Did the A.D. 365 Crete earthquake/tsunami trigger synchronous giant turbidity currents in the Mediterranean Sea?

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ABSTRACT

In the Ionian Sea, one of the most seismically active regions in the Mediterranean, subduction is commonly associated with uplift of coastal mountains, enhanced erosion, and seismic activity along the Calabrian Arc and Hellenic Arc, thus potentially resulting in repetitive mass failures. Some of the turbidites observed in the deep basins are thick and prominent on seismic records because of the acoustic transparency of their upper structureless mud layer. Our high-resolution study of the most recent of these megabeds, the homogenite Augias turbidite (HAT), provides key proxies to identify pelagic sediments deposited following the catastrophic causative event. Radiometric dating in an area >150,000 km^2 indicates that the different Mediterranean so-called homogenite deposits are in fact synchronous and were deposited during a single basin-wide event within the time window A.D. 364–415. Unlike interpretations that relate this turbidite to different triggering events, including the Santorini caldera collapse, the turbidite can be traced back to a large tsunami sourced from the A.D. 365 Crete megathrust earthquake. Correlation of the single-event HAT over a wide area of the Mediterranean, from the northern Ionian Sea to the Mediterranean Ridge and the anoxic Tyro Basin south of Crete, suggests that the A.D. 365 Crete earthquake and tsunami must have produced devastating effects, including widespread massive sediment remobilization in the eastern Mediterranean Sea.

INTRODUCTION

The Ionian Sea is a 4000-m-deep basin located between the Calabrian and Hellenic subduction systems. It represents the most seismically active region in the Mediterranean Sea, in which there were repeated strong tsunamigenic earthquakes (Papadopoulos et al., 2014). During the late Quaternary turbidite deposition dominates in the deep basins, where earthquake-triggered mass flow deposits represent more than 90% of the total sedimentation during historical time (Polonia et al., 2013a, 2013b).

Some of the turbidites are very thick and stand out in the seismic record because of the acoustic transparency of the upper mud layer (Rothwell et al., 1998; Hieke, 2000). The most recent of these megabeds was termed homogenite, and is observed over a wide area of the eastern Mediterranean Sea (Kastens and Cita, 1981).

The homogenite has been identified from different tectonic and physiographic settings. Type A homogenite (Cita and Aloisi, 2000) refers to pelagic turbidites of local origin deposited in small perched basins of the Calabrian Arc and western Mediterranean Ridge. Type B homogenite, as much as 25 m thick, refers to a terrigenous megaturbidite thought to originate from shelf-related areas, and has been recovered from the Sirte and central Ionian abyssal plains and from the western Herodotus Trough (Cita and Aloisi, 2000). The Augias turbidite (Hieke and Werner, 2000) refers to the type B homogenite.

The homogenite was interpreted as being related to the Santorini volcano explosion, caldera collapse, and subsequent tsunamis that occurred ~3500 yr ago (Kastens and Cita, 1981). The turbidite composition and structure, as well as radiometric dating and age modeling in the western Ionian Sea (Item DR1 in the GSA Data Repository[1]), revealed that, at least in this re-gion, it was not triggered by the Santorini event but by the later A.D. 365 Crete earthquake tsu-nami (Polonia et al., 2013a). However, such age estimates were determined in a different area relative to that studied by earlier works, while the deposition of the initial homogenite was never radiometrically dated. For this reason, the different homogenites are still described as re-lated to different triggering events, including the Santorini caldera collapse (Papadopoulos et al., 2014; Periáñez and Abril, 2014).

To summarize, large uncertainties still ex-ist on the correlation of mass-flow deposits assigned to the homogenite in different Mediterranean basins. This study aims to fill this gap by correlation of well-dated turbidite sequences in 12 different physiographic settings. These range from the 4000-m-deep abyssal plain to shallower slope basins, including the Botticelli Basin, where the homogenite was first investigated (Kastens and Cita, 1981; Blechschmidt et al., 1982), the outer Mediterranean Ridge, and the Tyro Basin (Fig. 1). Radiometric dating was used to constrain the emplacement time of the different so-called homogenite deposits and to better understand whether they were triggered by a single basin-wide catastrophic event.

