GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48940.1

Manuscript received 11 February 2021
Revised manuscript received 12 May 2021
Manuscript accepted 16 May 2021

Published online 15 July 2021

Earthquake doublet revealed by multiple pulses in lacustrine seismo-turbidites

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ABSTRACT

Earthquake doublets have been described in fault systems around the world but have not yet been confidently resolved in paleoseismic records. Our current knowledge is limited to historical occurrences, preventing researchers from uncovering potential patterns or recognizing common fault behavior. Identification of prehistoric doublets is thus of crucial importance for adequate seismic hazard assessment and risk mitigation. We developed a new methodology to reveal the sedimentary imprint of earthquake doublets in lacustrine paleoseismic records based on flow direction analysis in multipulsed turbidites, because the delayed arrival of turbidity currents originating from the same source location demonstrates the occurrence of individual triggering mechanisms. As grains tend to align in the presence of a flow, we analyzed flow directions by determining the dominant orientation of elongated grains using a combination of grain size, paleomagnetism, and high-resolution X-ray computed tomography. This methodology was applied to a turbidite deposited by the 2007 CE earthquakes in West Sumatra (M_w 6.4 and 6.3, 2 h apart), and it provides the first unmistakable sedimentary evidence for an earthquake doublet. We argue that this methodology has great potential to be applied to multipulsed turbidites in various subaquatic paleoseismic records and can reveal the occurrence of unknown earthquake sequences.

INTRODUCTION

When two earthquakes with similarly high magnitudes on nearby fault segments occur within a few hours' time, they are considered to form an earthquake doublet (e.g., Lay and Kanamori, 1980). Although such doublets have been described around the world (e.g., Wong and Bott, 1995; Lin et al., 2008; Daryono et al., 2012), evidence is limited to instrumental archives. The lack of traces of prehistoric earthquake sequences in paleoseismic records has implications for seismic hazard assessments based on those records, as inferred major ruptures could have resulted from separate, consecutive earthquakes. Moreover, the recurrence of earthquake doublets along particular faults might point to common fault behavior, and local awareness of such consistency can greatly reduce the risk associated with an imminent second shock. Earthquake doublets thus form a particular challenge for seismic hazard analysis, and identifying them in paleoseismic records is of crucial importance.

Turbidite stratigraphy has proven to be a powerful approach for paleoseismic reconstructions in subaqueous settings (e.g., Goldfinger et al., 2003; Howarth et al., 2012; Moernaut et al., 2014; Wils et al., 2020), and seismo-turbidites have the potential to record closely timed events (e.g., Van Daele et al., 2015; Migeon et al., 2017). However, deposition of a turbidite, and especially its fine-grained cap, usually takes longer than a few hours: once the current has ceased, settling of 1 μm particles from a 1-m-thick suspension cloud would take ∼2 weeks (Stokes, 1851). Consecutive earthquakes within such time frames therefore do not result in separate turbidites but in the deposition of a single, amalgamated turbidite that consists of multiple flow pulses, potentially originating from various source areas, deposited on top of each other. Identification of similar source areas in multiple successions of turbidite pulse amalgamation, clearly offset in time, then forms the most compelling argument for the occurrence of an earthquake sequence. To determine turbidite source areas, flow directions can be used, which in sediment cores can be reconstructed by ripples or convolute laminations (e.g., Van Daele et al., 2014). In the absence of such sedimentary structures, the orientation and imbrication of individual grains can also reveal paleoflow directions, as have been successfully used for coarse-grained tsunami deposits (e.g., Paris et al., 2010; May et al., 2016).

We combined grain size, paleomagnetic core orientation, and high-resolution X-ray computed tomography (μCT) to establish sediment microfabrics in lacustrine turbidites and infer depositional and flow dynamics. As a test case, we studied a seismo-turbidite related to the 2007 CE earthquake doublet in West Sumatra identified in short sediment cores from Lake Singkarak.

SETTING

Sumatra is the largest island in the Indonesian archipelago, located along the Sunda megathrust where the Indo-Australian plate subducts beneath the Eurasian plate (Fig. 1A). The trench-parallel component of the oblique subduction is partially accommodated by the Sumatran fault, a large dextral strike-slip fault system (Sieh and Natawidjaja, 2000). Lake Singkarak is located on this fault, occupying a tectonic basin formed by dextral slip on two overstepping segments in the highlands close to Padang, the capital of West Sumatra. These are termed the Sumani and Sianok segments, which consecutively ruptured in M_w 6.4 and 6.3 earthquakes in March 2007 within a 2 h time frame (Fig. 1). Both of these earthquakes nucleated in the northwestern part of the lake,

CITATION: Wils, K., et al., 2021, Earthquake doublet revealed by multiple pulses in lacustrine seismo-turbidites: Geology, v. 49, p. 1301–1306, https://doi.org/10.1130/G48940.1

