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Dual control of fault intersections on stop-start rupture in the 2016 Central Italy seismic sequence

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ABSTRACT

Large continental earthquakes necessarily involve failure of multiple faults or segments. But these same critically-stressed systems sometimes fail in drawn-out sequences of smaller earthquakes over days or years instead. These two modes of failure have vastly different implications for seismic hazard and it is not known why fault systems sometimes fail in one mode or the other, or what controls the termination and reinitiation of slip in protracted seismic sequences. A paucity of modern observations of seismic sequences has hampered our understanding to-date, but a series of three $M_w > 6$ earthquakes from August to November 2016 in Central Italy represents a uniquely well-observed example. Here we exploit a wealth of geodetic, seismological and field data to understand the spatio-temporal evolution of the sequence. Our results suggest that intersections between major and subsidiary faults controlled the extent and termination of rupture in each event in the sequence, and that fluid diffusion, channelled along these same fault intersections, may have also determined the timing of rupture reinitiation. This dual control of subsurface structure on the stop-start rupture in seismic sequences may be common; future efforts should focus on investigating its prevalence.

1. Introduction

In regions of distributed continental faulting, networks of active faults are commonly segmented on length scales of 10–25 km, approximately equal to the seismogenic thickness of the Earth's crust (Scholz, 1997; Stock and Smith, 2000; Klinger, 2010). This intrinsic maximum fault size limits the magnitude of continental earthquakes that rupture a single fault or segment to $<M_w \sim 6$–7 (Pacheco et al., 1992; Triep and Sykes, 1997), depending on local seismogenic thickness and fault geometry. Therefore, large continental earthquakes above this threshold (Scholz, 1997) such as the 2010 M7.2 El Mayor–Cucapah, Mexico, 2016 M7.8 Kaikoura, New Zealand, and 1980 M6.9 Irpinia, Italy events (Wei et al., 2011; Hamling et al., 2017; Westaway and Jackson, 1987) necessarily involve failure of multiple faults or segments. Multi-fault failure in seismic sequences, spanning a longer period of hours to years, is also common, with static stress transfer invoked as the major cause for this spatio-temporal clustering of large earthquakes within a small fraction of their estimated recurrence intervals (e.g. Hubert et al., 1996; King and Cocco, 2001; Wedmore et al., 2017).

Both large earthquakes and seismic sequences require that all component faults are near-critically stressed, a condition that is thought likely to occur commonly in nature through stress-synchronisation of faults (Scholz, 2010). In addition, recent work suggests that as in seismic sequences, the final magnitude of a multi-fault earthquake cannot be predicted from the initial rupture process (Wei et al., 2011). This similarity in initial conditions means that multi-fault earthquakes and seismic sequences begin in the same way and differ according to when rupture *stops:* ei-

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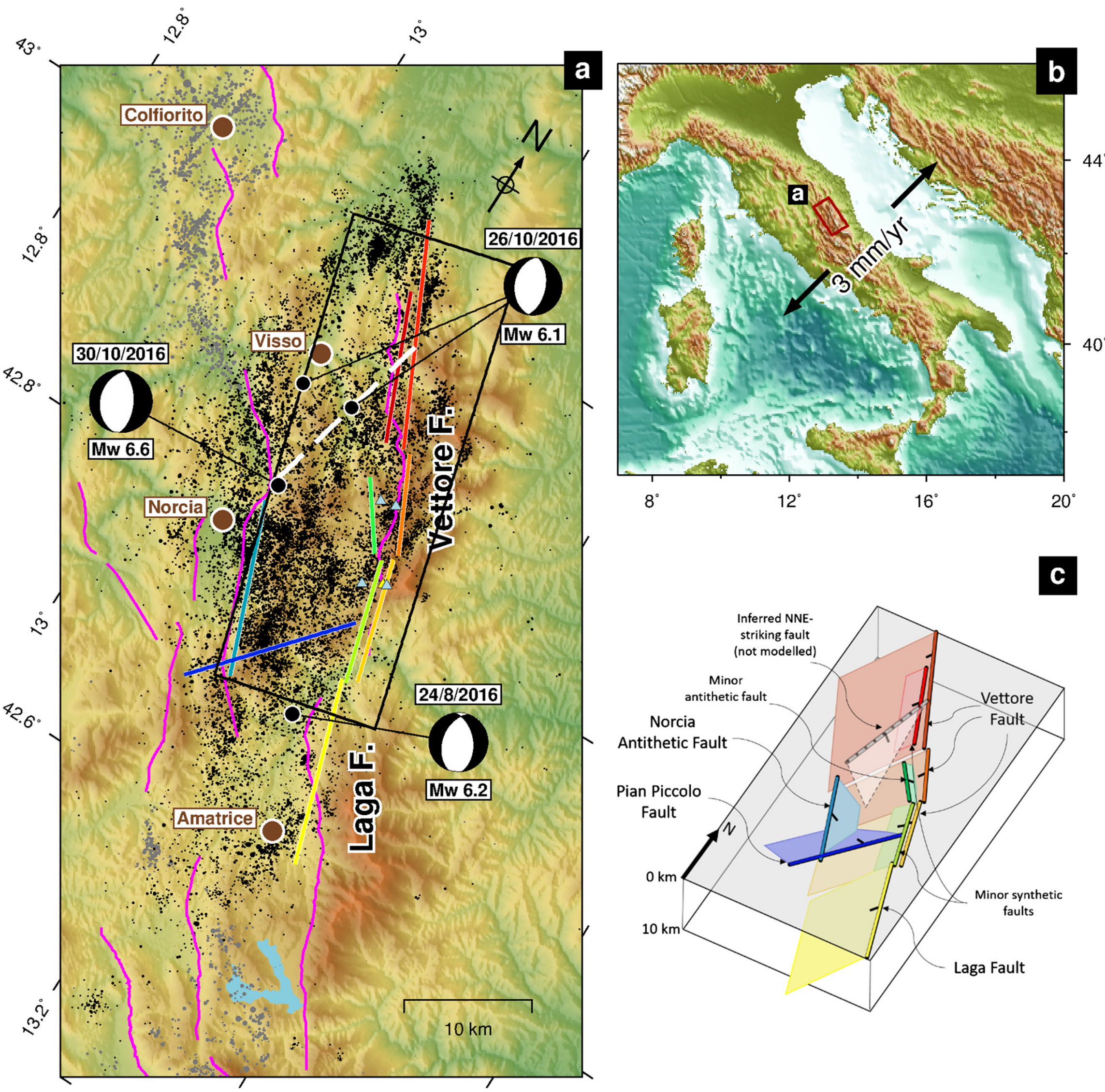