CORING SITES AND METHODS

Sediment cores presented in this study were collected in 6 different areas (Fig. 1) using a 1.2 t Kullenberg gravity corer (CALA cores of the CALAMARE project: Calabrian Arc Marine Geophysical Experiment study of active defor-mation and seismic hazard assessment), a box corer (core SL139), and a piston corer (core P46). To select coring sites, we were guided by analy-sis of subbottom Chirp seismic data (Fig. 2; Item DR2). The western transect (WT) is located at the base of the Malta escarpment (cores CALA04, CALA05, CALA07), and the eastern transect (ET) extends from the Ionian abyssal plain upslope (cores CALA09, CALA02, CALA03) across the Cobblestone Area 4 of Blechschmidt et al. (1982). Between those transects, two addi-tional cores (CALA01 and CALA08) were col-lected in the region of the Botticelli Basin (BB). A fourth study area is located in the Calabria re-gion, and cores SL139 and P46 were collected in the Mediterranean Ridge (MR) and Tyro Basin, respectively (Fig. 1). To achieve an accurate age modeling of our ^{14}C data, we describe the criteria followed to identify top and bottom boundaries of the turbidite.

The turbidite bottom boundary is invariably characterized by a sharp and irregular sandy base; its top coincides with a facies change identified through micropaleontological analysis and the presence of a redox front marked by a millimeter-thick layer enriched in Mn-Fe (Item DR3). The transition between the turbidite tail and in situ pelagic sediments (Fig. 3) was described in terms of color, mean grain size, sedimentary structures, and microfossil assem-blages (Item DR4).

Accelerator mass spectrometry radiocarbon dating (Item DR5) was performed on mixed planktonic foraminifera and pteropod fragments. Samples were collected from 1 to

[1]GSA Data Repository item 2016056, methods, microfossil assemblages, ^{14}C ages and calibration, stratigraphic logs, and subbottom Chirp profiles, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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the top of the turbidite (Fig. 3); dating of the homogenite was done by considering the time span corresponding to the thickness of pelagic deposits between the top of the turbidite and the dated level. Pelagic sedimentation rates in the abyssal plain and enclosed slope basins (cores CALA04 and CALA05) are 0.095–0.100 mm/yr and 0.054–0.083 mm/yr (Polonia et al., 2013a). In core CALA21, the chronology is based on the presence of the Pompeii A.D. 79 tephra layer (Z1) and average sedimentation rate (Polonia et al., 2015). In core SL139 (Item DR7), the chronology is based on extrapolation from known synchronous deposition for the marker bed and top and bottom of sapropel S1 (de Lange et al., 2008); this results in a standard deviation of ~330 yr (uncalibrated), while in core P46, chronology is based on extrapolation from radiometric dating and age modeling (Items DR8 and DR9).

RESULTS

Chirp Subbottom Profiles and Homogenite Thickness

The physiographic setting of coring sites in the Ionian Sea is shown in Item DR2, which includes Chirp sonar seismic profiles collected along the coring transects. Cores CALA04 and CALA09 were collected from the abyssal plain, at the base of the Calabrian Arc accretionary wedge, where the homogenite Augias turbidite (HAT) is thickest. Cores CALA01, CALA02, CALA03, CALA05, CALA07, and CALA08 were collected within slope basins of the accretionary wedge. The Calabria region coring sites are in a confined sedimentary basin (CALA10) and from a topographic high (CALA21). The thickness of the turbidite varies from 0.1 m to >12 m (Item DR6).

Transition Between Homogenite and Upper Pelagic Sediments

The upper part of the turbidite displays similar features in all cores, and consists of structureless clayey silt mud with small amounts of size-selected (63–125 μm) planktonic foraminifera (Item DR4) reflecting deposition from the diluted tail of the turbidity current.

Above the millimeter-thick Mn-Fe–enriched redox front marking the top of the turbidite (Item DR3) is 2–7 cm of purplish-gray and massive mud that includes abundant planktonic foraminifera, but no evidence of sorting and common pteropod fragments. Lithofacies characteristics and foraminiferal assemblages dominated by planktonic specimens, with the occurrence of *Articulina tubulosa* (Item DR4), indicate that deposition took place in a pelagic undisturbed environment. Planktonic foraminifera and pteropods collected for radiocarbon analyses were all hand-picked from samples with this assemblage.

