Conversing Faults: The 2019 Ridgecrest Earthquake

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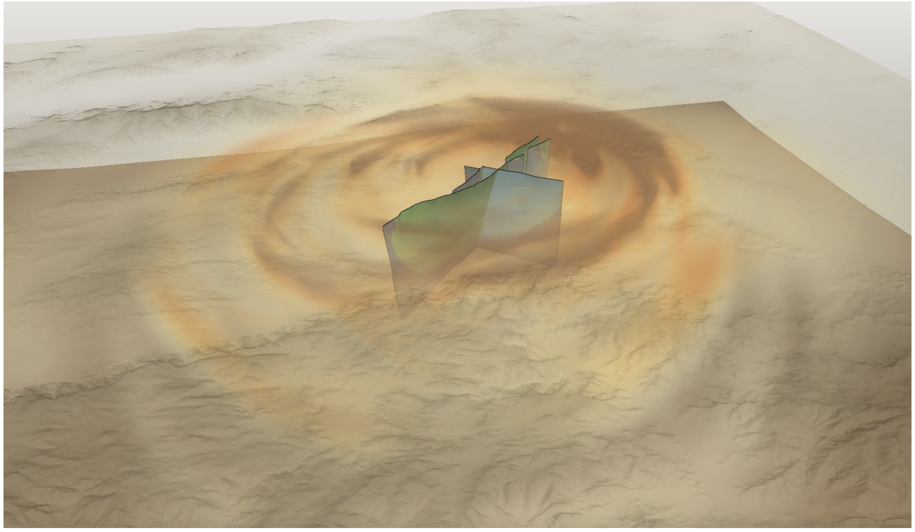

Fig. 1. Volume rendering of seismic waves

The 2019 Ridgecrest earthquakes occurred in a complex system of fault lines in the Mojave desert. Separated by 34 hours, the earthquakes were caused by ruptures in separate but nearby faults. In this study of the geophysical processes underlying these events the surface, known faults and the volumetric subsurface are modeled on HPC systems. Visualization techniques are used to analyze the simulation results in their three-dimensional context.

CCS Concepts: • **Human-centered computing** → **Scientific visualization**.

Additional Key Words and Phrases: Earthquake simulation

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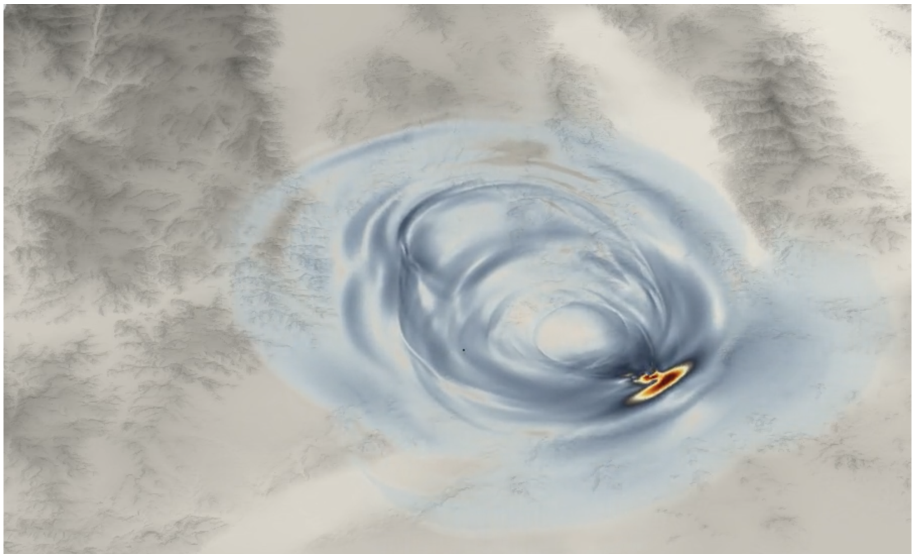

Fig. 2. Aerial view of the seismic shock waves of the 2019 Ridgecrest Earthquake's mainfault rupture.

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1 INTRODUCTION

July 4, 2019. The sun rises over California's Mojave Desert. Suddenly, a Magnitude 6.4 earthquake unzips several complex fault lines of the Eastern California Shear Zone and shakes Southern California. Fast forward to 34 hours later, while aftershocks are still reverberating, a magnitude 7.1 earthquake breaks the same fault system, which millions feel, not just in California but far across Arizona, Nevada, and even Baja California, Mexico.

The Ridgecrest earthquakes are the biggest earthquakes to hit California in more than 20 years, with aftermaths of extensive structural damage, power outages, and injuries (e.g., [4]). Understanding the dynamics of multi-fault ruptures is important because these types of earthquakes are typically more powerful than those that occur on a single fault, as illustrated by the deadly Turkey earthquake doublet earlier this year [2].