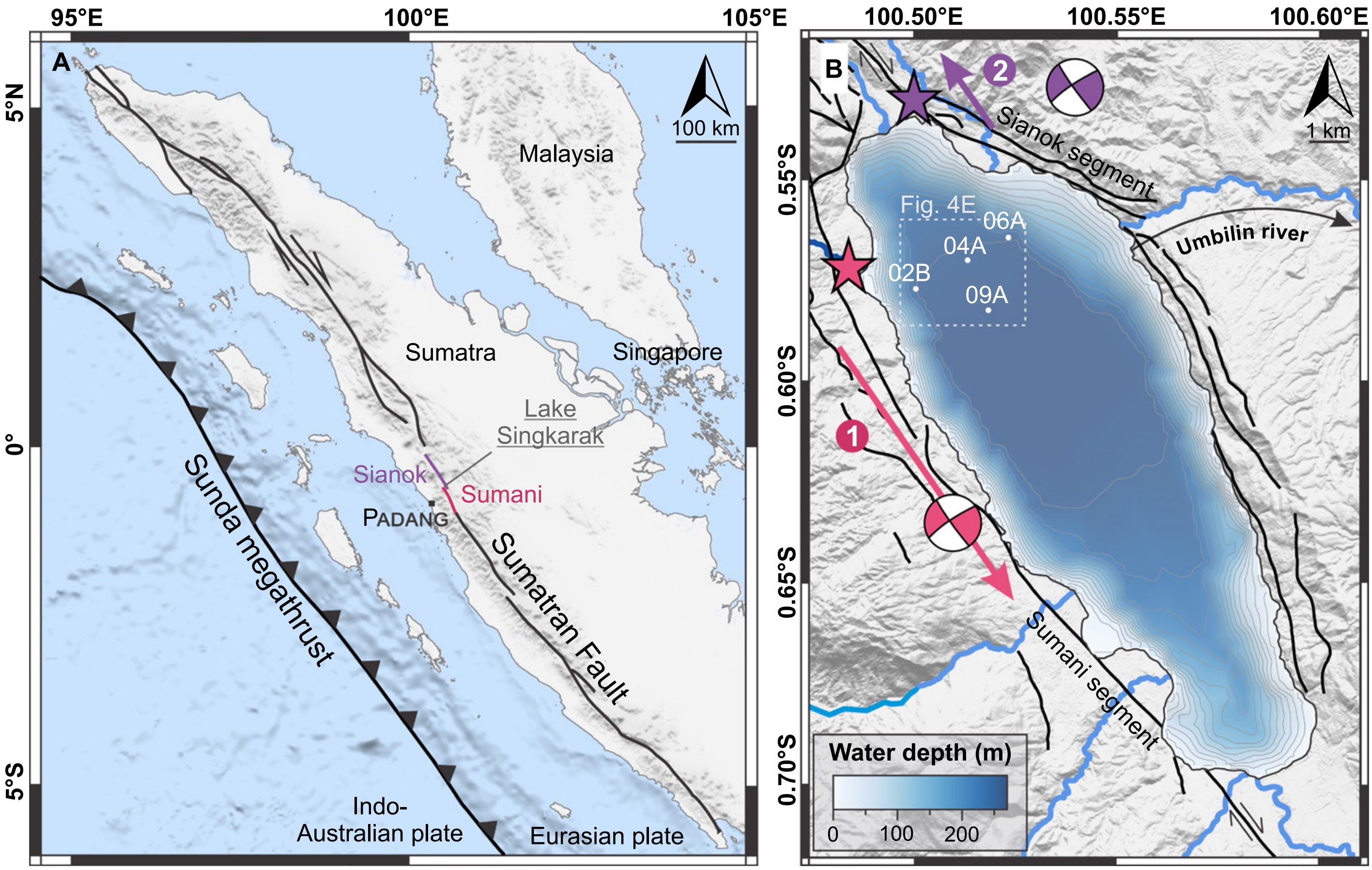

Figure 1. (A) Setting of Lake Singkarak, West Sumatra, located on the Sumani and Sianok segments of the Sumatran fault and along the Sunda megathrust. The lake is located close to the regional capital of Padang. (B) Bathymetric map of the lake (20 m contours) showing locations of four studied cores (SN17–02B, SN17–04A, SN17–06A, and SN17–09A) and the most important rivers. Fault traces of both segments involved in the 2007 CE earthquake doublet are after Sieh and Natawidjaja (2000); rupture propagation (colored arrows), epicenter locations, and focal mechanisms are after Nakano et al. (2010). Figure is modified from Wils et al. (2021).

causing local shaking intensities of VI–VI½, and propagated in opposite directions along the respective fault segments (Nakano et al., 2010). The sedimentary imprint of the 2007 earthquakes has been identified in short sediment cores retrieved from Lake Singkarak as a widespread turbidite, which in two distal core locations consists of separate coarse-grained subdivisions that could represent the individual earthquakes in the doublet (Wils et al., 2021).

METHODS

We analyzed the 2007 turbidite in Lake Singkarak in four cores collected in 2017 (Fig. 1B): two slope-proximal cores for methodological verification (cores SN17–02B and SN17–06A) and two distal cores with two coarse-grained intervals (SN17–04A and SN17–09A) (core characteristics and methods are further elaborated in the Supplemental Material[1]). In each core, the 2007 turbidite was characterized by laser diffraction grain-size analysis and we report the D10 (portion of particles with diameters smaller than this value is 10%), geometric mean, and sorting values (Table S2 in the Supplemental Material; Blott and Pye, 2001).