Homogenite Emplacement Time in the Different Coring Sites

Radiometric dating (Item DR5; Fig. 3) indicates that the narrowest emplacement time window for the turbidite is A.D. 364–530, with the exception of two samples from two different cores indicating a younger age (Fig. 3). Three additional age ranges of A.D. 265–451, 302 B.C. to A.D. 438, and A.D. 115–415 are obtained through chronological reconstructions in cores CALA21, SL139, and P46 (Fig. 3).

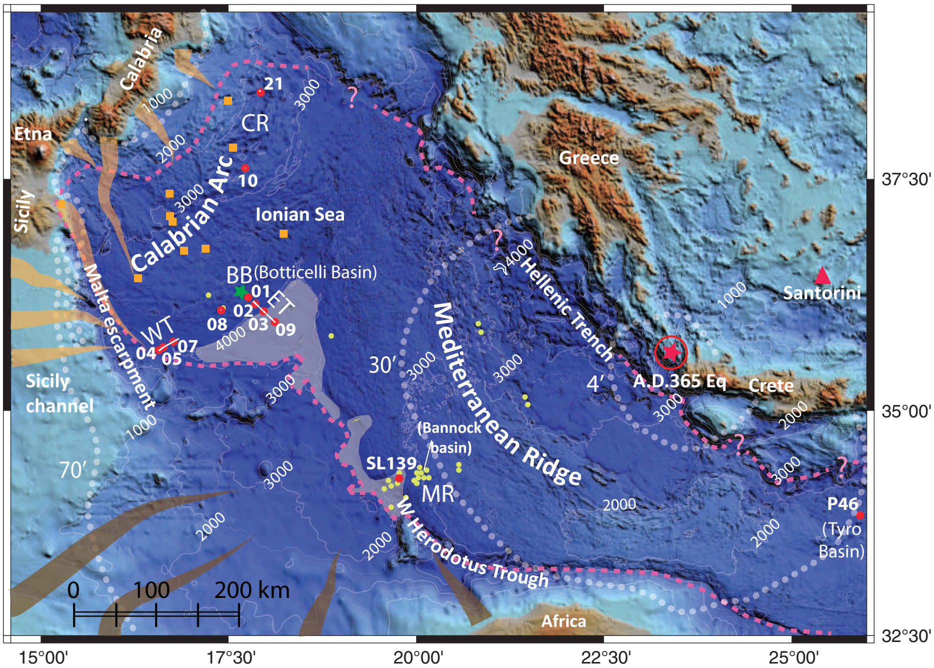

Figure 1. Shaded relief map of topography and bathymetry of the central and eastern Mediterranean Sea (data from Shuttle Radar Topography Mission Plus and Loubrieu et al., 2008). Gray patterns show the extent of homogenite Augias turbidite (HAT) deposits according to Hieke and Werner (2000). Yellow dots are coring stations (after Cita and Rimoldi, 1997). Orange dots are homogenite-bearing gravity cores (this study); red dots are dated gravity cores. White lines show Chirp profiles (WT—Western Transect, ET—Eastern Transect; Fig. 2; Item DR2 [see footnote 1]). Green star shows Botticelli Basin (BB). CR—Calabria region; MR—Mediterranean Ridge area; Eq—earthquake. Gray dots show tsunami wave front at 4, 30, and 70 min after the earthquake (Shaw et al., 2008). Brown lines are HAT sediment source areas as deduced by Cita and Aloisi (2000); orange lines are from Polonia et al. (2013a). Pink dotted line marks HAT occurrence (after this study; question mark if uncertain).

