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Seismites as new indicators of regional tectonism

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By linking paleoearthquakes and fault-zone rupture behavior with regional deformation, long-term seismite records can provide a fresh perspective for understanding regional tectonism.

Problematic sedimentary indicators of tectonism

Sharp increases in sediment accumulation rates and grain sizes around most steep mountain ranges, such as the Rocky Mountains, have been interpreted to result from intensive tectonic activity (Blackstone 1975). Using similar arguments, previous studies have inferred intensive tectonic activity in NE Tibet during the time interval ~4.5–1.7 Ma (Li et al. 1979; Zheng et al. 2000). However, these interpretations have been challenged by others who argue that the sedimentary evidence used to infer tectonism could be climatically induced (Molnar and England 1990; Peizhen et al. 2001).

Since erosion may be enhanced either by intense tectonic activity or by high-amplitude climate change, some form of independent evidence or sedimentary criteria is required to distinguish between the two alternatives. Seismite –sedimentary units preserved in subaqueous stratigraphic sequences that are caused by earthquake shaking (Seilacher 1969)– are potential indicators of regional tectonic activity. Here, a case study from the Qaidam Basin (NE Tibet) is used as an example to show the potential of this option (Lu et al. 2021).

Drilling for seismites in NE Tibet

The Qaidam Basin is the largest topographic depression in Tibet. It was formed by the ongoing India-Asia collision and bounded by the Altyn Tagh Fault on the west and the Kunlun Fault on the south (Tapponnier et al. 2001) (Fig. 1b). The late Cenozoic northeastward growth of Tibet, and the propagation of deformation along the Kunlun Fault, formed a series of NW-trending folds in the basin. One such fold is the Jianshan Anticline, which is linked to a shallow thrust that developed beneath the paleo-Qaidam lake floor since the Oligocene (Lu et al. 2021) (Fig. 1b). The crest of the anticline has been in a shallow lake environment since ~3.6 Ma, and finally dried up at ~1.6 Ma (Lu et al. 2015). Late Cenozoic regional deformation may have been recorded by the continuous lacustrine sedimentary sequence accumulated above the anticline.

A 723 m deep Core SG-1b (SG: Sino-German) was drilled on the crest of the Jianshan Anticline in 2011 (Fig. 1c). The core section consists of laminations, layered mud, massive mud, marl, ooids, and mud containing evaporites (Lu et al. 2020a). Four types of seismites have been identified in Core SG-1b. A 2 Myr long seismite record was recovered based on the upper 260 m (3.6–1.6 Ma) of the drill core (Lu et al. 2021).

Types of seismites

Type I: in situ soft-sediment deformations. These are observed within laminated (mm scale) and layered (cm scale) sediments, featured by layer-parallel displacements (Fig. 2a–b). They are formed in situ since no erosional base is observed. Gravitational instability (mechanism for overloading; Owen et al. 2011) and Kelvin-Helmholtz instability (mechanism for layer-parallel displacement; Lu et al. 2020b) are the most common driving mechanisms for soft-sediment deformations.

The layered and laminated sediments are not susceptible to gravitational instability (requires inverted density) due to their stable density structures. No soft-sediment deformations are observed beneath dense sand layers. Further, these deformations show no association with ooid layers (indicating strong marine waves) and tempestites (indicating storms), and are thus not triggered by strong waves or storms.

Similar to in situ soft-sediment deformations observed in tectonically active regions, such as the Dead Sea (Lu et al. 2020b) and California (Sims 1973), the deformations observed in the Qaidam drill core are interpreted as seismites. Earthquake-triggered Kelvin-Helmholtz instability is the most plausible mechanism for these deformations (Lu et al. 2021).

Type II: Micro-faults. These are characterized by millimeter- to-centimeter-scale displacements (Fig. 2c) and developed within layered and laminated sediments which have stable density structures. Also, no micro-faults are observed beneath sand layers. Thus, these micro-faults are unlikely to be induced by gravitational loading. In addition, the micro-faults are not confined to the edge of the drill core, and thus, are unlikely to be triggered by drilling disturbance.

Micro-faults are usually the result of brittle deformation induced by high strain rates,

