Caltech/USGS Southern California Seismic Network (SCSN) and Southern California Earthquake Data Center (SCEDC): Data Availability for the 2019 Ridgecrest Sequence

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Abstract

The 2019 M_w 6.4 and M_w 7.1 Ridgecrest earthquake sequence occurred in the eastern California shear zone (ECSZ). The mainshock ruptured the Little Lake fault zone, and aftershocks extended from the Garlock fault in the south to the southern end of the 1872 M 7.5 Owens Valley earthquake rupture in the north. We present data from the Southern California Seismic Network (SCSN) and partner seismic networks recorded by the SCSN in the region. These time-series data and related products such as the SCSN earthquake picks and catalogs, available from the Southern California Earthquake Data Center, provide the most comprehensive seismic datasets for the 2019 Ridgecrest earthquake sequence.

Cite this article as Hauksson, E., C. Yoon, E. Yu, J. R. Andrews, M. Alvarez, R. Bhadha, and V. Thomas (2020). Caltech/USGS Southern California Seismic Network (SCSN) and Southern California Earthquake Data Center (SCEDC): Data Availability for the 2019 Ridgecrest Sequence, *Seismol. Res. Lett.* **XX**, 1–10, doi: 10.1785/0220190290.

Introduction

The 2019 M_w 6.4 and M_w 7.1 Ridgecrest earthquake sequence, located in the eastern California shear zone (ECSZ), occurred within the footprint of Southern California Seismic Network (SCSN). The permanent SCSN and partner stations recorded the complete sequence and provided an unprecedented and detailed picture of the seismic activity.

We present seismic data recorded by the California Institute of Technology & U.S. Geological Survey (Caltech/USGS) SCSN and distributed by the Southern California Earthquake Data Center (SCEDC) at Caltech. The SCSN provided real-time data to ShakeAlert (the USGS west-coast-wide earthquake early warning project) and reports on earthquake activity for the southern California region of the USGS Advanced National Seismic System (ANSS). The SCSN operates permanent stations under the CI network code. The SCSN and its collaborators also operate temporary stations under the ZY network code in southern California. The SCSN collaborates with other seismic networks, including CE, GS, NP, and PB in the Ridgecrest region (Table 1). These networks share real-time data feeds to provide the best possible earthquake coverage in the region.

The SCSN data provide a complete recording of the whole 2019 Ridgecrest sequence as well as the past seismicity in the region back to the 1930s (Hutton *et al.*, 2010; Hauksson *et al.*, 2019). The foreshocks, M_w 7.1 mainshock, and $>40,000$ aftershocks were all recorded by the permanent SCSN and partner stations (Fig. 1). In addition, three seismicity clusters that were located away from the main aftershock zone were recorded near the Garlock fault, in the Panamint Valley, and near the southern terminus of the 1872 **M** 7.5 Owens Valley earthquake rupture (Haddon *et al.*, 2016). These data were used to provide hypocenters, magnitudes, and moment tensors or focal mechanisms as well as ShakeMap in near-real time. The ShakeMap provides the geographical distribution of ground shaking. We show the time progression of the magnitude distribution for the SCSN catalog, which is being continuously improved with human postprocessing (Fig. 2). We also show the template-matching catalog of Ross *et al.* (2019) for the corresponding time period. These two catalogs have different resolutions, but both show clear foreshock activity and the expected temporal decay of aftershock activity (Fig. 2). The detailed field observations of the 2019 Ridgecrest earthquake sequence are provided by Brandenberg *et al.* (2019) and Kendrick *et al.* (2019).

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TABLE 1
Seismic Network Codes in the Ridgecrest Region and Operators

Network Code	Network Abbreviation	Status	Operator
CI	SCSN	Permanent	Caltech and USGS Pasadena
CE	CSMIP	Permanent	California Geological Survey
GS	USGS/ASL	Portable	USGS, Albuquerque Seismic Lab
NP	NSMP	Permanent	USGS, Moffett
PB	PBO	Permanent	UNAVCO
ZY	SCSN	Portable	USGS/Caltech and partners

Caltech, California Institute of Technology; NSMP, National Strong Motion Program; PBO, Plate Boundary Observatory; SCSN, Southern California Seismic Network; USGS, U.S. Geological Survey.

SCSN Configuration

The SCSN has operated stations in the Ridgecrest–Coso eastern California region since 1948. The first station was CI.CLC, and the network started growing in the late 1970s with a number of analog short-period stations. In the mid-1990s, the station CI.CLC and other stations were upgraded to digital recording and broadband sensors. The latest phase of upgrades and station additions has been sponsored by ShakeAlert (Kohler *et al.*, 2017).