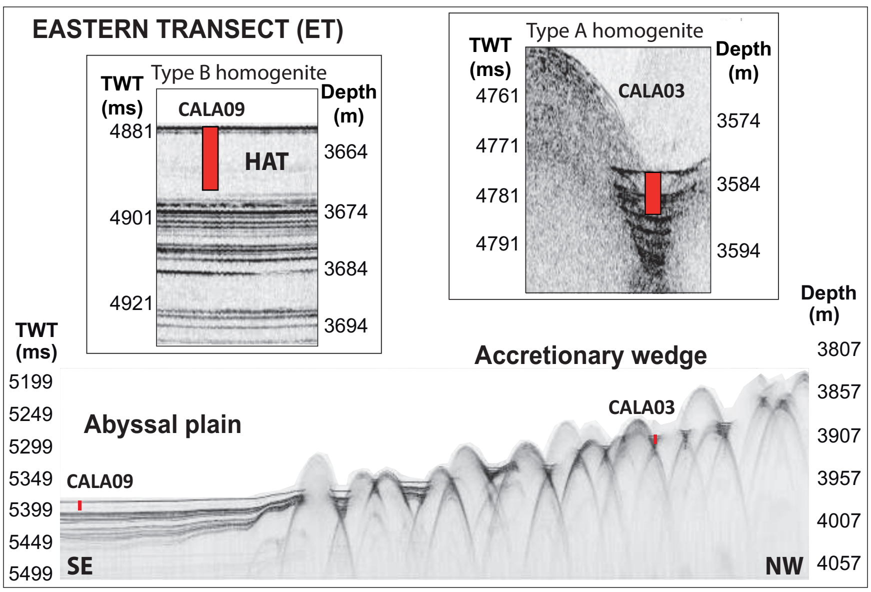

Figure 2. Subbottom Chirp profile across the transition between the undeformed abyssal plain and the accretionary wedge (location in Fig. 1). TWT—two way traveltime. Insets show the Chirp profiles on the coring stations (in red).

