Imprint of the continental strike-slip fault geometrical structure in geophysical data

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Key Points

1. Chu et al. [2021] interpret high-frequency in earthquake spectrum as fault geometry signature
2. Independent observations from various earthquake research fields hint at spatial structure of strike-slip faults.
3. The spatial structure of strike-slip fault should be included in earthquake rupture scenario.

Abstract

The geometry of continental fault systems, and more specifically the spatial organization of faults, is a central topic to understand how earthquake ruptures start, propagate, and stop. By exploring the origin of unexpected high frequency emission during earthquakes, *Chu et al.* [2021] (https://doi.org/10.1029/2021GL095271) show that the most likely source for these emissions is the interaction between nearby misaligned faults. Thus, this result emphasizes the discrete nature of the strike-slip fault segments at seismogenic crustal scale, adding to a set of evidence for spatially structured fault systems drawn from independent observations in geophysics and geology. This observation should bring some new constrains to earthquake rupture scenario by limiting the range of possible ruptures included in these models.

Plain language summary

The geometry of faults at depth remains difficult to document, although it exerts a critical influence on the way earthquakes propagate along faults. In the case of continental strike-slip faults, a long-lasting discussion questions if the ground surface complexity is matched by similar complexity at depth, or conversely, if the strike-slip geometry at depth is smoother. In this paper *Chu et al.* [2021] (https://doi.org/10.1029/2021GL095271) bring additional evidence of the fault structural complexity. Such evidence could be related to other independent observations pointing in a similar direction of the existence of a specific spatial scaling for strike-slip fault structures. Such scaling should be considered in the development of seismic hazard models.

Geometrical structures of continental faults are a long-lasting topic of interest in the earthquake community. Significance of the complex fault geometry at the surface has often been questioned in favor of a smoother geometry at depth [*Schmittbuhl et al.*, 2006; *Sylvester*, 1988]. Part of this discussion is driven by our limited capacities to image the fault geometry at depth, combined with the medium to low resolution of earthquake source models, making detail of fault geometry unresolvable. On the other hand, however, it has long be recognized that fault discontinuities, especially in strike-slip fault systems, are playing a key role in the initiation and ending of an earthquake rupture [*King*, 1986], or possibly in supershear transition for rupture velocity [*Vallee et al.*, 2008]. In fact, taking advantage of a denser instrumental coverage, it has been shown for recent earthquakes in California that fault structure does matter when it comes to rupture propagation and that fault complexity as observed at the surface is, at least at kilometric scale, reflecting similar, although not necessarily perfectly identical, complexity at depth [*Ruhl et al.*, 2021; *Wang et al.*, 2020; *Wei et al.*, 2011]. Attempts to introduce fault structure into hazard assessment rupture scenario exist that emphasize the importance of the fault structure in the range of possible earthquake magnitudes generated by such models [*Field et al.*, 2014]. The rational to decide on a relevant

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spatial scale to characterize geometrical fault complexity in such models, however, remains usually subjective rather than based on any strong physical knowledge.

In the case of continental faults, and more especially for strike-slip faults, which are the type of faults addressed in the work of *Chu et al.* [2021], a strong constraint exists in term of the down-dip extent of the seismogenic faults, which is limited by the brittle-ductile transition in the crust. The depth of this transition, about 15 ± 5 km, is quite homogeneous across all continental settings, although small regional variations exist depending on the age of the crust [*Klinger*, 2010]. This limit is usually highlighted by the absence of background seismicity below the transitional depth. Conversely, the lateral scaling of fault geometrical heterogeneity is more difficult to assess. It has been suggested that lateral segmentation of faults might be totally independent of physical properties of the brittle crust and would obey some fractal distribution [*Turcotte*, 1989] or would relate to deterministic stress concentrations controlling lateral extent of fault segments [*Manighetti et al.*, 2015]. On the other hand, combining field observations of fault traces and maximum depth of the ambient seismicity, *Bilham and Williams* [1985] had suggested that for southern California, strike-slip fault should be laterally segmented and that this segmentation would relate to the thickness of the brittle crust. Similar scaling has also been suggested independently by *Gusev* [1983], based on the existence of a bump in the amplitude of earthquake spectrum that he correlated with geometrical scaling of faults, with a scale on the order of 10 to 20 km.