The CI, CE, GS, and NP stations have three-component strong-motion sensors, and most have either a three-component broadband sensor or a single vertical-component short-period sensor. These sensor combinations allow high-fidelity recording of signals from the smallest to the largest earthquakes. Most waveforms are collected at 100 samples per second, but in some cases, strong-motion waveforms are available at 200 samples per second. The UNAVCO-operated PB stations are installed in boreholes and equipped with short-period sensors that provide important sensitivity for recording small events. These stations do not have strong-motion channels. In Figure 1, CI stations are shown as yellow triangles with a red outline, and stations from other networks are denoted as yellow triangles with a black outline.

Data Quality and Availability

The SCSN records data from more than 600 stations in southern California. The data quality of the SCSN recorded data meets the ANSS performance standards. The data communications and latency as well as waveform quality are routinely monitored by the SCSN data analysts using various tools to look for abnormal data. If abnormal data suggesting a problem with the field equipment are discovered, a field technician is dispatched to the field to carry out repairs. The broadband sensors are automatically checked daily and centered if needed. Manual comparison of broadband and strong-motion sensors has shown that the routinely updated metadata are accurate for nearly all sites (Li, Hauksson, and Andrews, 2019; Li, Hauksson, Heaton, *et al.*, 2019). The metadata for all of the SCSN recorded stations are stored in the Station Information System (SIS; Yu *et al.*, 2018). Dataless SEED and stationXML files are available from the SCEDC.

The ShakeMap in Figure 3 shows the distribution of ground shaking from the M_w 7.1 mainshock, with reporting stations shown as faint triangles. In addition, it indicates the availability of strong-motion data recorded on-scale by the California Integrated Seismic Network (CISN) collaborative seismic networks.

The portable GS network of 10 stations was installed between 7 and 12 July (Cochran *et al.*, 2019). These data are telemetered in real time to the Albuquerque Seismic Lab (ASL) via cell modems and transmitted to SCSN via an Internet SEEDlink connection. The SCSN began recording the GS data streams of continuous velocity channels and event-triggered strong-motion channels within hours of each station deployment. Metadata were provided via SIS by ASL staff. The data continue to be used for hypocenter determination, ShakeMap, and focal mechanism calculations to this day. The ZY network did not have real-time communications, and thus the data were not available for real-time processing. The portable data from the GS and ZY networks are available from the SCEDC archives for downloading with SCSN data. The station deployments and collection of these portable datasets are described in detail by Cochran *et al.* (2019) in a separate paper in this volume.

The generation of SCSN products is described by Hutton *et al.* (2010). The primary products that are provided routinely by the SCSN and SCEDC include:

1. continuous waveforms;
2. triggered and associated waveforms for each detected event;
3. associated arrival-time picks;
4. earthquake catalog with origin times, hypocenters, and magnitudes;
5. ShakeMaps for $M_w \geq 3.5$;
6. focal mechanisms for mostly $M_w > 2.0$ using the method of Yang *et al.* (2012); and
7. seismic moment tensors for mostly $M_w > 4.0$.

