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, which prevents uncovering potential patterns or common fault behavior. Identifying prehistorical doublets is thus of crucial importance for adequate seismic hazard assessment and risk mitigation. We develop a new methodology to reveal the sedimentary imprint of earthquake doublets in lacustrine paleoseismic records based on flow direction analysis in multipulsed turbidites, as 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 analyze 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 is applied to a turbidite

deposited by the 2007 earthquakes in West Sumatra (M_w 6.4 and 6.3, 2 hours apart) and provides the first unmistakable sedimentary evidence for an earthquake doublet. We argue that this methodology has great potential to analyze 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 $1\ \mu\text{m}$ particles from a 1 m thick suspension cloud would take about two weeks (Stokes, 1851). Consecutive earthquakes within such timeframes 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 absence of such sedimentary structures, the orientation and imbrication of individual grains can also reveal paleoflow directions, as has been successfully used for coarse-grained tsunami deposits (e.g. Paris et al., 2010; May et al., 2016).

Here, we combine grain size, paleomagnetic core orientation and high-resolution X-ray computed tomography (μ CT) to establish sediment micro-fabric in lacustrine turbidites and infer depositional and flow dynamics. As a test case, we study a seismo-turbidite related to the 2007 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 2 hours' time (Fig. 1). Both of these earthquakes nucleated in the NW part of the lake, 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

This section provides the essentials of the studied sediment cores and used methods—further elaborated in the Supplemental Material.

We analyzed the 2007 turbidite in Lake Singkarak in four cores (Fig. 1B)—two slope-proximal cores for methodological verification (SN17-02B, SN17-06A) and the distal cores with two coarse-grained intervals (SN17-04A, SN17-09A)—by laser diffraction grain-size analysis and report the D10, geometric mean and sorting values (Table S2, Blott and Pye, 2001).

U-channel subsamples with a 2x2 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 is precisely defined with maximum angular deviations (MAD) 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 the magnetic north.

The coarse-grained intervals of the 2007 turbidite in each U-channel were μ CT scanned. A voxel size of 15 μ m was chosen for all overview scans, visualizing grains with sizes down to ~100 μ m. Region-of-interest (ROI) scans of the U-channel center were obtained using a voxel size of 7 μ m. To digitally identify individual grains, all obtained μ CT volumes were processed

using the same workflow set out in the Avizo software package. 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 $>100/150\ \mu\text{m}$ (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, the Bingham axial distribution algorithm (Fisher et al., 1987) was applied to all retained grains to show the principal component (PC1, Table S6) and objectively reveal the main paleocurrent direction. In case 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 they are measured with respect to the actual basal plane rather than a horizontal one.

FLOW DIRECTIONS

To infer the orientation of each core, sediments are first categorized as background (steady-state accumulation) or event (turbidites and slumps) deposits following interpretations by Wils et al. (2021). Background deposits show consistent magnetic declinations in each core, illustrating that of the geomagnetic field during deposition (Fig. 2). The majority of event deposits, including the 2007 turbidite, show similar declinations, indicating that their magnetic moment also aligned to the magnetic north. In contrast, the oldest event deposits in SN17-04A and SN17-06A show an abrupt shift in declination that points to reworked (slumped) material. In SN17-02B, a gradual change in declination (and inclination) is observed below the 2007 turbidite and coincides 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 are discarded for calculation of the average declination (Fig. 2).

For each pulse identified in the 2007 Singkarak turbidite (Fig. 3), the preferential orientation of all elongated grains (PC1) is translated into paleoflow directions (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 (Fig. 4A-D). 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 is used to derive flow sense. This shows that the single coarse-grained interval in SN17-02B consists of three individual pulses with a distinct origin (Fig. 4). Grain-size data supports this interpretation, showing a new graded sequence in each pulse of which the base is coarser than the top of the previous sequence (Fig. 3). The PC1 of pulse 1a indicates a flow coming from the gradual N lake slope, followed by pulse 1b originating from the steep slopes located NW of the core location. Similarly, the single turbidite pulse in SN17-06A likely originates from the slopes NE of the core location although imbrication in this core cannot be reliably determined due to a non-uniformly dipping basal plane (Fig. 3). The first turbidite pulses in the slope-proximal cores can thus be linked to the lake slopes nearest to the respective core site, indicating that combining paleomagnetic orientation of the cores and our assumptions on grain fabric is a reliable approach to reveal paleoflow directions.

EARTHQUAKE DOUBLET IDENTIFICATION

The 2007 turbidite in SN17-04A and SN17-09A contains two coarse-grained subdivisions, separated by a few cm of fine-grained diatomaceous sediment (Wils et al., 2021). These intervals show limited sorting variability (Fig. 3) and MAD intermediate between those obtained in the coarse-grained sediments below and background sediments (Fig. 2). This suggests gradual deposition from the body of the turbidity current during a waning flow, further supported by their decreasing D10 trend (~ 6 to $4\ \mu\text{m}$, Table S2). A delay is thus present between deposition of both coarse-grained intervals, which is shorter than the time required for all fine-grained material to settle (turbidite cap, $<4\ \mu\text{m}$). This would be in 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 km difference in distance to the core site resulted in an arrival delay in the order of minutes to hours for flow velocities of 0.2 to 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 as the successive sandy beds in both cores show similar flow direction (Fig. 4; mostly originating from the NE slopes in SN17-04A and W slopes in SN17-09A). The similar color and radiodensity signature of pulse 1d and 2c in SN17-09A additionally supports their common origin (Fig. 3). As 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 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 forms an amalgamated turbidite with a

stacked appearance triggered by both earthquakes in the doublet, of which the 2 hour 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 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 absence of a second external trigger. As such 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 prehistorical earthquake sequences in subaquatic settings around the world, which would significantly advance seismic hazard assessments.

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FIGURE CAPTIONS

Fig. 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
Padang, the region's capital. B: Bathymetry map of the lake (20 m contours) showing the
location of the four studied cores (SN17-02B, SN17-04A, SN17-06A and SN17-09A) and the
most important rivers. Fault trace of both segments involved in the 2007 earthquake doublet after
Sieh and Natawidjaja (2000), rupture propagation (colored arrows), epicenter location and focal
mechanisms after Nakano et al. (2010). Modified from Wils et al. (2021).

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

Fig. 3. μ CT scans and pictures of the 2007 seismo-turbidite in Lake Singkarak (see Fig. 2) with indication of grain-size parameters (mean, light blue and sorting, gray). White rectangles mark the μ CT-scanned sections. Turbidite pulses are indicated by colored rectangles and alphabetically named per coarse-grained interval in order of deposition. For SN17-02B, SN17-04A and SN17-06A, overview scans were used (resolution 15x15x15 μ m) while for the finer-grained SN17-09A, ROI scans (7x7x7 μ m) were required to achieve adequate grain segmentation.

Fig. 4. A-D: Lower-hemisphere stereoplots showing plunge and trend of strongly elongated grains derived from μ CT data analysis and measured with respect to the basal plane for each pulse in the 2007 seismo-turbidite for the four cores in Lake Singkarak (see Fig. 3). Each stereoplot, in the μ CT 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 Fig. 2). Considered grain sizes and total amount 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 the main orientation in each dataset (principal component PC1, red square) and indicate the flow direction (colored arrows). Flow sense is derived by considering the dominant imbrication as up-current dipping. E: Geographical context of the resulting flow directions at each of the core sites (see Fig. 1B). The dashed arrow for SN17-06A indicates an unlikely flow direction that cannot be ruled out with the available data.