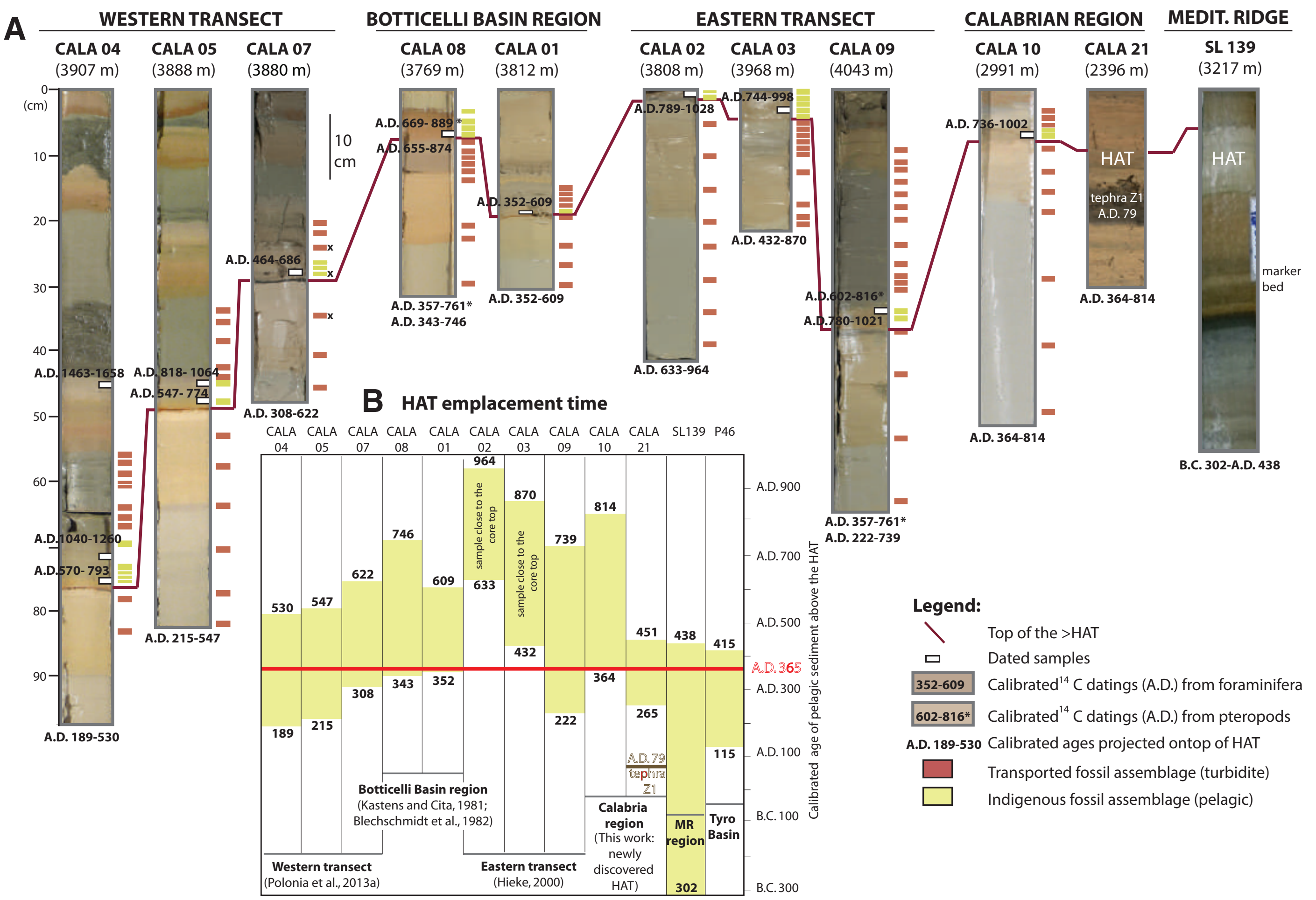

Figure 3. A: Core photographs, dated samples, and foraminiferal assemblages in the study cores. Calibrated homogenite Augias turbidite (HAT) ages are shown below core photographs. The x indicates the fossil assemblage shown in Item DR4 (see footnote 1). Medit.—Mediterranean. B: HAT emplacement time. The dated pelagic samples yield a cluster of ages centered on the A.D. 365 Crete earthquakes. Where two radiocarbon dates are available for a single sample, we used the age obtained with foraminifera. Details for core P46 are given in Items DR8 and DR9.

Coring sites on the abyssal plain (cores CALA04 and CALA09), where the turbidite upper boundary is deeper in the succession and the pelagic units are thicker relative to those found in other cores, are ideal sites for radiometric dating and allow for a more detailed chronological resolution. In these cores, collected in the WT and the ET areas, the homogenite age is consistent. This implies that the turbidite studied by Polonia et al. (2013a) in the WT and that described by Hieke and Werner (2000) from the ET are chronologically coincident. Similarly, in the MR, Tyro Basin, and BB regions, the age of the turbidite emplacement indicates synchronicity with the HAT in the other areas. In the Calabria region, where the turbidite was never described before this study and the first site where it was identified on a structural high, we find a coincidence with the age ranges recorded in the other cores (Fig. 3). The relatively young ages obtained in cores CALA02 and CALA03 have been deduced from samples very close to the core top: bioturbation and the low sedimentation rate in this area reduce the sampling resolution. To summarize, according to our age estimates, all the turbidites collected in different physiographic settings were deposited synchronously, and the narrowest emplacement time window is A.D. 364–415.

DISCUSSION

Results from this study indicate that, within the errors associated with radiometric dating, HAT emplacement time is the same in the different basins of the Mediterranean Sea. This supports the idea of a single basin-wide event, able to resuspend sediments over a very wide region including the Mediterranean Ridge, the Ionian abyssal plain, the Tyro Basin, and the Sicily and Calabria slopes. This latter finding (HAT off Calabria) widens the region of its occurrence, as this deposit was never previously described so far north.

The HAT was radiometrically dated over an area of >25,000 km^2, and considering chronologies recorded in the Calabria region and MR integrated with revised age modeling in the Tyro Basin (Items DR8 and DR9), the area might increase to >150,000 km^2. The process that caused this huge event was thus capable of synchronously triggering sediment remobilization in Crete, northern Africa, Calabria, and Sicily.