U-channel subsamples with a 2 × 2 cm cross section were taken over the full length of each core. They were stepwise demagnetized by alternating fields to reveal the direction of the characteristic remanent magnetization (ChRM; inclination, declination) defined by principal component analysis (Table S4). The ChRM was precisely defined with maximum angular deviations (MADs) mostly below 3°. Because the magnetic moment of minerals deposited by hemipelagic settling is lined up according to the prevailing magnetic field, the core can be geographically oriented in the horizontal plane by aligning the obtained average declination to magnetic north.

The coarse-grained intervals of the 2007 turbidite in each U-channel were μCT scanned. We chose a voxel size of 15 μm for all overview scans, visualizing grains with sizes down to ~100 μm. Region-of-interest (ROI) scans of the U-channel center were obtained using a voxel size of 7 μm. To digitally identify individual grains, we processed all obtained μCT volumes using the same workflow set out in the Avizo software package (Thermo Fisher Scientific). This included a series of binary operations and a watershed algorithm, after which the size, elongation, and orientation (trend and plunge) of each grain were measured. The orientations of all elongated grains >100/150 μm (Table S5) were plotted on a stereoplot (Cardozo and Allmendinger, 2013). Several pulses (a, b, c, d), marked by a single flow direction, could be identified within the coarse-grained intervals (1 or 2) of the turbidite at each location (e.g., the first turbidite pulse in the second coarse-grained subdivision is referred to as pulse 2a for that core). For each of these pulses, we applied the Bingham axial distribution algorithm (Fisher et al., 1987) to all retained grains to show the principal component (PC1; Table S6) and objectively reveal the main paleocurrent direction. In the case where the basal plane of a specific pulse was tilted, likely due to core deformation during or after core retrieval (e.g., degassing), orientation parameters were corrected so that

[1]Supplemental Material. Detailed information on the studied sediment cores and methods. Please visit https://doi.org/10.1130/GEOL.S.14810562 to access the supplemental material, and contact editing@geosociety.org with any questions.