Fig. 1. Overview of epicentral region and fault geometry used in this study. (a) Regional tectonic map, showing mapped active normal faults (magenta, modified from Roberts and Michetti, 2004), up-dip surface projection of model faults displayed in Figs. 6–9 (coloured to match (c) and Figs. 3, 4 and 6), and bodywave focal mechanisms for each earthquake (see Fig. 2). White dashed line shows inferred east-dipping fault from Fig. 7, and relocated aftershocks from Chiaraluce et al. (2017) are shown in black. Locations of short-baseline GNSS instruments are shown by blue triangles. Black box shows extent of Fig. 3c. (b) Regional map showing the location of (a) and direction of regional crustal extension. (c) 3D cartoon of model fault geometry adopted in this study. Thick coloured lines show the surface projection of each fault and correspond to the coloured faults in (a) and Figs. 3, 4 and 6. (For interpretation of the colours in this figure and other figures, the reader is referred to the web version of this article.)

ther dynamic and static stress transfer cause cascading failure of multiple critically-stressed faults or rupture is arrested before all these faults have failed. In the latter case the *start* of rupture in subsequent subevents determines the temporal evolution of the seismic sequence. Large earthquakes and seismic sequences have vastly different implications for seismic hazard: high hazard in a single event, or moderate hazard spanning years or potentially decades. But our understanding of what controls whether multi-fault rupture occurs over days to years or in seconds, and of what controls the spatio-temporal evolution of seismic sequences, has been severely limited by a paucity of high-resolution observations of modern seismic sequences.

Combined analysis of geodetic and seismological data can image stop-start rupture behaviour and address these questions, by disentangling the spatial pattern and temporal evolution of slip in seismic sequences at high resolution. A sequence of 3 $M_w > 6$ earthquakes from August to November 2016 in the Central Apennine mountains, Italy (Fig. 1) presents a rare chance to investigate a seismic sequence with modern datasets and here we exploit seismological and field observations, as well as geodetic data, to image the kinematics of the sequence, and to understand structural and dynamic controls on its evolution. Our results suggest that structural complexity, namely the intersections between two sets of oblique faults, may have played an important dual role in the Central Italy seismic sequence: first by limiting the extent of individual ruptures and second by channelling fluid flow and controlling the timing of subsequent failure throughout the sequence.

2. Seismological constraint on earthquake source mechanisms

The Central Italy seismic sequence started with an $M \sim 6$ earthquake on the 24th August 2016, and was followed by tens of thousands of aftershocks, including two large $M > 6$ events on the 26th and 30th October (Chiaraluce et al., 2017, Fig. 1). We refer to these three major earthquakes as the Amatrice, Visso and Norcia events respectively. The seismic sequence continued into 2017, with several earthquakes $M < 5.7$ on January 18th, but here we focus on the three largest events only.