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Examples of fault steps controlling event migration in seismic swarms

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Summary

This study provides spatiotemporal constraints on seismicity within fault zones and identifies key links between fault step and event migration. We show that event distributions in seismic swarms can image stepping geometries reminiscent of relay zones commonly observed along fault zones. Earthquake migration can propagate across steps, indicating a transfer of deformation, but can be obstructed by others. Preliminary quantitative results show that whether a step transfers or blocks deformation depends on the separation between the bounding segments relative to the maximum magnitude of the events. These findings support the importance of understanding the role of internal fault geometry on seismicity and show that high accuracy event locations provide a critical understanding of seismicity.

Introduction

Previous studies investigating global seismicity and microseismic patterns often idealize faults as simple planar discontinuities. However, this simplification is not usually supported by outcrops studies showing that faults have complex geometries and content. The simplest and most common departure from a planar geometry includes partitioning the deformation onto stepping segments at relay zones (Figure 1) (Roche et al., 2021). In this study, we examine a series of examples of seismicity to establish how seismicity images fault steps and unravel the role of fault steps on the migration and distribution of events. To achieve our objectives, we investigate swarms of events migrating in pre-existing tectonic fault zones due to underground fluid migration. Here, we present observations from two swarms observed in two areas, the Kagoshima and the Oklahoma datasets, attributed to natural fluid migrations and large-scale wastewater disposal, respectively.

Method

In both datasets, seismicity data are based on catalogues of events, including the hypocenter location, time, and magnitude, published in previous studies (i.e. Schoenball and Ellsworth 2017 and Yoshida and Hasegawa 2021). The events have been located using various methods (i.e. Double-Difference, GrowClust algorithm, waveform cross-correlation), producing high-resolution images of seismicity, with horizontal and vertical relative errors of c. 50-100 m. The readers are referred to the associated publications for more details on the geological settings and earthquake location procedures.

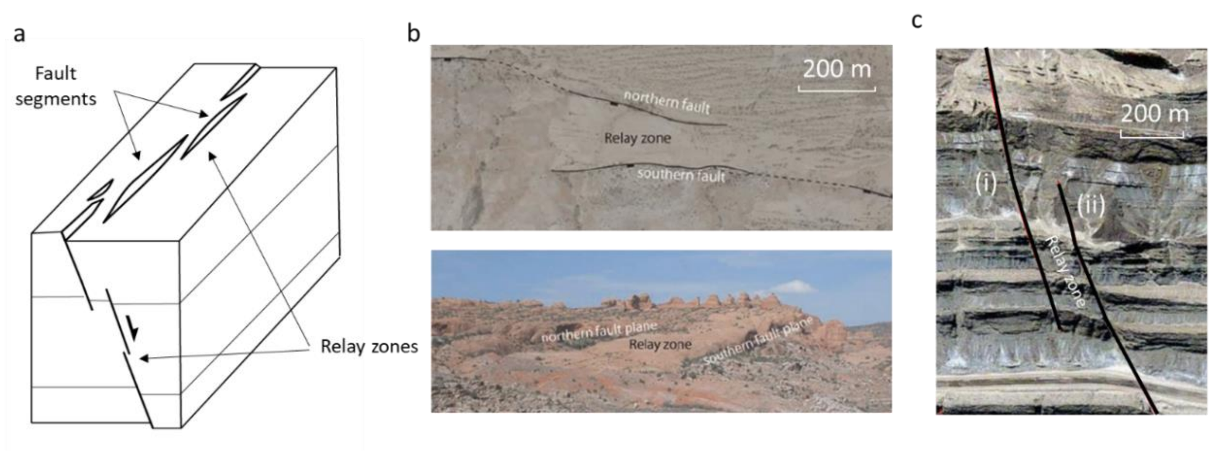

Figure 1: (a) Illustration of a segmented normal fault with segments stepping along the fault strike and down the fault dip at relay zones. (b) Example of a relay zone along the fault strike from Arches National Park, Utah, modified from Rotevatn et al., 2007. (c) Example of a relay zone down the fault dip from the Buzi range, Pakistan.