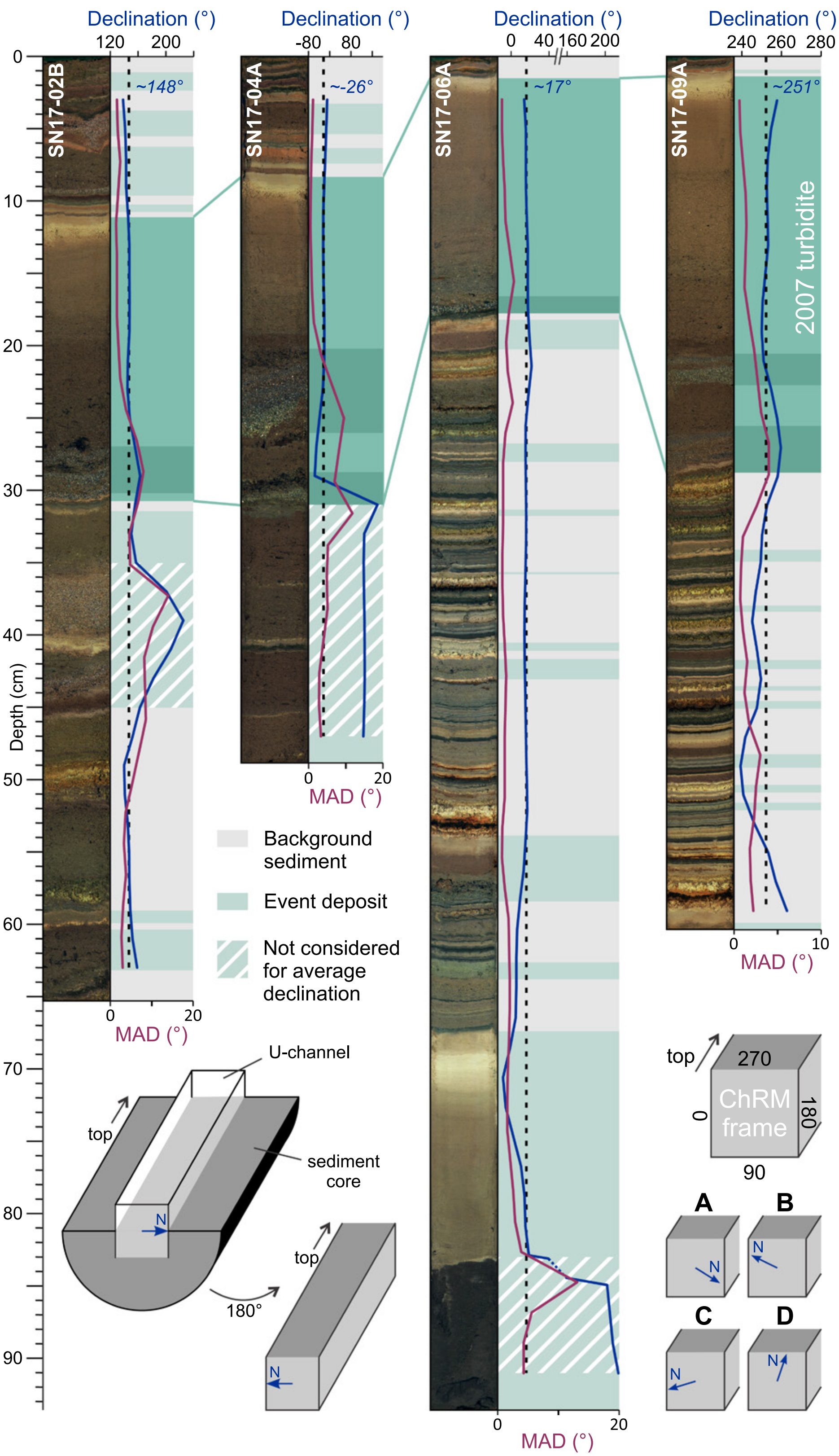

Figure 2. Declination (dark blue) and maximum angular deviation (MAD, purple) derived from paleomagnetic analysis of four cores from Lake Singkarak (West Sumatra), with interpretation of background (gray) and event sedimentation (green) following Wils et al. (2021). Here, the 2007 CE seismo-turbidite and its coarse-grained intervals are indicated in dark green (see Fig. 3). Average declination (dashed line) indicates north direction in characteristic remanent magnetization (ChRM) reference frame for each U-channel, calculated by discarding event deposits with unreliable declination values (white shading). Lower-left schematic shows a representation of the U-channel with respect to the sediment core. Lower-right schematic shows U-channel bottom views that show declination direction for each core.

they were measured with respect to the actual basal plane rather than a horizontal one.

FLOW DIRECTIONS

To infer the orientation of each core, we first categorized sediments as background (steady-state accumulation) or event (turbidites and slumps) deposits following interpretations by Wils et al. (2021). Background deposits showed consistent magnetic declinations in each core, illustrating the declination of the geomagnetic field during deposition (Fig. 2). The majority of event deposits, including the 2007 turbidite, showed similar declinations, indicating that their magnetic moments also aligned to the magnetic north. In contrast, the oldest event deposits in cores SN17–04A and SN17–06A showed an abrupt shift in declination that indicates reworked (slumped) material. In core SN17–02B, a gradual change in declination (and inclination) was observed below the 2007 turbidite, and it coincided with a significant increase in MAD (up to 14°; Fig. 2). The magnetization in these horizons is thus unstable, leading to an unreliable record of the geomagnetic field that may result from changes in the magnetic content (e.g., grain-size mixture). These horizons were discarded and not used in the calculation of the average declination (Fig. 2).

For each pulse identified in the 2007 Singkarak turbidite (Fig. 3), we translated the preferential orientation of all elongated grains (PC1) into paleoflow direction (Fig. 4). While the dominant flow direction can be either parallel or perpendicular to the longest shape axis of elongated grains (Allen, 1982), transverse fabrics are rare in turbidites, and flow-parallel long axes are generally assumed (e.g., Sakai et al., 2002; Mulder et al., 2009; Felletti et al., 2016). Furthermore, grains are imbricated along their long axis, as can be seen on the stereoplots (Figs. 4A–4D). The dominant orientation of the long axis in the 2007 turbidite thus indicates the flow direction. Grain imbrication results in an up-current dipping direction of the grain (e.g., Sakai et al., 2002; Felletti et al., 2016), and this was used to derive flow sense. These results showed that the single coarse-grained interval in core SN17–02B consists of three individual pulses with a distinct origin (Fig. 4). Grain-size data support this interpretation, showing a new graded sequence in each pulse, where the base is coarser than the top of the previous sequence (Fig. 3). The PC1 of pulse 1a indicated a flow coming from the gradual northern lake slope, followed by pulse 1b originating from the steep slopes located northwest of the core location. Similarly, the single turbidite pulse in SN17–06A likely originated from the slopes northeast of the core location, although imbrication in this core could not be reliably determined due to a nonuniformly dipping basal plane (Fig. 3). The first turbidite pulses in the slope-proximal cores