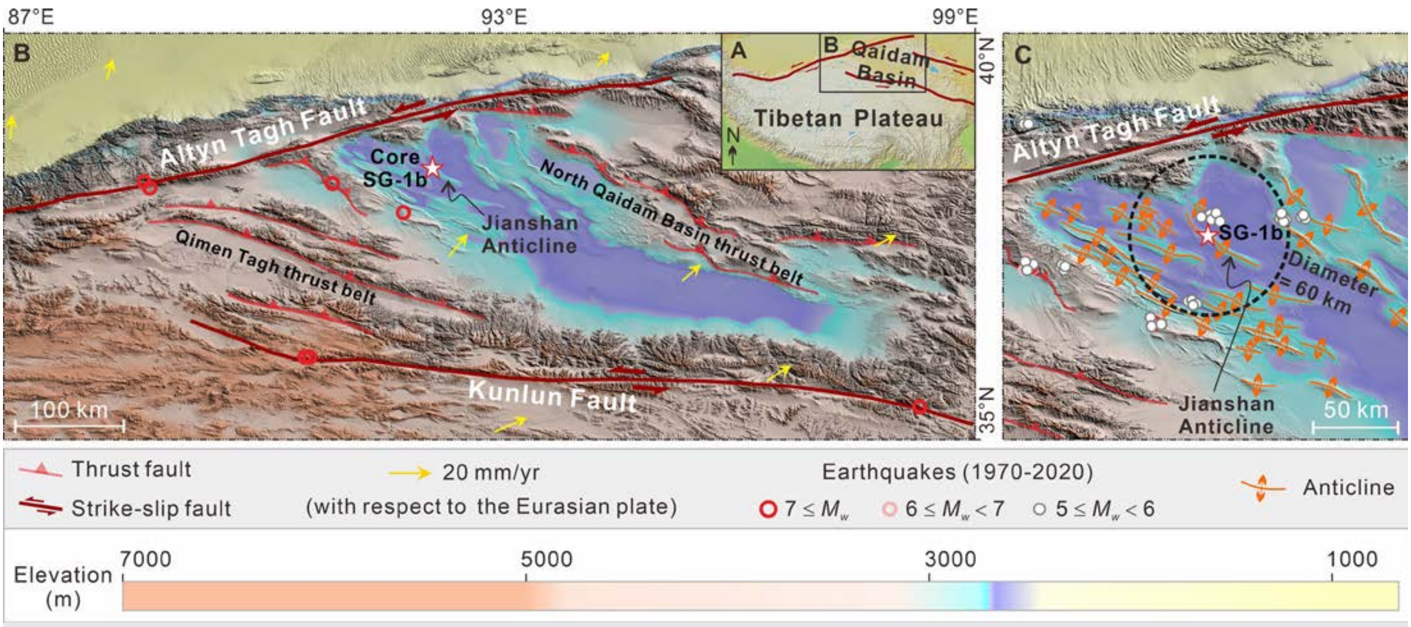

Figure 1: Geological setting of the study area (modified from Lu et al. 2021). **(A-B)** Location of Qaidam Basin and major faults. **(C)** Folds-thrusts system, drill site, and seismicity within the basin. Figure reused under the CC-BY-4.0 license.