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Event migration at fault steps

In the two studied swarms, except for some outliers, events are distributed within two distinctive fault surfaces, which are kilometers long, while the seismicity is contained within a zone that is tens of meters wide in the fault-surface-normal direction (Figure 2). In addition, these two fault surfaces form a step along the fault strike, with geometries reminiscent of left- and right-lateral cylindrical relay zones according to the classification from Camanni et al., (2019). The perpendicular distance between the bounding segments is referred to as the separation. The following section describes the control of these fault steps on the spatiotemporal migration and clustering of the events, with results based on observation in 3D and magnitude-time diagrams.

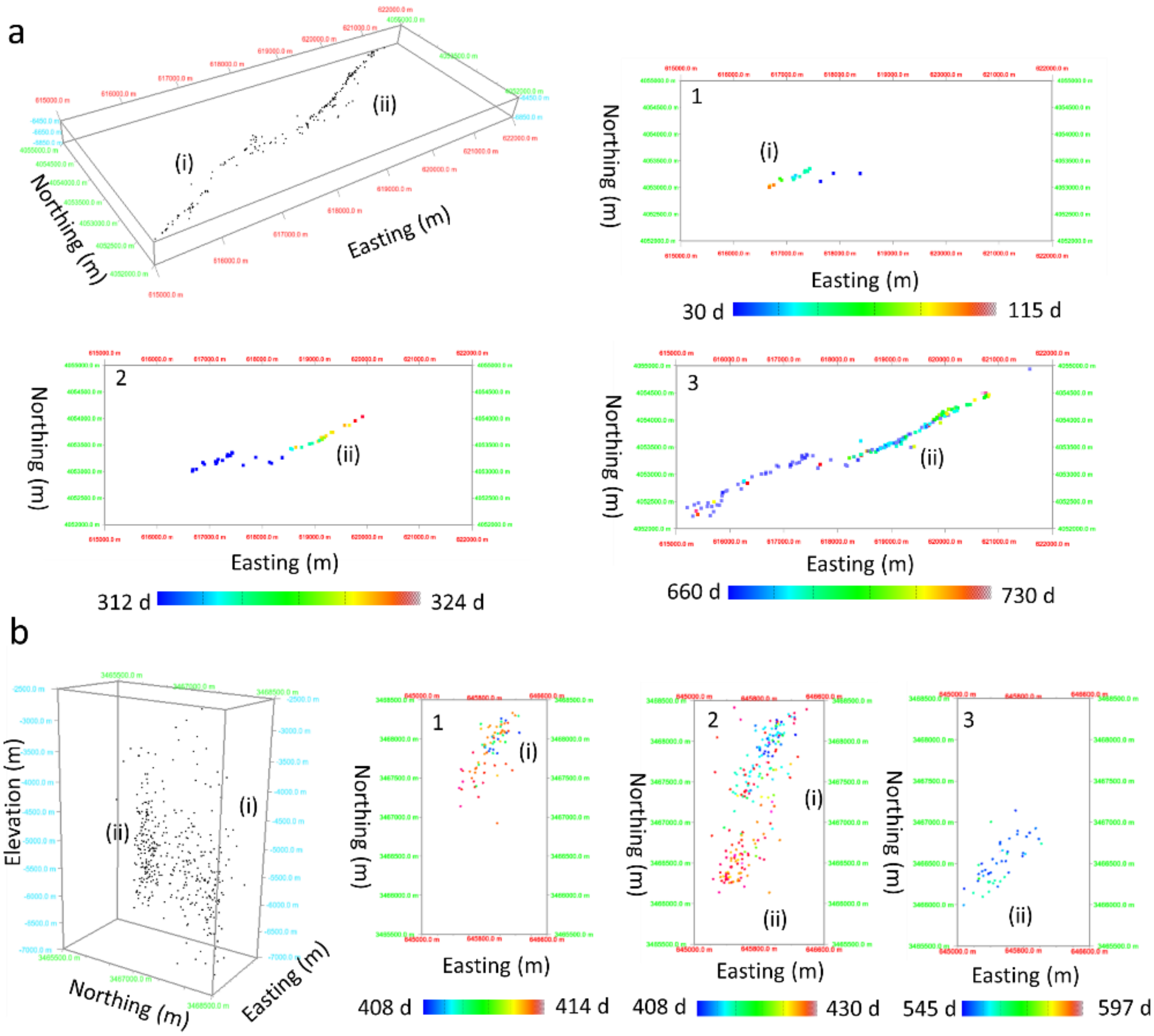

Figure 2: (a) Swarm showing a step blocking deformation associated with multiple sequences from the Oklahoma dataset. (b) Swarm showing a step transferring deformation from the Kagoshima dataset. (a-b) The entire clusters are represented with events in black in 3D views. The event migrations are represented with events coloured as a function of times (see legend) in map views representing three different stages of growth (labels 1-3). (i-ii): Labels of the segments.

Event migration at fault steps

Observations on two example swarms

The swarm in Figure 2a is from the Oklahoma dataset and shows a 250 m right-lateral step. Seismicity starts mainly on the western segment (i) with a westward migration away from the step for about 50 days (Stage 1 in Figure 2a). Then, the eastern segment (ii) is activated 200 days later, with an eastward migration, again away from the step. After this, an unconnected portion of the western segment becomes active. Finally, many events occur on segment (ii) during Stage 3, with an eastward migration. Throughout all these sequences, the step mostly remains devoid of events. Only during the final stage of the sequences do a few events occur between the bounding segments (i) and (ii).

The previous example shows how the absence of deformation transfer across a step can influence event migration on active bounding segments. By contrast, the swarm in Figure 2b from the Kagoshima Bay shows a step that transfers deformation during the migration of events. In this case, despite the apparent noise in the distribution of the events, we recognize a c. 300 m left-lateral step ((i) and (ii) in Figure 2b). Seismicity starts on segment (i) with a southward migration (Stage 