Chu et al. [2021] in their work question the origin of the enhancement of the high-frequency part of the seismic waves spectrum for earthquakes. This unexpected excess of high-frequency in fact affects the measurement of the corner frequency for earthquakes, which in turn affects the estimate of the static stress drop, a fundamental metric of seismology nearly invariant by magnitude [*Allmann and Shearer*, 2009; *Shearer et al.*, 2006]. More specifically *Chu et al.* [2021] review several possible source mechanisms for this excess of high-frequencies, all pertaining to some aspects of the fault geometry, which include the roughness of the fault surface [*Dunham et al.*, 2011], the creation and activation of a damage zone directly surrounding the rupture along the main fault [*Okubo et al.*, 2019], and the interaction between several close-by fault sections [*Tsai et al.*, 2021]. To test further the latter possibility, in their paper *Chu et al.* [2021] propose to quantify the fault system geometrical complexity, as such complexity is the primary reason to have several active faults clustered in the same area. Hence, *Chu et al.* [2021] have developed two new metrics to measure fault network complexity, based on the surface fault traces. The two characteristics of a fault network that are considered in these new metrics are respectively the co-linearity and the density of independent fault sections in the area under consideration. These two parameters allow addressing a broad range of fault configurations, with complexity possibly acting on one or the other, or both metrics. The co-linearity metric, called by *Chu et al.* [2021] the misalignment ratio, is the ratio between the cumulative fault length when faults are projected in a direction that would minimize this length and the cumulative fault length when faults are projected in a direction that would maximize this length. This ratio ranges between 0 for a set of perfectly parallel faults and tends towards an upward limit value of 1 for a large number of faults homogeneously distributed in azimuth. The density metric is considering the ratio between the cumulative fault length for the area considered and the length of the perimeter for the same area. This minimum value of this ratio is 0.5 and it is unbounded upward. Although these metrics are dependent on the resolution of the data considered, as well as on the area considered, the authors show that in fact for a region larger than a minimal size (~10 km in perimeter length), which would be rather homogeneous in fault pattern, both ratios are stable and do not change abruptly for small changes in the definition of the area of concern. Thus, these two metrics appear to not be very sensitive to change in scale.

To test the new metrics, *Chu et al.* [2021] have focused on the Southern California region where both an homogeneous fault map and seismological catalogues are available. This region includes three different styles of faulting with different strain rates: The Ridgecrest/Coso area. This area includes the Ridgecrest earthquake series in 2019, which was particularly notorious because it activated a set of several faults almost perpendicular to each other's [*Ross et al.*, 2019]. The southeastern fault zone includes the continuation of the main San Andreas Fault system and the less active East California Shear zone. The last zone includes the Transverse Ranges fault zone, which is mostly formed by thrust faults. Eventually the authors have defined 41 polygons for which they could both measure the two metrics, the misalignment ratio and the density ratio, and have a sufficiently large ensemble of earthquakes for a statistical assessment of the stress drop.

Examination of the evolution of the static stress drop for different values of the metrics shows first that the static stress drop, i.e. the generation of high-frequencies, increases together with the misalignment ratio, confirming that change of orientation for nearby fault is triggering high frequency. Indirectly, in fact, it also confirms that sharp azimuthal changes between successive fault sections, visible at the ground surface from fault maps, correspond to changes in fault azimuth at depth, although not necessarily absolutely identical, and is not related only to some free surface effect, while the down-dip part of the fault would be significantly smoother. On the other hand, comparative variation of the static stress drop in relation to fault misalignment and density shows that fault misalignment is the main factor when it comes to generate additional high frequency in earthquake spectrum.