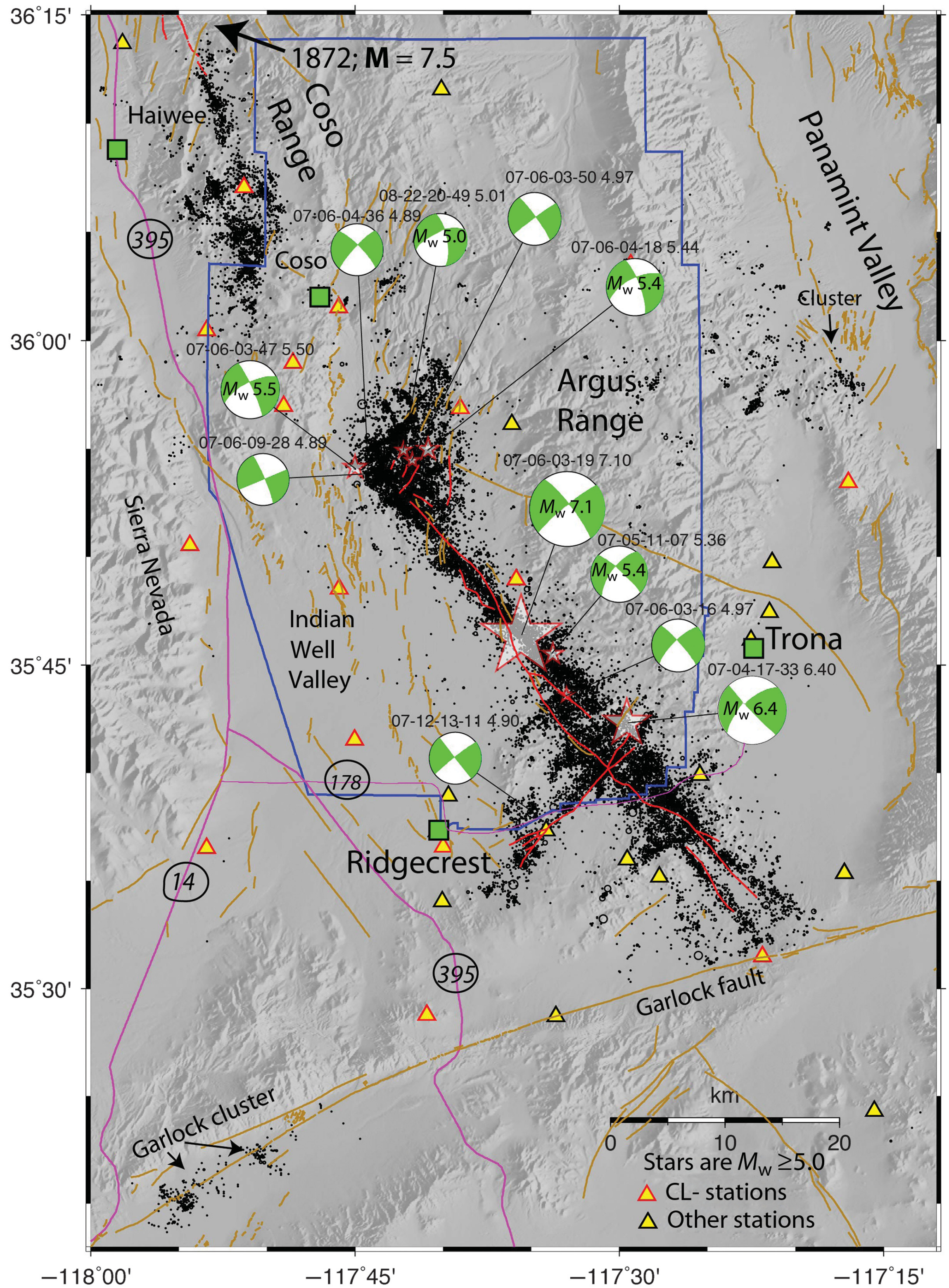


Figure 1. Map showing the M_w 6.4 foreshock and M_w 7.1 mainshock (stars) and their ~40,000 aftershocks and three off-fault clusters near the Garlock fault, Panamint Valley (black dots) and near the southern terminus of the 1872 **M** 7.5 earthquake (red lines at top of map). First-motion and *S*/*P*-based focal mechanisms for the $M_w \geq 5$ events are also included labeled with month, day, hour, minute, and magnitude. The 2019 surface rupture (red lines) is from Kendrick *et al.* (2019). Late Quaternary faults (brown lines) are from Jennings and Bryant (2010). Yellow triangles denote seismic stations; CI network stations are outlined in red, and partner permanent and portable stations are outlined in black. The main highways, 14, 178, and 395 are shown as purple lines; Coso geothermal area and nearby cities, including Ridgecrest and Trona, are shown as green squares; and the boundary of Naval Air Weapons Station China Lake is shown in blue.

