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Reply to comment by Andrea Argnani et al. on "On the cause of the 1908 Messina tsunami, southern Italy"

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1. Introduction

[1] On 28 December 1908, a catastrophic earthquake (M $\approx$ 7.1) struck the region of the Messina Straits, Ionian Sea, southern Italy (Figure S1 of the auxiliary material).[1] Within minutes after the passage of the seismic waves, a tsunami with maximum observed runup of almost 12 m hit the coasts of Calabria and Sicily [*Platania*, 1909; *Baratta*, 1910]. Soon after the catastrophic events, *Omori* [1909] concluded that: "One remarkable fact is that the tsunami was strongest at those places where the earthquake shock was not most violent, indicating the probable non-coincidence in position of the origin of the earthquake with that of the tsunami". By using computer simulations, *Tinti and Armigliato* [2003] reached a similar conclusion: "The first conclusion we arrive at is that it is difficult to find a single source matching simultaneously both tsunami and leveling data". Recently, we presented new results supporting the hypothesis that the tsunami was generated by a submarine landslide triggered by the earthquake at *c.* 40 km from the epicentral area [*Billi et al.*, 2008]. *Argnani et al.* [2009] now produce new marine data and numerical models to question some of our inferences. Here we reply to their criticisms.

2. Evidence in Favor of the Landslide-Tsunami or Against the Earthquake-Tsunami

[2] 1. *Argnani et al.* [2009] question our backward-ray tracing [*Billi et al.*, 2008] by deeming it as "too simplistic". Regardless of whether this technique is "simplistic" or not, the tsunami travel times reported by *Baratta* [1910] show that the tsunami source area is spatially well-separated from the area where the maximum coseismic topographic dislocation is inferred based on geodetic measurements (i.e., off Reggio Calabria [*Loperfido*, 1909]). The minimum travel times were, in fact, recorded at Giardini (i.e., where the tsunami arrived immediately after the earthquake) and in the adjacent localities (Figure S1), which are *c.* 40 km distant from Reggio Calabria, where, in contrast, the tsunami arrived 10 minutes after the earthquake was felt [*Baratta*, 1910].

[3] Moreover, the assumption made by *Argnani et al.* [2009] about landslide-tsunamis being typically produced at the onset of the slide movement near its headscarp may not be true for slumps and slides that do not move all at once. *Okal and Synolakis* [2004], for instance, examined the case in which a submarine landslide evolves into turbidity current and demonstrated that time-consuming evolution influences tsunami propagation. *López-Venegas et al.* [2008], in simulating the 1918 Mona Passage landslide-tsunami, used a range of slide durations from 75 to 400 s and found that slide duration affects the tsunami propagation (see also *Liu et al.* [2005] for analogous conclusions in the near-field).

[4] 2. *Argnani et al.* [2009] argue that "the use of the ratio between maximum run-up height (R) and distance (D) along the coast of Calabria gives little information, for two reasons: i) it is a very first approximation method that typically is valid only for very simple basin geometries, and (ii) the stretch of coastline is too short (40 km) and shifted aside with respect to the inferred tsunami source, hampering the attempt to evaluate the impact of the tsunami".

[5] The runup distribution along the Sicilian and Calabrian coasts [*Billi et al.*, 2008] is typical of a landslide-tsunami, as demonstrated by comparison with the scaling invariants posited by *Okal and Synolakis* [2004]. Their models were successfully validated against numerous historic events, for some of which the involved marine basins are even more complicated than the Ionian Sea basin [*Okal and Synolakis*, 2004; *Okal et al.*, 2009]. Concerning the runup distribution along the Calabrian shore, this coast includes runup values spanning over the entire range of the observed runup (i.e., between about 1–2 and 10 m [*Baratta*, 1910]). This range suggests that the data set along the Calabrian coast is complete and, hence, our analysis is appropriate. This inference is also supported by similar runup decays (i.e., over a distance of *c.* 40 km) documented for landslide-tsunamis, e.g., the case of the 1998 Papua New Guinea tsunami [*Okal and Synolakis*, 2004].