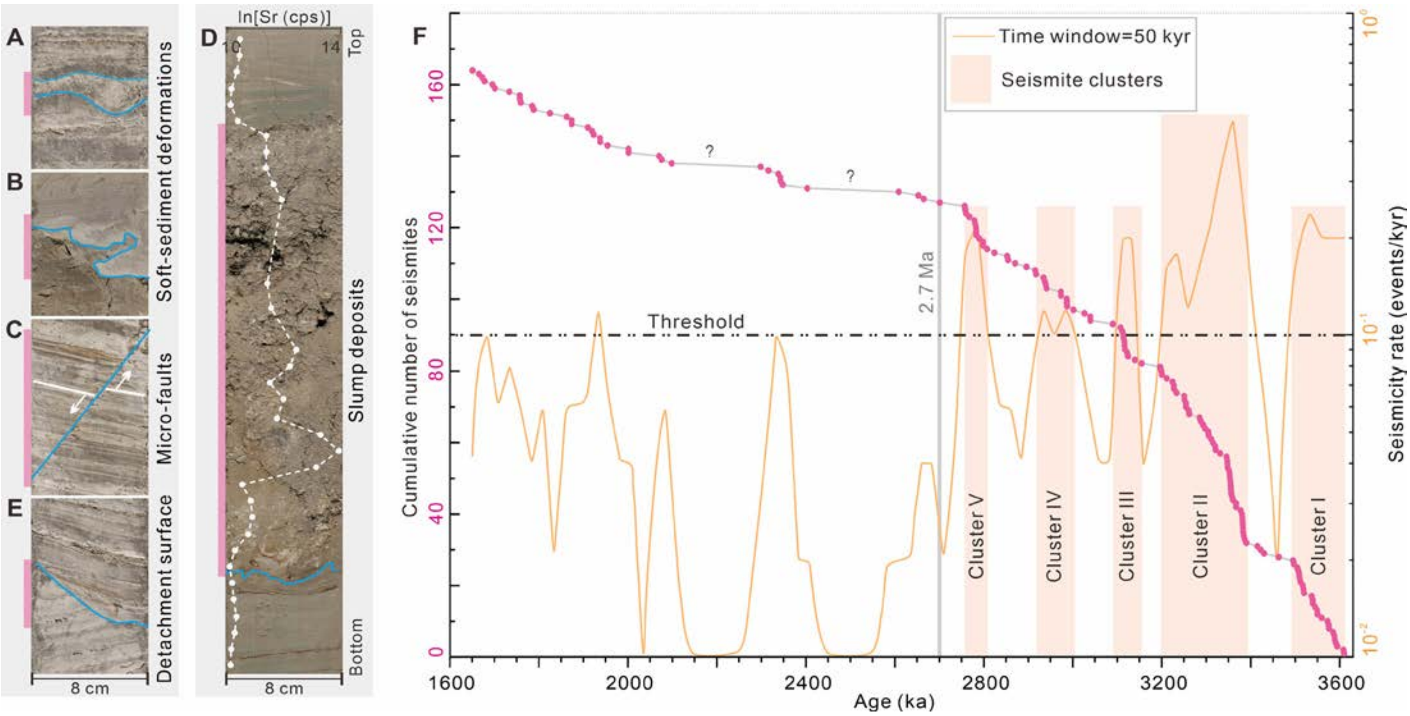

Figure 2: A 2 Myr long seismite record (modified from Lu et al. 2021). **(A-E)** Four types of seismites; **(A-B)** Soft-sediment deformations; **(C)** Micro-fault; **(D)** Slump deposits; **(E)** Detachment surface. Sr counts in **(D)** were measured using an XRF-core scanner, showing the variation in evaporite elements; cps: count per second. **(F)** A 2 Myr seismite record and distribution of five seismite clusters during the time interval 3.6–1.6 Ma. Figure reused under the CC-BY-4.0 license.

and are commonly triggered by seismic shaking (Seilacher 1969). Thus, these Qaidam micro-faults are interpreted as seismites.

Type III: Slump deposits. These are characterized by deformed laminations or mud layers with a high content of evaporite (as indicated by Sr content shown as a dashed white line in Fig. 2d). They are mainly sourced from the crest of the Jianshan Anticline. The crest of the anticline has very gentle slope gradients (<1°) and lacks coarse particles, thus making gravitational sliding or sediment overloading unlikely. Under such conditions, seismic shaking is the most plausible trigger for these slump deposits.

Type IV: Detachment surfaces. These are characterized by having had sharp contact with underlying sediment layers (Fig. 2e). These structures are interpreted as head scarps of earthquake-triggered slumps.

A 2 Myr long seismite record and implications

In total, 34 soft-sediment deformations, 79 layers with micro-faults, 41 slump horizons, and 10 detachments have been identified in Core SG-1b during the time interval 3.6–1.6 Ma. Since sedimentation rate between 2.7–2.1 Ma and coring rate during the 2.1–1.6 Ma period are relatively low, fewer earthquakes have been recorded in Core SG-1b. Thus, the seismite record of 2.7–1.6 Ma was not considered for further analysis. Moreover, the maximum seismicity rate during the 2.7–1.6 Ma period (~10^{-1} events/kyr) is used as a threshold for identifying earthquake clusters from the rest of the record (Fig. 2f). The seismite record during the time interval 3.6–2.7 Ma comprises five paleoearthquake clusters, with a mean recurrence rate of 6.8 kyr. In contrast, the mean recurrence rate within the clusters ranges between 4 and 6 kyrs.

Usually, earthquake moment magnitude (M_w) >5 (or shaking intensity >IV) is required to form a seismite (Lu et al. 2021). Two potential source regions of these recorded paleoearthquakes are discussed in the literature (Lu et al. 2021): one proximal source area within 60 km (5< M_w <6.6) and one distal source with distances >70 km (6.6< M_w <8). Applying these findings to the study site, the potential source could be either the proximal Jianshan Anticline and its surrounding folds-thrusts system, or more distal Kulun, and Altyn Tagh strike-slip faults. Large earthquakes occurred on the distal Kulun and Altyn Tagh strike-slip faults show a much shorter recurrence (~1 kyr; Van Der Woerd et al. 2002; Yuan et al. 2018) compared to those in Core SG-1b (6.8 kyr). Thus, the former is more likely the major source for the recorded paleoearthquakes at the SG-1b drill site. Therefore, the clustered seismite record during the 3.6–2.7 Ma period points to a clustered rupture behavior of the folds-thrusts system within the basin during that time interval, and thus indicates episodic deformation in the region. Such clustered rupture behavior further implies that the regional deformation is focused more in the folds-thrusts system within the basin during the earthquake clusters, while more deformation is concentrated along the strike-slip faults that bound the basin during the intervening quiescent periods (Lu et al. 2021).

Outlook

By applying the subaqueous paleoseismology method, we are able to discriminate tectonic-induced sedimentation from climate-forced deposits in a sedimentary sequence. This study case from NE Tibet highlights the great potential of using seismites to understand the history of regional seismo-tectonic deformation. The innovative method may also be suitable for similar tectonically active regions elsewhere in the world. Such research provides a fresh perspective for understanding regional tectonism by linking paleoseismic events and fault zone rupture behavior, with regional deformation, which can expand the ability of paleoseismology to understand regional deformation.

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