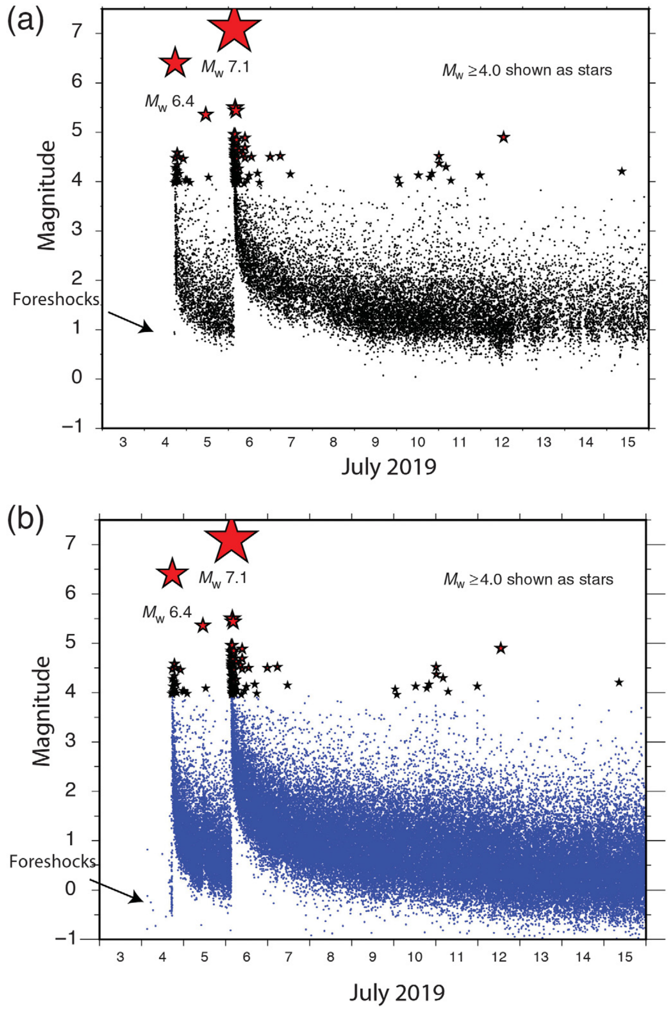


Figure 2. Magnitude versus time for the 2019 Ridgecrest earthquake sequence for 3–15 July from (a) the Southern California Seismic Network (SCSN) real-time catalog and (b) the postprocessing template-matching catalog from Ross *et al.* (2019).

Specialized products that are made and periodically updated are as follows:

1. waveform relocated catalog using the approach of Hauksson *et al.* (2012);
2. recalculated focal mechanisms from Yang *et al.* (2012); and
3. template-matching catalog from Ross *et al.* (2019).

The completeness of the archived waveforms is 98% or better in most cases. All of the SCSN stations located near the Ridgecrest sequence are equipped with strong-motion three-component sensors and most with broadband seismometers, which are recorded continuously by 24 bit digitizers. The closest three SCSN stations with strong-motion accelerometers recorded the M_w 7.1 mainshock on scale as is shown in Figure 4, and the broadband velocity transducers near the source experienced clipping as the *S* wave and surface waves arrived. Figure 5 shows on-scale vertical-component accelerograms for the M_w 7.1 event, recorded on scale at SCSN stations at epicentral distances ranging from ~15 km to >350 km.

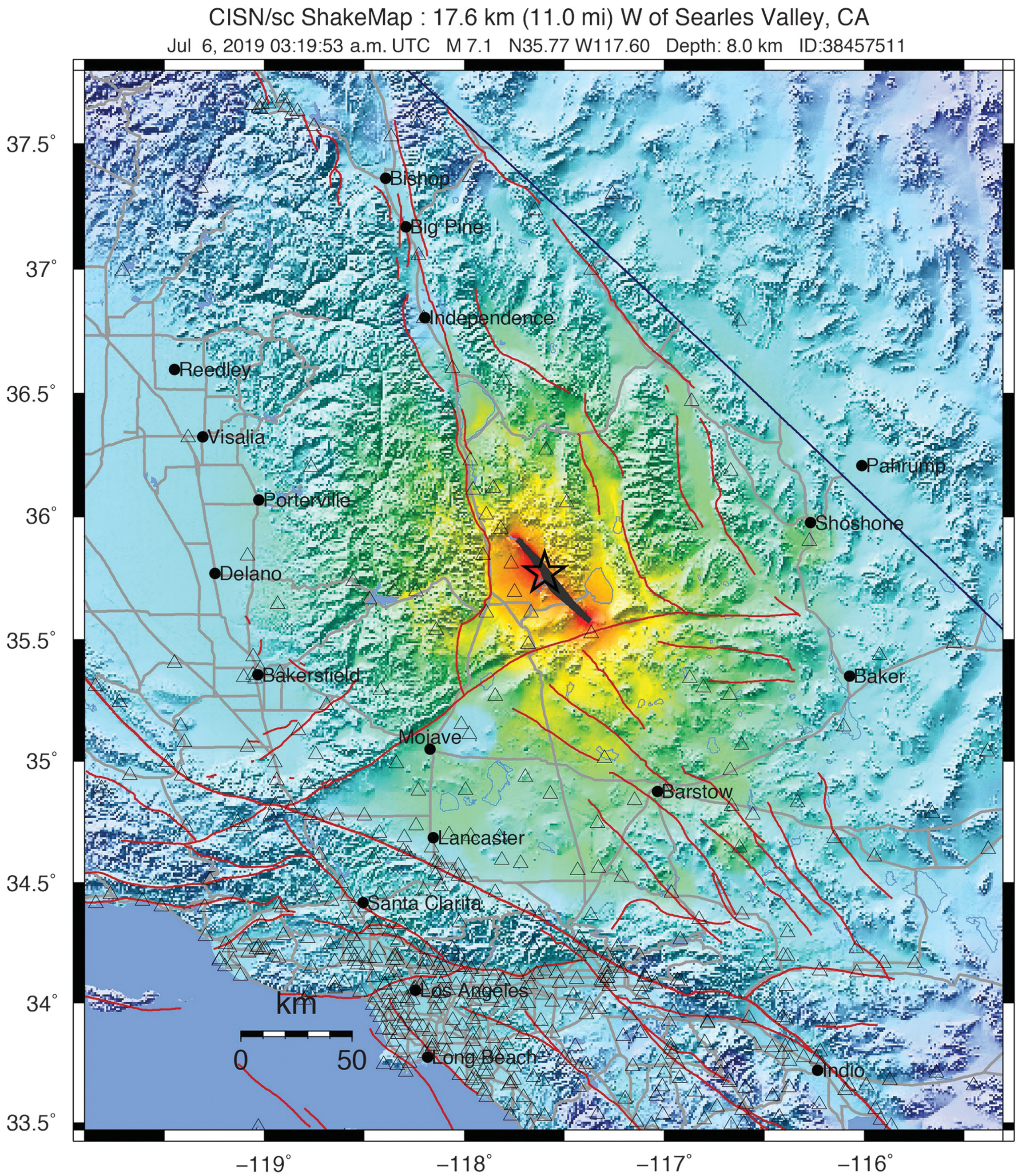
Noise levels for the time period from January through June 2019 computed using a power spectral density method developed by McNamara and Buland (2004) show a variation in background noise (Fig. 6). For example, station CI.SRT, which is located directly within the Ridgecrest seismic zone, exhibits high-noise levels for frequencies between 1 and 100 Hz, whereas station CI.DAW, which is 40 km away, has ~20 dB lower noise levels across the same frequencies. The overall signal-to-noise ratio levels are excellent across a wide band (100–0.01 Hz) for the majority of the SCSN stations. This is due in large part to the uniformity of station design and high-quality equipment across the network.