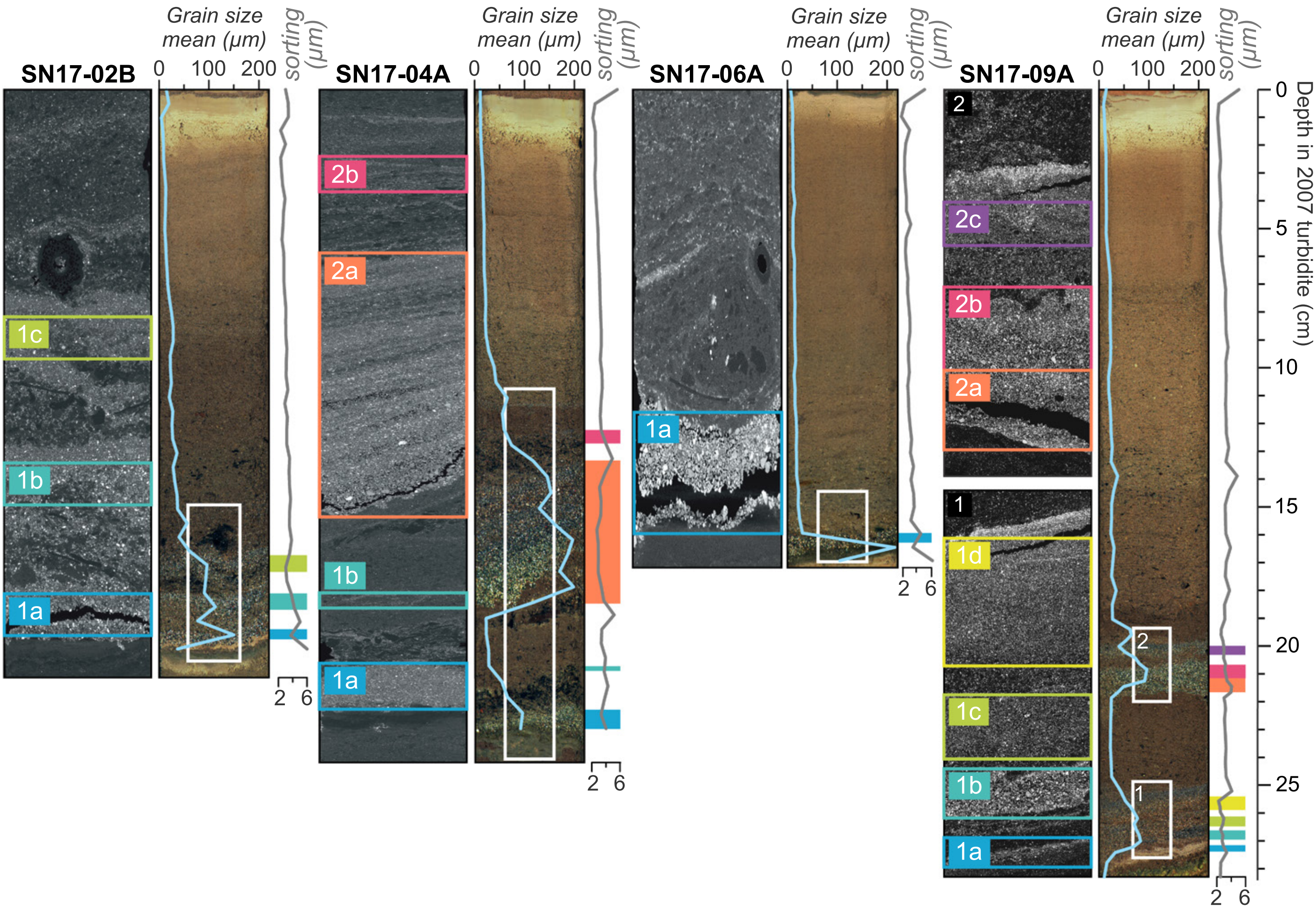

Figure 3. High-resolution X-ray computed tomography (µCT) scans and pictures of the 2007 CE seismo-turbidite in Lake Singkarak (West Sumatra; see Fig. 2) with an indication of grain-size parameters (mean—light blue; sorting—gray). White rectangles mark µCT-scanned sections. Turbidite pulses are indicated by colored rectangles, alphanumerically named per coarse-grained interval in order of deposition. For cores SN17–02B, SN17–04A, and SN17–06A, overview scans were used (resolution 15 × 15 × 15 µm); for finer-grained core SN17–09A, region-of-interest scans (7 × 7 × 7 µm) were required to achieve adequate grain segmentation.

can thus be linked to the lake slopes nearest to the respective core site, indicating that the paleomagnetic orientation of the cores and our assumptions about grain fabric can be combined to provide a reliable approach to reveal paleoflow directions.

EARTHQUAKE DOUBLET IDENTIFICATION

The 2007 turbidite in cores SN17–04A and SN17–09A contains two coarse-grained subdivisions separated by a few centimeters of fine-grained diatomaceous sediment (Wils et al., 2021). These intervals show limited sorting variability (Fig. 3) and MADs intermediate between those obtained in the coarse-grained sediments below and in the background sediments (Fig. 2). This suggests gradual deposition from the body of the turbidity current during waning flow, as further supported by their decreasing D10 trend (~6–4 µm; Table S2). A record of delay is thus present between deposition of both coarse-grained intervals, and this delay is shorter than the time required for all fine-grained material to settle (turbidite cap, <4 µm). This would be on the order of hours to days, depending on the thickness of the suspension cloud (Stokes, 1851). A similar sedimentation pattern has been observed for diatom-rich turbidity currents in lakes in Chile and Kenya (Van Daele et al., 2017), where synchronous triggering on multiple basin slopes at up to several kilometers difference in distance to the core site resulted in an arrival delay on the order of minutes to hours for flow velocities of 0.2–1 m/s, which is the most likely flow velocity range for the deposits described here (cf. Sumner et al., 2009). In our data, an arrival delay due to destabilization of other lake slopes can be ruled out because the successive sandy beds in both cores show similar flow directions (Fig. 4; mostly originating from the northeast slopes in core SN17–04A and western slopes in core SN17–09A). The similar colors and radiodensity signatures of pulses 1d and 2c in core SN17–09A additionally support their common origin (Fig. 3). Because deposition of coarse-grained material occurs at higher flow velocities (Sumner et al., 2009), and the upper of both coarse-grained subdivisions is also coarsest in both cores, the second turbidity current must have had a higher flow velocity. This further challenges the possibility for a delayed turbidity current arrival in the absence of a second external trigger mechanism. The combination of flow direction and grain-size analysis thus confirms that the 2007 turbidite at both distal core sites represents an amalgamated turbidite with a stacked appearance triggered by both earthquakes in the doublet, where the 2 h separation is in range with the estimated depositional delays.