[6] *Argnani et al.* [2009] also state: "A recent analysis of runup data in the same area [*Gerardi et al.*, 2008] suggests, in fact, that the R/D ratio, though used beyond the limit of applicability, is typical of a fault-induced tsunami". We point out that this statement involves a paradox, as it invokes a

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method considered "beyond the limit of application" to confute our model of landslide-tsunami.

[7] Moreover, we remark that the application of the *Okal and Synolakis* [2004] best-fit – $\zeta(y) = b/\{[(y - c)/a]^2 + 1\}$ – to all available runup data (i.e., including those provided by *Gerardi et al.* [2008]) makes the landslide hypothesis the most viable one as shown by the minimum residuals between observed and expected distributions (Figure S2).

[8] 3. The seafloor maximum dislocation associated with the 1908 earthquake is assessed as *c.* −0.7 m off Reggio Calabria (Figure S1), whereas the coseismic slip is assessed as between about 1.3 and 2.7 m [e.g., *Valensise and Pantosti*, 1992]. Analyses of historic and simulated tsunamis show that such coseismic dislocations alone can not generate a tsunami runup of almost 12 m [*Okal and Synolakis*, 2004].

[9] 4. In the numerical simulations hitherto attempted, the extreme runup values of the 1908 tsunami could not be explained on the basis of the tectonic source alone [*Tinti and Armigliato*, 2003; *Piatanesi et al.*, 2008; *Tappin et al.*, 2008]. In the most recently-published simulation, for instance, by using the tectonic source alone to infer an initial condition for the hydrodynamic computation, *Piatanesi et al.* [2008] obtained a maximum runup of only ~2 m and concluded that an additional landslide source is necessary to explain the observed extreme runup.

[10] 5. By bathymetric surveys and deep ocean drilling, *Ryan and Heezen* [1965] concluded that a turbiditic flow induced by a seismically-triggered tsunamigenic submarine landslide along the Ionian coast of Sicily interrupted the submarine cables connecting Malta to Zakynthos, Greece, *c.* ten hours after the 1908 earthquake at a site located *c.* 150 km far away from the Messina Straits. Moreover, *Ryan and Heezen* [1965] found turbiditic channels running from about the central-eastern coast of Sicily, where we located the potential causative landslide (Figure S1), to the site in the Mediterranean Sea where the cables were interrupted.

3. Considerations on the Proposed Landslide

[11] 1. Based on bathymetry and seismic data, we proposed that a seafloor reentrant and a sediment accumulation off Giardini are evidence of a potentially causative landslide (Figure S1) for the 1908 tsunami. *Tappin et al.* [2008], by using a higher resolution bathymetry, concluded that there is a landslide present at the location identified by us, but probably smaller than we had proposed, i.e., of the order of few cubic kilometers, as also pointed out by *Argnani et al.* [2009]. *Argnani et al.* [2009] also recognize the occurrence of a landslide deposit in the submarine area off Giardini (Figure S2), but question its recent age by noting the presence of gullies and strata overlapping a portion of the inferred landslide deposit, suggestive of erosion and deposition longer than 100 yr. We remark, in contrast, that these clues are not conclusive to constrain any landslide age, particularly in a region of high erosional (*c.* 2 mm/yr [*Cyr*, 2008]) and depositional rates connected with the very rapid regional uplift (i.e., *c.* 2 mm/yr), very steep slopes, lack of continental shelf, strongly-eroding drainages, and turbiditic activity induced also by large discharges of volcanic material from the nearby Etna volcano. In the northwestern section, the chaotic deposit underlying some recent strata (i.e., onlapping strata) may simply represent a landslide accumulation older than the one recognized toward the southeast (Figures S3 and S4).