1 in Figure 2b). Then, rather than being halted by the step, like in the previous example, the events migrate through the step, activating segment (ii) (Stage 2 in Figure 2b). After the period of growth, both segments are active, with decreasing seismicity rate. Finally, after 60 days of relative quiescence, the segment (ii) is reactivated, but, contrary to the former sequence, the step seems to halt the lateral extent of the cloud in this later sequence (Stage 3 in Figure 2b).

The observations above illustrate how event migration is linked to fault segmentation and depends on whether deformation occurs through a step. In the example from Kagoshima bay, we also observe that the same step can block or transfer deformation at different times. Specifically, the step first transfers deformation during the earlier sequence with a maximum magnitude of 3 and then blocks deformation during the later sequence with a maximum magnitude of 2. These observations suggest that both magnitudes and separations are key parameters controlling the transfer of deformation at a step. Wesnousky (2006) proposed a similar control for large earthquakes, i.e. magnitudes between 6.1 and 7.9, and large steps, i.e. separations between 1 km and 40 km, with a limiting dimension of step (3–4 km) above which earthquake ruptures do not propagate and below which rupture propagation ceases only c. 40% of the time. Combining these observations, we suggest that steps blocking deformation tend to have larger separation to magnitude ratios than steps transferring deformation. Although these are preliminary results, we anticipate that better defining the relationship between the transfer of deformation, magnitude and separation through scale could provide a new basis for assessing the seismicity of reactivated faults.

Conclusions and future works

Observational data provided in this study supports the influence of fault segmentation on event migration and distribution, particularly the role of large steps in halting seismicity. Our study highlights the requirement to integrate more realistic fault geometries into ongoing analyses, in order to improve our understanding of natural or induced seismicity. In the future, we will progress our quantitative analysis of seismicity case studies, including those from volcanic areas and fluid injections operations, with particular emphasis on the development of associated predictive tools. In addition, we will investigate event migration in 3D and key processes involved in the control of segmentation on seismicity.

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