Our study shows that lacustrine seismo-turbidites can reveal past earthquake doublets, even if individual events are separated by no more than a few hours. Identification of separate turbidity currents originating from the same source area in a series of amalgamated

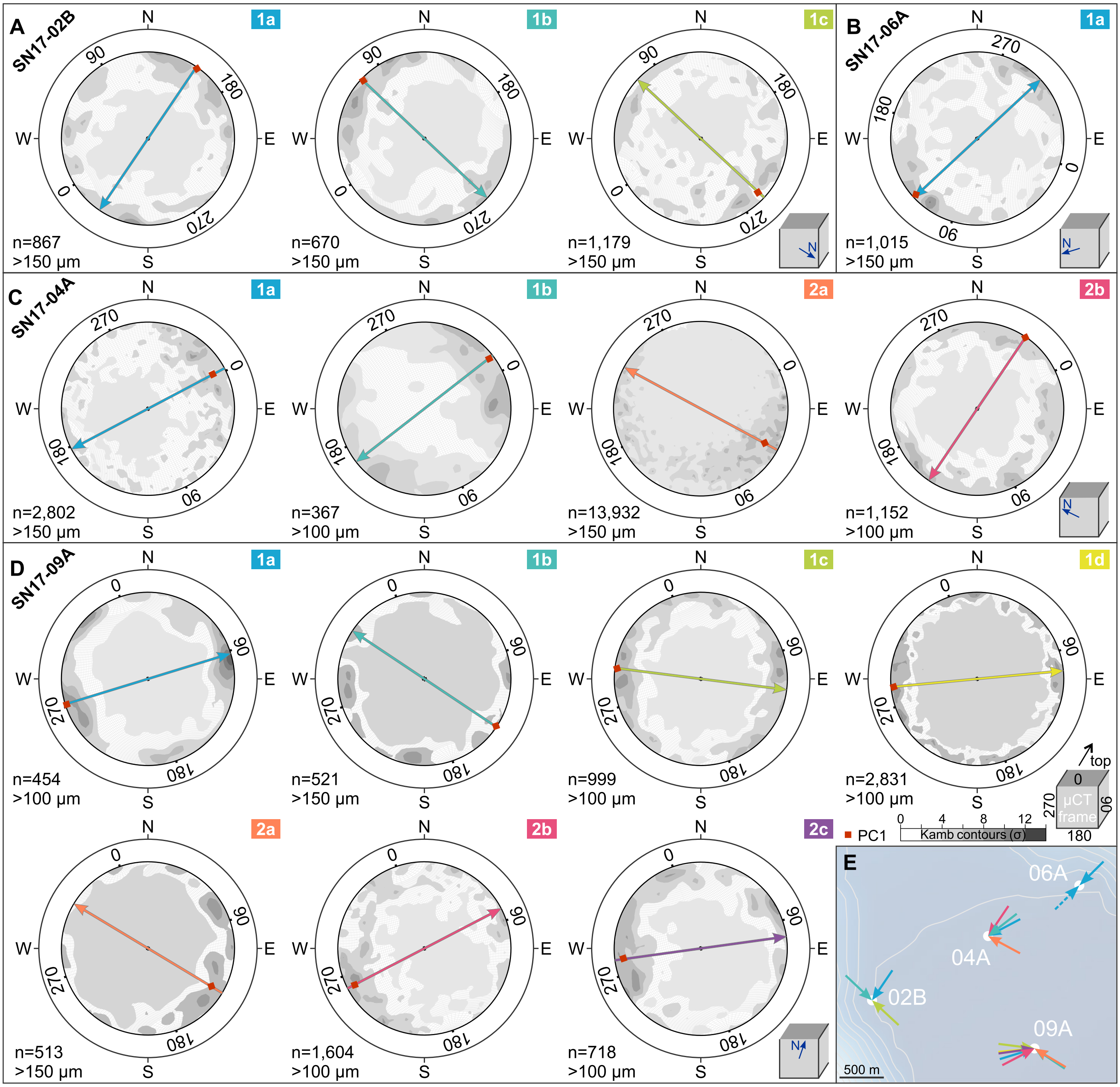

Figure 4. (A–D) Lower-hemisphere stereoplots showing plunge and trend of strongly elongated grains derived from high-resolution X-ray computed tomography (µCT) data analysis and measured with respect to the basal plane for each pulse in the 2007 CE seismo-turbidite from four cores in Lake Singkarak (West Sumatra; see Fig. 3). Each stereoplot, in µCT reference frame of the U-channel, is rotated so that geographic north is oriented to the figure top (see U-channel bottom view insets and compare to Figure 2). Considered grain sizes and total number of grains (*n*) are indicated at the bottom-left of each plot. Contour lines (Kamb, 1959) and Bingham axial distribution analysis (Fisher et al., 1987) show main orientation in each data set (principal component, PC1, red square) and indicate flow direction (colored arrows). Flow sense was derived by considering dominant imbrication as up-current dipping. (E) Geographical context of resulting flow directions at each core site (see Fig. 1B). Dashed arrow for core SN17–06A indicates unlikely flow direction that cannot be ruled out with available data.

turbidity currents is the most compelling argument for successive earthquakes. Nevertheless, the combination of paleoflow analysis with grain-size data is crucial to rule out potential confounding processes such as seiching or slope failures in the absence of a second external trigger. Because such an external trigger could also be a local event (e.g., aftershock), our methodology is especially suitable in locations where overlapping fault segments occur and should ideally be combined with other paleoseismic studies along these fault segments. This opens up prospects for recognizing prehistoric earthquake sequences in subaquatic settings around the world, which would significantly advance seismic hazard assessments.

ACKNOWLEDGMENTS

K. Wils acknowledges the Special Research Fund (BOF) of Ghent University (Belgium). Field work was funded by the Research Foundation Flanders

(FWO, G042812N) and carried out with an Indonesian Foreign Research Permit (7B/TKPIPA/E5/Dit.KI/VII/2017). We thank all field-work participants and S.Y. Cahyarini and the Indonesian Customs for sediment core shipment. We are grateful for the constructive comments provided by M. Strasser, J. Howarth, and an anonymous reviewer on an earlier version of this manuscript.

