yr. The sliding surface of the initial rockslide corresponds to a splay in the trace of the Philippine Fault. As such, the source rock mass was of low rock quality resulting from the shearing and brecciation associated with fault movement. This fact, and the presence of older rockslide-debris avalanche deposits on the valley floor parallel to the fault, not only raises the possibility of future catastrophic landslide events along the Philippine Fault on Leyte Island but also the question of the magnitude and frequency of past events.

With respect to climate, the lag time between the end of the period of heavy rainfall and the occurrence of the rockslide-debris avalanche is also of interest as it presents problems in determining threshold rainfall for landslide occurrence and the issuance of associated appropriate warning measures.

Agricultural development in the valley bottom had a major effect on the run-out of the rock avalanche. In terms of post-failure behaviour, the run-out of the rockslide-debris avalanche was enhanced by undrained loading of rice paddy fields on the valley floor beneath the debris sheet. This led to a spreading and thinning of the rockslide-debris avalanche debris.

The 2006 rockslide-debris avalanche is one of several disastrous landslides to have occurred in the Philippines in the last twenty years confirming the Philippines as one of the landslide hotspots in the world (cf. Nadim et al., 2006). In terms of loss of life, the Guinsaugon rockslide-debris avalanche is the most devastating single-event landslide to have occurred worldwide since the Casita Volcano rock avalanche-debris flow which was triggered by Hurricane Mitch in Nicaragua in 1998.

Finally, work carried out on the landslide illustrates the utility of readily-available optical space-borne imagery and orbitally-collected digital terrain data in the rapid characterisation of a major catastrophic landslide in support of detailed field work.

Appendix A

The rapid characterisation of the Guinsaugon Landslide – methodology and data sources

The rapid characterisation of the Leyte Island landslide was made possible by the availability of a variety of space-borne imagery and data augmented by field work. Topographic data was derived from the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), which has a 3 arcsecond (∼90 m) spatial resolution in both latitude and longitude, and an absolute height accuracy better than 16 metres (90% confidence). Although SRTM data is of reasonably good coverage, some data anomalies exist and reflect the method of data collection (Interferometric Synthetic Aperture Radar; InSAR). Errors include missing data resulting from shadows, layover, and poor surface reflective properties for microwave radiation. Gaps in the data set appear most commonly in areas of rough terrain, especially along ridgelines. This is evident in Fig. 6. Analysis of the head scarp of the landslide using the SRTM data was complicated by voids in the topographic data.

Orbital optical imagery from both before and after the event are available. Both the pre- and post-disaster images were geo-referenced to the UTM zone 51 N. As is commonly the case for both near-equatorial and mountainous regions, cloud cover was a complicating factor in collection of post-disaster imagery having high utility – at the time of submission, only one cloud free ASTER scene collected on 1 March 2006, of the many ASTER scenes collected at the location, was available.

Pre-disaster imagery (Fig. 7) was a SPOT scene provided by the European Space Agency. The high resolution (10 m mutispectral, 5 m panchromatic) orthorectified SPOT 5 image (030601_00148057004) was imaged on 1 June 2003. Visual analysis of pan-sharpened colour infrared composites provided best interpretation results.

A post-disaster ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) scene (00303012006021025_03122006120419) was used, in association with field data, to delineate the limits of the landslide. The scene, imaged on 12 March 2006, was the first known orbital image clearly showing the majority of the landslide. Georectified visual and near infrared bands (15 m resolution) were interpreted as a colour infrared composite. The localized cloud cover along the ridge from which the rockslide-debris avalanche initiated obscured some of the source area and the entire head scarp. Consequently, field observations were the main source of observation for this part of the landslide. These observations were carried out between 11 March and 14 March 2006 and included

GPS-controlled ground traverses of the debris and aerial inspection by helicopter.

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