The Bronze Age Santorini eruption cannot be the triggering event for any of the studied turbidites because the Santorini caldera collapse and related tsunamis occurred in 1627–1600 B.C. (Friedrich et al., 2006), ~2000 yr before HAT emplacement. Our radiocarbon ages for HAT emplacement are centered around the age of the strongest Mediterranean seismic event reported in historical catalogues, i.e., the Crete A.D. 365 earthquake with magnitude estimated as 8.4 (Shaw et al., 2008). We consider this event the only candidate capable of generating devastating effects over a wide area of the Mediterranean Sea.

Although Italian medium-size earthquakes [such as the M_s 6.60, A.D. 361 Sicily and M_s 6.30, A.D. 374 Reggio Calabria earthquakes; Rovida et al., 2011] cannot be considered possible likely mechanisms to produce such widespread and exceptional allochthonous sedimentary deposits, we should consider the possible occurrence of two seismic triggering events within the same time window, i.e., a Calabrian earthquake triggering turbidity currents close to offshore Italy and the A.D. 365 Crete earthquake triggering the HAT in the rest of the deep basin. However, we consider this hypothesis unlikely, because the HAT in core CALA10 close to Calabria is ~1.70 m thick and is the only turbidite of such thickness found in the entire core. This implies that it marks an exceptional event during Holocene time, unlikely to be related to a local medium-magnitude earthquake, which probably reoccur every 100–700 yr (Polonia et al., 2015). Only the high-magnitude A.D. 365 Crete–type seismic events have recurrence times of 6000–7000 yr (Shaw et al., 2008). However, a different triggering earthquake in the eastern Mediterranean in unlikely. Four moderate to large earthquakes (M 6–7.8) in A.D. 115–415 occurred in Syria, Lebanon, and Israel (Salamon et al., 2007), but these were too far from the Tyro Basin to trigger a 2-m-thick turbidite in an isolated basin not fed by canyon systems.

The terrigenous versus pelagic composition of type B and A homogenites requires very different sedimentary processes, triggered simultaneously: (1) gravity instability and large channelized turbidity currents along major canyon systems with shallow-water material transported downslope to the deepest part of the basin; and (2) mass flows in more localized confined basins supplied by local sediment sources from nearby structural highs.

Seismic shaking from a single large event is not capable of triggering giant turbidity currents 600–800 km from the epicenter, such as northern Calabria and the Sicily Channel, which were postulated to be source areas for the HAT in the western Ionian Sea (Polonia et al., 2013a). The areal extent of the HAT as shown by our new radiometric dating supports the hypothesis that it was the tsunami following the Crete earthquake that triggered giant turbidity currents along a front >1000 km long from northern Africa to Sicily and Calabria (Fig. 1).

The earthquake and tsunami of A.D. 21 July 365 have stimulated discussions between historians, archaeologists, and geophysicists mainly because historical records are not always concordant in chronology and extent of reported damages. Guidoboni et al. (1994) proposed a scenario of earthquake effects as restricted to Crete, with the tsunami hitting Egypt, Libya, and few effects in the central Adriatic. However, an unusual event with magnitude >8.5 was proposed by Stiros (2010), with a tsunami spread across the Mediterranean Sea (Shaw et al., 2008). The synchronous deposition of the HAT over an area >150,000 km^2 implies an exceptional seismic event and tsunami triggering catastrophic sedimentary processes.

CONCLUSIONS

Radiometric dating of the HAT in an area covering ~150,000 km^2 and including basins where this turbidite was originally described provides evidence for synchronous sedimentation in the eastern Mediterranean Sea during a catastrophic event that occurred between A.D. 364 and 415, consistent with the A.D. 365 M_w 8.3–8.5 Crete earthquake tsunami time frame. Although this has been previously demonstrated for the HAT deposited in the western Ionian abyssal plain, dating the turbidite in the Botticelli and Tyro Basins directly links this result to a large amount of different homogenites described in the eastern Mediterranean, providing clues for an exceptional event related to a megathrust tsunami. The landlocked Mediterranean Sea has high uplifting coastal mountain ranges that amplify seismically induced sedimentary processes. The HAT is thus the thickest and largest seismo-turbidite tsunamite yet known and can be used to define proxies to reconstruct super-earthquake recurrence time in other megathrust regions.

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