Thus, this observation emphasizes the existence of the geometrical structure of a fault system formed by successive nearby fault segments separated by jogs. This new observation underlines the assumption that crustal faults, and more specifically strike-slip faults, have geometrical structures at specific scale. In fact, other independent observations (Fig. 1) are hinting at the same fault pattern from different perspectives: The study of source time function for large shallow crustal earthquakes shows that unlike dip-slip earthquakes, strikes-slip earthquakes are characterized by series of sub-events, with the number of sub-events increasing monotonically with the magnitude of the event [*Danré et al.*, 2019; *Yin et al.*, 2020]. Sub-events are interpreted as reflecting the spatial complexity of the earthquake source, and the overall similarity in size between the successive sub-events suggests that they would correspond to individual fault segments of similar size rupturing in cascade during large composite earthquakes. Systematic measurements of the lateral extent for these sub-events shows that their length is limited to about 20 km [*Klinger*, 2010]. On the other hand, analyses of ground surface rupture patterns for large continental strike-slip earthquakes, either based on fieldwork investigations or remote sensing studies, have shown that surface ruptures also display characteristic spatial scaling. Large ground surface ruptures can in fact be split in several fault segments of similar size, about 15 ± 5 km. This observation seems to hold independently of the specific local conditions of the earthquake. It has been proposed that the principal parameter controlling the lateral extent of strike-slip fault segment would be the thickness of the brittle crust [*Klinger*, 2010]. Analogue model experiments [*Lefevre et al.*, 2020] as well as numerical models [*Jiao et al.*, 2021] were used to test further this assumption and to demonstrate that a linear relation between the average lateral extent of fault structures and the thickness of the brittle material is observed for a wide range of thickness and that such relation seems to hold beyond only geomaterials [*Cambonie et al.*, 2019]. Thus, *Chu et al.* [2021] add to a set of independent observations that points to the existence of a permanent specific scaling of the strike slip fault segments consistent with the thickness of the crust (Fig. 1), and likely independent of the fault maturity [*Manighetti et al.*, 2021].

The existence of a typical size for the lateral extent of strike-slip fault segments could have significant implication for our understanding of strike-slip fault structure and the way such structures are implemented into seismic hazard assessment models. Indeed, as such model cannot address the full range of magnitude in a continuous manner, there is some need to define a minimum size of earthquake source to consider. For example, the UCERF3 model for California requires a rupture length equal to the local thickness of the crust as the minimum rupture length for a discrete earthquake [*Field et al.*, 2014]. Any larger rupture is a combination of several of such segments, including the possibility of involving only one half of a segment. Any smaller earthquake is considered as part of the background seismicity and is not directly tightened to a specific fault. These choices, so far, do not rely on any clearly identified physical processes, although they are consistent with the idea that there is a direct relation between fault structure and thickness of the seismogenic crust. Hence, an important topic of research in the coming years would be to confirm the specific spatial scaling of fault segments for continental fault, and not only for strike-slip faults, but also for dip-slip faults. Indeed, providing unambiguous physical basis to sustain the spatial structuration of continental faults, as indirectly shown by *Chu et al.* [2021], will be key. On the other hand it is also important, especially for dip slip faults, not to overlook the existence of inherited tectonics that might strongly imprint the current active structures [*Vallage et al.*, 2016; *Villani et al.*, 2018] beyond first-order geometrical scaling relationships. Ideally, more fault structure should be included in earthquake rupture scenario to constrain the range of possible ruptures using earthquake physics criteria and, thus, to improve seismic hazard assessment.

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Open Research:
No data was used.

Caption

Figure 1: Schematic view of a strike-slip rupture including 3 sub-events. Interactions between nearby fault segments with different azimuth are generating additional high-frequencies. Independent evidence of consistent segmentation scaling are also found in surface-slip distribution, kinematic inversion results, source time function, and surface rupture geometry.

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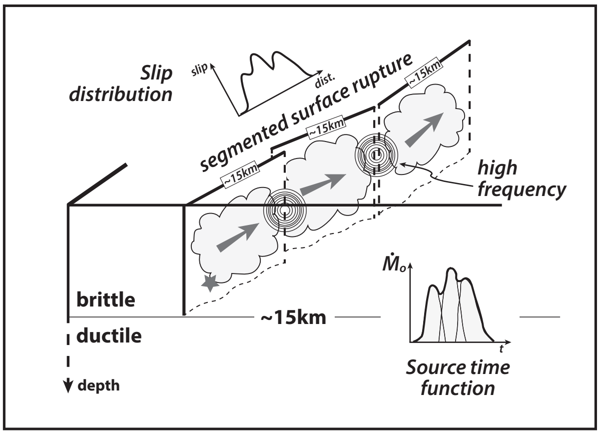
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