[12] More in general, marine geological evidence can rarely be conclusive in the discrimination of earthquake- vs. landslide-tsunamis, as also demonstrated by studies on the 1998 Papua New Guinea tsunami, for which the final interpretation as a landslide-tsunami derived from the proper combination of research methods and available evidence including seismology, hydroacoustics, and tsunami data in addition to marine geology [*Okal and Synolakis*, 2001; *Synolakis et al.*, 2002a].

[13] 2. The Coulomb stress change at the bottom of the landslide scar (from which we propose that the sliding process may have initiated) is positive and results to be *c.* 0.1 bars, a value small indeed as *Argnani et al.* [2009] suggest, but nonetheless capable of triggering landslides [*Parsons et al.*, 1999]. This stress change may have contributed to the landslide jointly with the dynamic stress related to the passage of seismic waves. Moreover, a higher stress level change at a larger depth may have triggered a local deeper slide, which undercut the slope above it and triggered landsliding in shallower water to the headscarp.

[14] 3. Regarding the specific volume of the slide, we posit that, given the uncertainties in initializing hydrodynamic computations that model landslide tsunamis, and the lack of knowledge of the material properties of this slide, it is futile to claim what a coupled landslide-free surface wave model would predict for any particular landslide volume - see the discussion of *Okal et al.* [2009] in the context of the 1956 Amorgos tsunami and the arguments for and against landslide versus tectonic triggers. The slide we suggested qualitatively (i.e., off Giardini) explains most observations. A slide of smaller volume than our original hypothesized slide would probably produce a smaller wave, unless of course the material properties were different, and here there is uncertainty. Even for the same material properties, if the landslide originated from deeper water by undercutting the deposits upslope, as in the case of the 1994 Skagway tsunami [*Synolakis et al.*, 2002b], its runup would had been very different than if the landslide originated from its headscarp. We thus reaffirm that coupled physical modeling of tsunami wave generation and propagation must be performed to reach more defensible quantitative conclusions concerning the appropriate landslide volume and specific arrival times [*Okal and Synolakis*, 2004; *Liu et al.*, 2005; *López-Venegas et al.*, 2008].

4. Conclusions

[15] Although unresolved questions remain, the preponderance of evidence favors a landslide as the main cause of the 1908 tsunami. In particular, the separate locations of the tsunami and earthquake sources, respectively constrained by tsunami runup and time data [*Billi et al.*, 2008], and by seismological, macroseismic, and geodetic evidence [e.g., *Valensise and Pantosti*, 1992], are the defining factors in differentiating whether the wave was primarily triggered by a landslide or the tectonic displacement.

[16] Moreover, we note that without invoking a landslide or turbidity current, the submarine cable interruption between Malta and Zakynthos addressed by *Ryan and Heezen* [1965] remains unexplained.

[17] *Argnani et al.* [2009] base their arguments on a single published transect and then refer to data unavailable for review and to generic statements (e.g., "the ray-tracing procedures lead to unreasonable results"). As studies on the 1998 Papua New Guinea landslide showed [e.g., *Synolakis et al.*, 2002a], marine evidence alone can not discriminate between earthquake- and landslide-tsunamis nor can models alone. This notion is, of course, particularly valid for a century old event.

[18] We thus remain convinced that the proposed landslide (Figure S1) is "an important candidate" to explain the 1908 tsunami [*Billi et al.*, 2008], but welcome future work with additional geologic data and comprehensive modeling that quantitatively refutes our hypothesis.

[19] **Acknowledgments.** We warmly thank P. Molin, D. Tappin, P. Watts, and an anonymous reviewer.

References

Argnani, A., et al. (2009), Comment on "On the cause of the 1908 Messina tsunami, southern Italy" by Andrea Billi et al., *Geophys. Res. Lett.*, *36*, L13307, doi:10.1029/2009GL037332.

Baratta, M. (1910), *La Catastrofe Sismica Calabro-Messinese (28 Dicembre 1908)*, 496 pp., Soc. Geogr. Ital., Rome.