REFERENCES CITED

Allen, J.R.L., 1982, Orientation of particles during sedimentation: Shape-fabrics, *in* Allen, J.R.L., ed., Sedimentary Structures, Their Character and Physical Basis, Volume I: Amsterdam, Elsevier, p. 179–235.

Blott, S.J., and Pye, K., 2001, GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments: Earth Surface Processes and Landforms, v. 26, p. 1237–1248, https://doi.org/10.1002/esp.261.

Cardozo, N., and Allmendinger, R.W., 2013, Spherical projections with OSXStereonet: Computers & Geosciences, v. 51, p. 193–205, https://doi.org/10.1016/j.cageo.2012.07.021.

Daryono, M.R., Natawidjaja, D.H., and Sieh, K., 2012, Twin-surface ruptures of the March 2007 M>6 earthquake doublet on the Sumatran fault: Bulletin of the Seismological Society of America, v. 102, p. 2356–2367, https://doi.org/10.1785/0120110220.

Felletti, F., Dall'Olio, E., and Muttoni, G., 2016, Determining flow directions in turbidites: An integrated sedimentological and magnetic fabric study of the Miocene Marnoso Arenacea Formation (Northern Apennines, Italy): Sedimentary Geology, v. 335, p. 197–215, https://doi.org/10.1016/j.sedgeo.2016.02.009.

Fisher, N.I., Lewis, T., and Embleton, B.J.J., 1987, Statistical Analysis of Spherical Data: Cambridge UK, Cambridge University Press, 329 p., https://doi.org/10.1017/CBO9780511623059.

Goldfinger, C., Nelson, C.H., and Johnson, J.E., 2003, Holocene earthquake records from the Cascadia subduction zone and northern San Andreas fault based on precise dating of offshore turbidites: Annual Review of Earth and Planetary Sciences, v. 31, p. 555–577, https://doi.org/10.1146/annurev.earth.31.100901.141246.

Howarth, J.D., Fitzsimons, S.J., Norris, R.J., and Jacobsen, G.E., 2012, Lake sediments record cycles of sediment flux driven by large earthquakes on the Alpine fault, New Zealand: Geology, v. 40, p. 1091–1094, https://doi.org/10.1130/G33486.1.

Kamb, W.B., 1959, Ice petrofabric observations from Blue Glacier, Washington, in relation to theory and experiment: Journal of Geophysical Research, v. 64, p. 1891–1909, https://doi.org/10.1029/JZ064i011p01891.

Lay, T., and Kanamori, H., 1980, Earthquake doublets in the Solomon Islands: Physics of the Earth and Planetary Interiors, v. 21, p. 283–304, https://doi.org/10.1016/0031-9201(80)90134-X.

Lin, C.-H., Yeh, Y.-H., Ando, M., Chen, K.-J., Chang, T.-M., and Pu, H.-C., 2008, Earthquake doublet sequences: Evidence of static triggering in the strong convergent zones of Taiwan: Terrestrial, Atmospheric and Oceanic Sciences, v. 19, p. 589–594, https://doi.org/10.3319/TAO.2008.19.6.589(PT).