This Ridgecrest sequence is specifically puzzling - why the 34-hour gap between what we now know was a foreshock and the larger mainshock? Why didn't the foreshock immediately trigger the mainshock? How did these earthquakes "jump" to connect the same geological fault segments in different ways growing larger than expected? What is the connection between both quakes, did the earthquakes "communicate" in a dynamic sense? What role did silent, slow fault movements play?

To solve these riddles, a team of seismologists harness the power of supercomputers. Utilizing data-infused, physics-based models, they strive to decipher the Ridgecrest earthquakes in a recent Nature paper [5]. They can explain the outstandingly high-quality observations, ranging from mapped fractures by field geologists to global seismograms to detailed geodetic measurements taken from space in a unique model of both earthquakes. They find that both events are intricately linked, interacting across a fault system normally strong but revealed as dynamically weak during rapid seismic motion. Their findings break new ground in understanding the conditions fostering cascading earthquakes, their dynamics, and delays.

The visualizations presented in this study illuminate the seismic waves as they ripple through the Earth, generated by the "unzipping" of fault lines during the 2019 Ridgecrest earthquakes. The earthquake sequence cascaded across previously unknown sets of "antithetic" faults. The 3D visualization illustrates how the multiple faults can rupture in unison and complementary ways, defying prior assumptions of earthquake behavior.

Due to the large data size generated, more than 15 TB per simulation, the team of seismologists was unable to analyze in detail how seismic waves travel through their model and what their effects on ground shaking and earthquake dynamics are. They based their analysis on 2D outputs and post-processed secondary data products.

Due to a lack of in-situ observations, the models lack small-scale details. The 3D visualization now helps to identify where smaller-scale heterogeneities may improve physics-based synthetics. This is especially important for pushing the simulations to generate seismic waves at higher frequencies, which are dangerous to buildings and infrastructure.

The observational difficulties and the complexity of earthquake physics have rendered seismic hazard assessment largely empirical. By harnessing the power of supercomputers, observations, and physics, we can now glimpse the detailed patterns of a complex earthquake rupture sequence more clearly than ever seen before. Powerful visualization is crucial to allow for physics-based interpretation of the big data now becoming available from observations and computer simulations and have a transformative impact on future geohazard mitigation.

2 MULTI-FAULT RUPTURES

To construct the Ridgecrest earthquake sequence model, we employ innovative assimilation methods and fuse tectonic, structural, coseismic, and interseismic data to inform physics-based dynamic rupture simulations jointly. The three-dimensional, non-vertical fault system crisscrosses in near-orthogonal patterns. The intricate network comprises four geometrically complex fault segments, each slipping during either the foreshock or the mainshock or both earthquakes. The largest of these segments takes on a helical form, mirroring the deep-seated ductile shear localization seen in geological studies.

While geophysical and geological measurements at Earth’s surface can give us valuable information on earthquakes, the true action happens beneath the surface. Buried stresses within the Earth’s crust remain hidden from our direct view. Furthermore, our instrumental records of earthquakes barely scratch the surface of history, covering less than a century, while large earthquakes recur over hundreds, even thousands of years. Instrumental earthquake records are available for Southern California since 1932 and Northern California since 1967.

Here’s where the power of simulations shines - they enable us to visualize the unseen tectonic processes beneath us that drive earthquakes. This 3D animation shows the shifting fault shear stresses across the fault system during the two earthquakes. The first earthquake takes on the shape of a narrow slip pulse and causes a significant accumulation of shear stress on a separate fault segment, setting the stage for its 34h later reactivation during the mainshock. As we see in Figure 3, the magnitude 6.4 foreshock generates a pronounced stress shadow. Yet, the mainshock dives beneath this seismic shadow, and a persistent rupture pulse continues to tunnel deep, defying the halt and continuing a slow but steady regrowth towards the southeast.

To achieve this degree of realism, we nest this complex fault system within a 3-D Earth structure, merging a community velocity model with a two-dimensional stress model. This combination depicts the regional state of stress in Southern California’s upper crust. To account for local stress variations resulting from past seismic events, we incorporate a 3D model mapping the stress changes following major historical earthquakes - covering a timescale of roughly 1,400 years. Finally, we harmonize this heterogeneous ambient stress model with the linear depth dependence of effective vertical stress. This intricate combination of data and physics allows us to understand what happened and learn about the future of earthquake dynamics.