Billi, A., et al. (2008), On the cause of the 1908 Messina tsunami, southern Italy, *Geophys. Res. Lett.*, *35*, L06301, doi:10.1029/2008GL033251.

Cyr, A. J. (2008), Quantifying relationships between erosion and uplift in tectonically active landscapes, Italy, Ph.D. thesis, Purdue Univ., West Lafayette, Indiana.

Gerardi, F., et al. (2008), Discrimination of tsunami sources (earthquake versus landslide) on the basis of historical data in eastern Sicily and southern Calabria, *Bull. Seismol. Soc. Am.*, *98*, 2795–2805, doi:10.1785/0120070192.

Liu, L.-F., et al. (2005), Runup and rundown generated by three-dimensional sliding masses, *J. Fluid Mech.*, *536*, 107–144, doi:10.1017/S0022112005004799.

Loperfido, A. (1909), Livellazione geometrica di precisione eseguita dall'IGMI sulla costa orientale della Sicilia, da Messina a Catania, a Gesso ed a Faro Peloro e sulla costa occidentale della Calabria da Gioia Tauro a Melito di Porto Salvo, pp. 131–155, Minist. dell'Agric., Ind. e Commer., Rome.

López-Venegas, A. M., et al. (2008), Submarine landslide as the source for the October 11, 1918 Mona Passage tsunami: Observations and modeling, *Mar. Geol.*, *254*, 35–46, doi:10.1016/j.margeo.2008.05.001.

Okal, E. A., and C. E. Synolakis (2001), Comment on "Origin of the 17 July 1998 Papua New Guinea tsunami: Earthquake or landslide?," by E.L. Geist, *Seismol. Res. Lett.*, *72*, 363–366.

Okal, E. A., and C. E. Synolakis (2004), Source discriminants for near-field tsunamis, *Geophys. J. Int.*, *158*, 899–912, doi:10.1111/j.1365-246X.2004.02347.x.

Okal, E. A., et al. (2009), The 1956 earthquake and tsunami in Amorgos, Greece, *Geophys. J. Int.*, in press.

Omori, F. (1909), Preliminary report on the Messina-Reggio earthquake of December 28, 1908, *Bull. Imp. Earthquake Invest. Comm.*, *3*, 37–46.

Parsons, T., et al. (1999), Stress sensitivity of fault seismicity: a comparison between limited-offset oblique and major strike-slip faults, *J. Geophys. Res.*, *104*, 20,183–20,202, doi:10.1029/1999JB900056.

Piatanesi, A., et al. (2008), Il grande maremoto del 1908: Analisi e modellazione, in *Il Terremoto e il Maremoto del 28 Dicembre 1908*, edited by G. Bertolaso et al., pp. 183–196, Ist. Naz. di Geofis. e Vulcanol., Rome.

Platania, G. (1909), Il maremoto dello Stretto di Messina del 28 Dicembre 1908, *Boll. Soc. Sismol. It.*, *13*, 369–458.

Ryan, W. B. F., and B. C. Heezen (1965), Ionian Sea submarine canyons and the 1908 Messina turbidity current, *Geol. Soc. Am. Bull.*, *76*, 915–932, doi:10.1130/0016-7606(1965)76[915:ISSCAT]2.0.CO;2.

Synolakis, C. E., et al. (2002a), The slump origin of the 1998 Papua New Guinea tsunami, *Proc. R. Soc. London, Ser. A*, *458*, 763–789, doi:10.1098/rspa.2001.0915.

Synolakis, C. E., et al. (2002b), Modeling of the November 3, 1994 Skagway, Alaska tsunami, in *Solutions to Coastal Disasters*, edited by L. Wallendorf and L. Ewing, pp. 915–927, Am. Soc. of Civ. Eng., Reston, Va.

Tappin, D. R., et al. (2008), The 1908 Messina tsunami. Some comments on the source: Earthquake, submarine landslide or a combination of both?, *Eos Trans. AGU*, *89*(53), Fall Meet. Suppl., Abstract S41D-07.