May, S.M., Falvard, S., Norpoth, M., Pint, A., Brill, D., Engel, M., Scheffers, A., Dierick, M., Paris, R., Squire, P., and Brückner, H., 2016, A mid-Holocene candidate tsunami deposit from the NW Cape (Western Australia): Sedimentary Geology, v. 332, p. 40–50, https://doi.org/10.1016/j.sedgeo.2015.11.010.

Migeon, S., Garibaldi, C., Ratzov, G., Schmidt, S., Collot, J.Y., Zaragosi, S., and Texier, L., 2017, Earthquake-triggered deposits in the subduction trench of the north Ecuador/south Colombia margin and their implication for paleoseismology: Marine Geology, v. 384, p. 47–62, https://doi.org/10.1016/j.margeo.2016.09.008.

Moernaut, J., Van Daele, M., Heirman, K., Fontijn, K., Strasser, M., Pino, M., Urrutia, R., and De Batist, M., 2014, Lacustrine turbidites as a tool for quantitative earthquake reconstruction: New evidence for a variable rupture mode in south central Chile: Journal of Geophysical Research: Solid Earth, v. 119, p. 1607–1633, https://doi.org/10.1002/2013JB010738.

Mulder, T., Zaragosi, S., Razin, P., Grelaud, C., Lanfumey, V., and Bavoil, F., 2009, A new conceptual model for the deposition process of homogenite: Application to a Cretaceous megaturbidite of the western Pyrenees (Basque region, SW France): Sedimentary Geology, v. 222, p. 263–273, https://doi.org/10.1016/j.sedgeo.2009.09.013.

Nakano, M., Kumagai, H., Toda, S., Ando, R., Yamashina, T., Inoue, H., and Sunarjo, 2010, Source model of an earthquake doublet that occurred in a pull-apart basin along the Sumatran fault, Indonesia: Geophysical Journal International, v. 181, p. 141–153, https://doi.org/10.1111/j.1365-246X.2010.04511.x.

Paris, R., Fournier, J., Poizot, E., Etienne, S., Morin, J., Lavigne, F., and Wassmer, P., 2010, Boulder and fine sediment transport and deposition by the 2004 tsunami in Lhok Nga (western Banda Aceh, Sumatra, Indonesia): A coupled offshore-onshore model: Marine Geology, v. 268, p. 43–54, https://doi.org/10.1016/j.margeo.2009.10.011.

Sakai, T., Yokokawa, M., Kubo, Y.S., Endo, N., and Masuda, F., 2002, Grain fabric of experimental gravity flow deposits: Sedimentary Geology, v. 154, p. 1–10, https://doi.org/10.1016/S0037-0738(02)00106-9.

Sieh, K., and Natawidjaja, D., 2000, Neotectonics of the Sumatran fault, Indonesia: Journal of Geophysical Research: Solid Earth, v. 105, p. 28295–28326, https://doi.org/10.1029/2000JB900120.

Stokes, G.G., 1851, On the effect of the internal friction of fluids on the motion of pendulums: Transactions of the Cambridge Philosophical Society, v. 9, p. 8–106.

Sumner, E.J., Talling, P.J., and Amy, L.A., 2009, Deposits of flows transitional between turbidity current and debris flow: Geology, v. 37, p. 991–994, https://doi.org/10.1130/G30059A.1.

Van Daele, M., Cnudde, V., Duyck, P., Pino, M., Urrutia, R., De Batist, M., and Trofimovs, J., 2014, Multidirectional, synchronously-triggered seismo-turbidites and debrites revealed by X-ray computed tomography (CT): Sedimentology, v. 61, p. 861–880, https://doi.org/10.1111/sed.12070.

Van Daele, M., et al., 2015, A comparison of the sedimentary records of the 1960 and 2010 great Chilean earthquakes in 17 lakes: Implications for quantitative lacustrine palaeoseismology: Sedimentology, v. 62, p. 1466–1496, https://doi.org/10.1111/sed.12193.

Van Daele, M., Meyer, I., Moernaut, J., De Decker, S., Verschuren, D., and De Batist, M., 2017, A revised classification and terminology for stacked and amalgamated turbidites in environments dominated by (hemi)pelagic sedimentation: Sedimentary Geology, v. 357, p. 72–82, https://doi.org/10.1016/j.sedgeo.2017.06.007.

Wils, K., et al., 2021, The sediments of Lake Singkarak and Lake Maninjau in West Sumatra reveal their earthquake, volcanic and rainfall history: Sedimentary Geology, v. 416, p. 105863, https://doi.org/10.1016/j.sedgeo.2021.105863.

Wils, K., Van Daele, M., Kissel, C., Moernaut, J., Schmidt, S., Siani, G., and Lastras, G., 2020, Seismo-turbidites in Aysén Fjord (southern Chile) reveal a complex pattern of rupture modes along the 1960 megathrust earthquake segment: Journal of Geophysical Research: Solid Earth, v. 125, https://doi.org/10.1029/2020JB019405.

Wong, I.G., and Bott, J.D.J., 1995, A new look back at the 1969 Santa Rosa, California, earthquakes: Bulletin of the Seismological Society of America, v. 85, p. 334–341.

Printed in USA