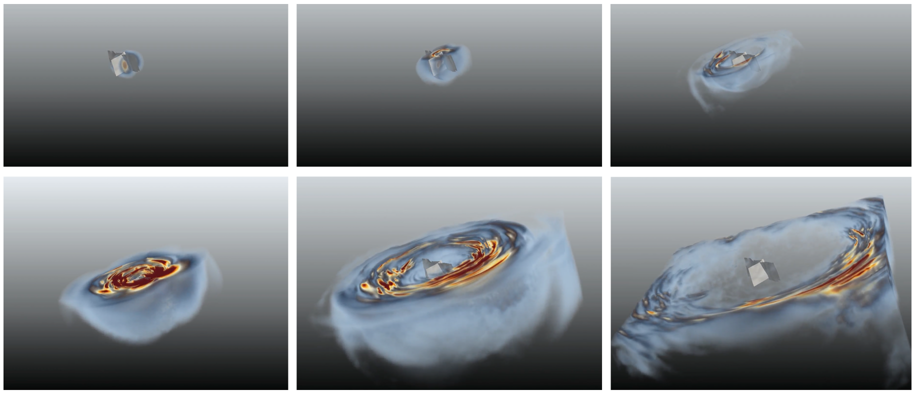

Fig. 3. Volume visualization of the seismic waves and dynamic earthquake rupture unzipping the complicated system of four intersecting geological faults during the 2019 Ridgecrest, California, earthquake sequence. The 15 TB simulation output uses a statically refined, unstructured tetrahedral mesh of 27,264,253 million tetrahedral elements. Top row: The magnitude 6.4 Searles Valley foreshock. Bottom row: 34 hours later, the magnitude 7.1 Ridgecrest mainshock. The differences in the seismic wavefields propagating through the complex 3D subsurface of Southern California are eminent, even though both earthquakes break the same fault system. For example, we observe clear directivity effects: similar to the Doppler effect of distorted sound when an ambulance is driving past, waves are stacking up, increasing shaking, in the respective forward directions of the earthquake ruptures. More importantly, the visualization helps us understand how the foreshock primes the fault system to create the larger mainshock.

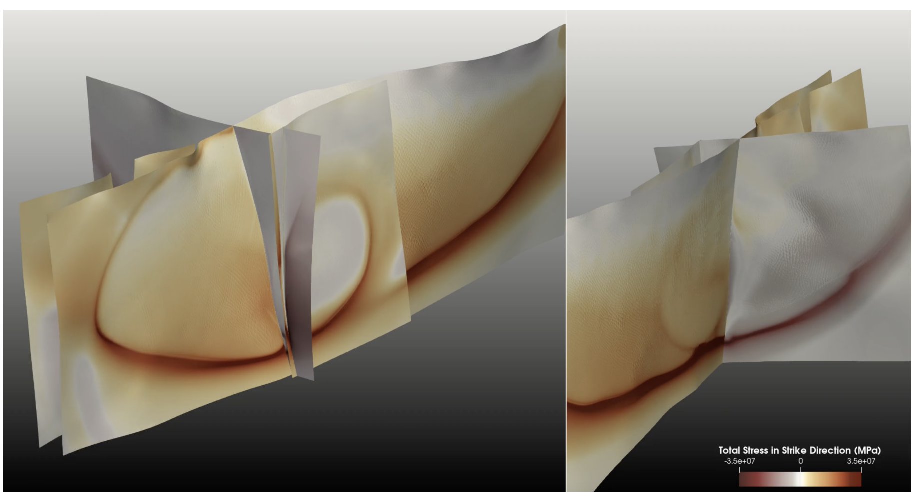

Fig. 4. Snapshots of a 3D animation showing the shifting fault shear stresses (in MPa) across the fault system during the two earthquakes. The first earthquake (left) takes on the shape of a narrow slip pulse, setting the stage for its 34 hour later reactivation during the mainshock (right) which dives beneath this seismic shadow.

The visualization data of the Ridgecrest Earthquakes consists of two main components: the fault system and the 3D seismic wavefield. The fault system data includes parameters such as slip distribution, rupture velocity, and stress drop, which play a significant role in governing the process of earthquake rupture. On the other hand, the 3D wavefield represents the computed seismic wave propagation throughout the simulation domain. This wavefield is expressed in terms of particle velocity at each point in the domain, considering three orthogonal directions.

To conduct this simulation, the open-source software SeisSol (www.seissol.org, [1, 3, 6]) was used. SeisSol utilizes the discontinuous Galerkin method with arbitrary high-order accuracy in space and time (ADER-DG). Moreover, it is optimized for efficient execution on high-performance computing systems, such as Frontera at TACC. Notably, it is recognized as one of the Characteristic Science Applications enabling next-generation science on the NSF Leadership-Class Computing Facility (LCCF).

The model domain was discretized in an unstructured tetrahedral mesh consisting of 27,264,253 million tetrahedral elements. For spatial adaptability, the mesh resolution was set to have an element edge length of 75 meters near all faults, gradually coarsening away from the fault surfaces. Additionally, the mesh was refined near the topography and set to 500-meter element edge lengths at the free surface. To simulate 200 seconds of physical time on this computational mesh, high-order basis functions of polynomial degree 4 were used. Running the simulation on 22,400 cores of the Frontera supercomputer typically required around 14.8 hours. Greg

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