Tinti, S., and A. Armigliato (2003), The use of scenarios to evaluate the tsunami impact in southern Italy, *Mar. Geol.*, *199*, 221–243, doi:10.1016/S0025-3227(03)00192-0.

Valensise, L., and D. Pantosti (1992), A 125 kyr-long geological record of seismic source repeatability: The Messina Straits (southern Italy) and the 1908 earthquake (Ms = 7½), *Terra Nova*, *4*, 472–483, doi:10.1111/j.1365-3121.1992.tb00583.x.

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Auxiliary Material for Paper 2009GL037499

Reply to Comment by Argnani et al.

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Introduction

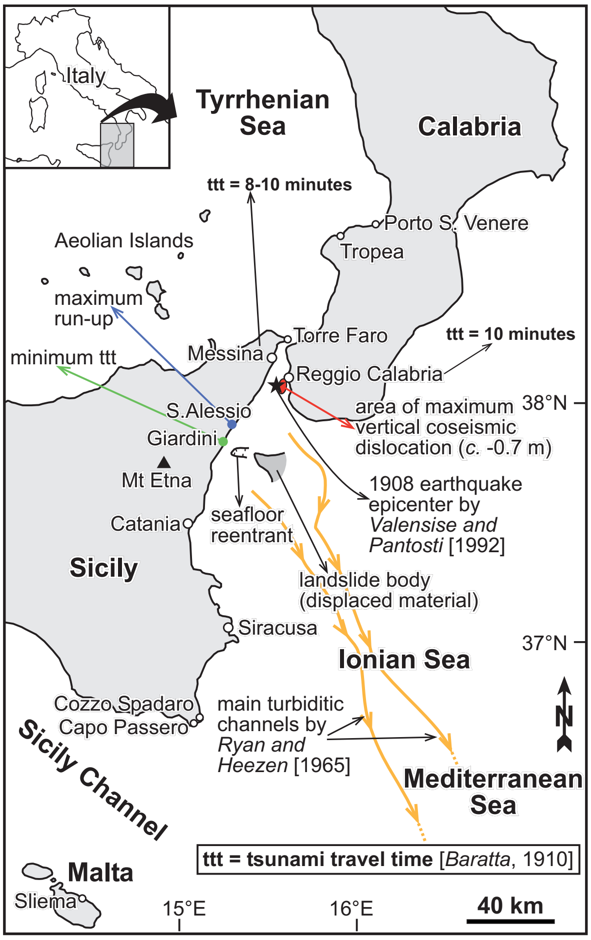
This auxiliary material contains four additional images.

2009GL037499-fs01_orig.jpg = Map of the Messina Straits area, Ionian Sea, southern Italy, and adjacent regions including Calabria, to the north, and Malta, to the south. The underwater landslide drawn off Giardini has been proposed as the hypothetical cause for the 1908 Messina tsunami [Billi et al., 2008].

2009GL037499-fs02_orig.jpg = Run-up distribution (after Gerardi et al. [2008]) for the 1908 Messina tsunami along the Sicilian coast. Inset shows the related track. Note the difference between the fitting curve (and related parameters a, b, and c) provided by Gerardi et al. [2008] (black curve) and that provided in this work (red curve) by fitting the same data set. The red curve is drawn by using the method of Okal and Synolakis [2004]. The parameters a, b, and c are optimized by the best-fit procedure and are, respectively, the lateral half-extent, maximum amplitude, and peak (b) abscissa of the best-fitting curve. Note that, according to Okal and Synolakis [2004], I2, which is the aspect ratio of the best-fitting curve (i.e., the b-to-a ratio), indicates a seismic source when it is smaller than 0.0001 and a non-seismic source (e.g., landslide) when it is greater than 0.0001. It follows that our analysis (red curve) of the data by Gerardi et al. [2008] shows a non-seismic source for the 1908 tsunami.

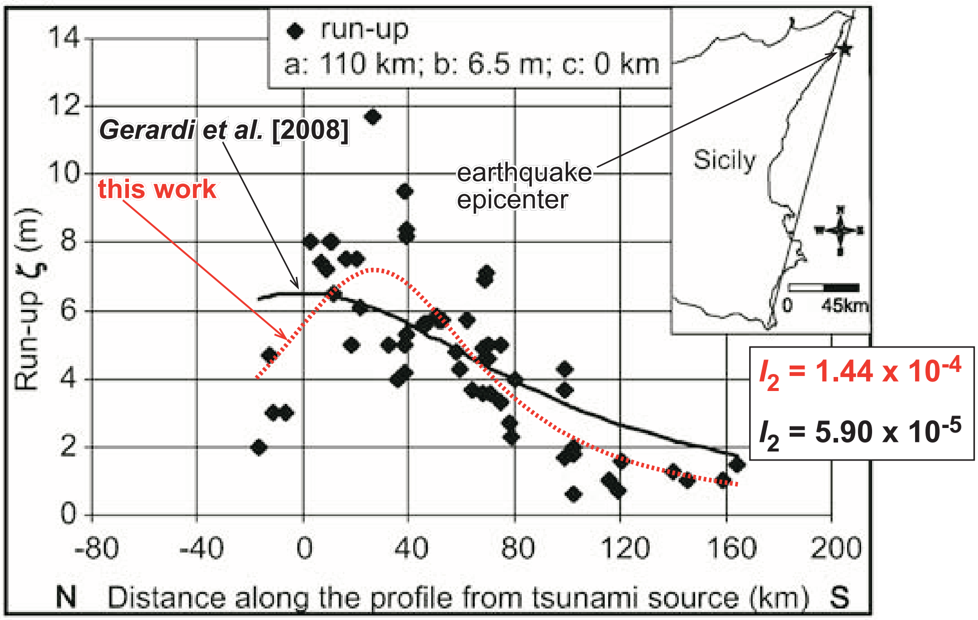
2009GL037499-fs03_orig.jpg = Bathymetric maps after Argnani et al. [2009]. The interruption and lack of erosive channels at the summit and within, respectively, the landslide scar (see the red arrows) suggest that the landslide scar postdates the channels.

2009GL037499-fs04_orig.jpg = Seismic reflection profile after Argnani et al. [2009]. The seabed morphology is gullied, suggesting a high erosional rate, a long erosional history, or both. Toward the south-southeast, we observe a surficial deposit that we interpret as the possibly-recent landslide identified in Billi et al. [2008]. Toward the north-northwest, as pointed out by Argnani et al. [2009], the onlapping strata suggest that the underlying deposit may be connected with a landslide older than the one located immediately to the south-southeast, which is probably the landslide identified by Billi et al. [2008].



Italy
Tyrrhenian Sea
Calabria
ttt = 8-10 minutes
Porto S. Venere
Tropea
Aeolian Islands
maximum run-up
minimum ttt
Messina
Torre Faro
ttt = 10 minutes
Reggio Calabria
area of maximum vertical coseismic dislocation (c. -0.7 m)
38°N
S.Alessio
Giardini
Mt Etna
1908 earthquake epicenter by Valensise and Pantosti [1992]
Catania
seafloor reentrant
Sicily
landslide body (displaced material)
Siracusa
37°N
Ionian Sea
Cozzo Spadaro
Capo Passero
main turbiditic channels by Ryan and Heezen [1965]
N
Sicily Channel
Mediterranean Sea
ttt = tsunami travel time [Baratta, 1910]
Malta
Sliema
15°E
16°E
40 km

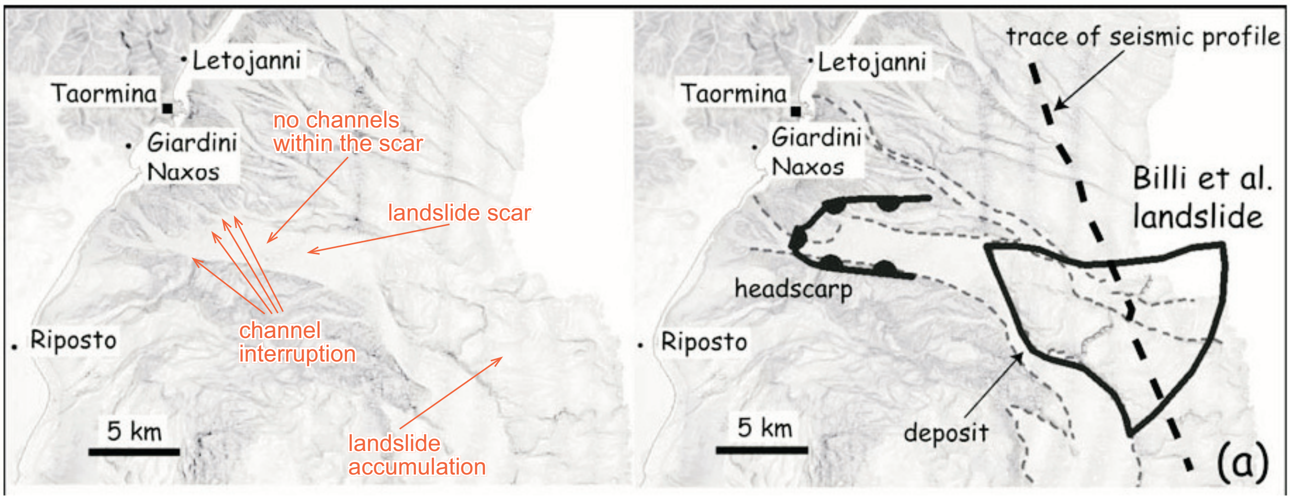
Figure S1



this work: *a* = 50.03 km; *b* = 7.19 m; *c* = 27.39 km

Gerardi et al. [2008]: *a* = 110 km; *b* = 6.5 m; *c* = 0 km

Figure S2



Letojanni
Taormina
Giardini
Naxos
no channels
within the scar
landslide scar
channel
interruption
Riposto
5 km
landslide
accumulation
Letojanni
Taormina
Giardini
Naxos
trace of seismic profile
Billi et al.
landslide
headscarp
Riposto
5 km
deposit
(a)

Figure S3

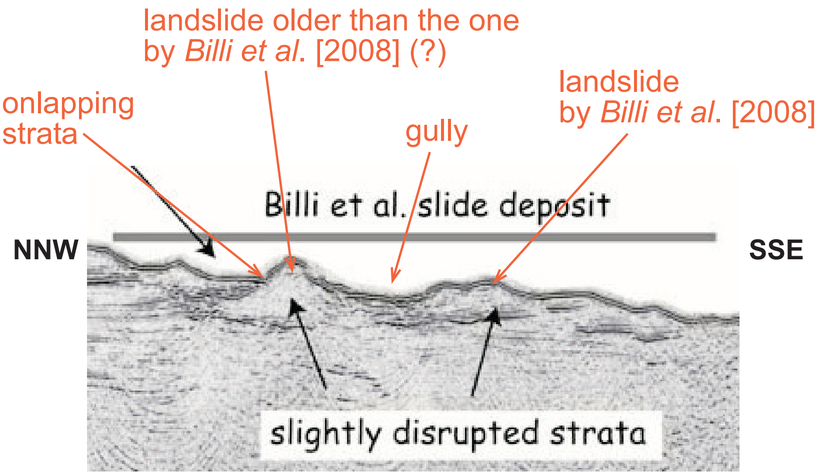

landslide older than the one
by *Billi et al*. [2008] (?)
onlapping
strata
gully
landslide
by *Billi et al*. [2008]
Billi et al. slide deposit
NNW
SSE
slightly disrupted strata

Figure S4