The SCEDC

The SCEDC distributes its holdings to the research community with modern webservices. Jointly, the SCSN and SCEDC maintain a database that includes (1) earthquake catalog (1932–present), (2) phase data (1932–present), (3) selected seismograms on microfilm (1930–1962), (4) selected scanned seismic records (1962–1992), (5) instrument responses, and (6) digital seismograms (1977–present). In 2010, we began to archive all continuous SCSN and partner data at 100 samples per second.

Recently, the SCEDC has developed and continues to refine its webservices and keep them compliant with latest community standards. Users can either use the form or call the service from the command line via curl or wget. The waveform webservice allows users to retrieve continuous or triggered waveform data, as well as download phase data using Seismogram Transfer Program (STP) for events in the SCSN earthquake catalog. The STP output is a tar file containing the data and a text file with the user request. With implementation of the Continuous Waveform Buffer (CWB), the SCEDC is able to distribute the CWB archived waveform data on a near-real-time basis. The implementation of Federation of Digital Seismograph Networks (FDSN) webservices has allowed the Data Center to be used with ObsPy (Krischer *et al.*, 2015), a popular Python framework for seismology. The SCSN and SCEDC continue to partner with strong-motion networks to make data recorded by both engineering and seismological communities available to each other in their respective formats.

The SCEDC archives in the FDSN SEED format waveforms available from the California Geological Survey (CGS) for $M_L > 4$ events recorded by SCSN. This allows the seismic user community to have access to a larger set of strong-motion data for large events. The SCEDC also distributes its waveforms in Cosmos V0 format to CGS for any station exceeding 0.5%g ground acceleration.



Perceived shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential damage	None	None	None	Very light	Light	Moderate	Mod./heavy	Heavy	Very heavy
Peak acc. (%g)	***<0.1***	***0.5***	***2.4***	***6.7***	***13***	24	44	83	>156
Peak vel. (cm/s)	<0.07	0.4	1.9	5.8	***11***	***22***	***43***	***83***	***>160***
Instrumental intensity	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald *et al.* (1999).

Figure 3. ShakeMap showing the distribution of shaking from the M_w 7.1 Ridgecrest mainshock as recorded by the SCSN, which is the southern California part of the California Integrated Seismic Network (CISN; see Data and Resources) and part of the Advanced National Seismic System California region. The seismic stations providing data are shown as gray triangles. The table below shows the color coding of modified Mercalli instrumental intensity (MMI), where the lower intensities are determined by peak ground acceleration (PGA) (shown with bold italic font), the higher intensities are determined by peak ground velocity (PGV) (shown with bold italic font), and those between MMI 5 and 7 are determined by a linear weighted average of the MMI determined by PGA and the MMI determined by PGV; also see Wald *et al.* (1999).

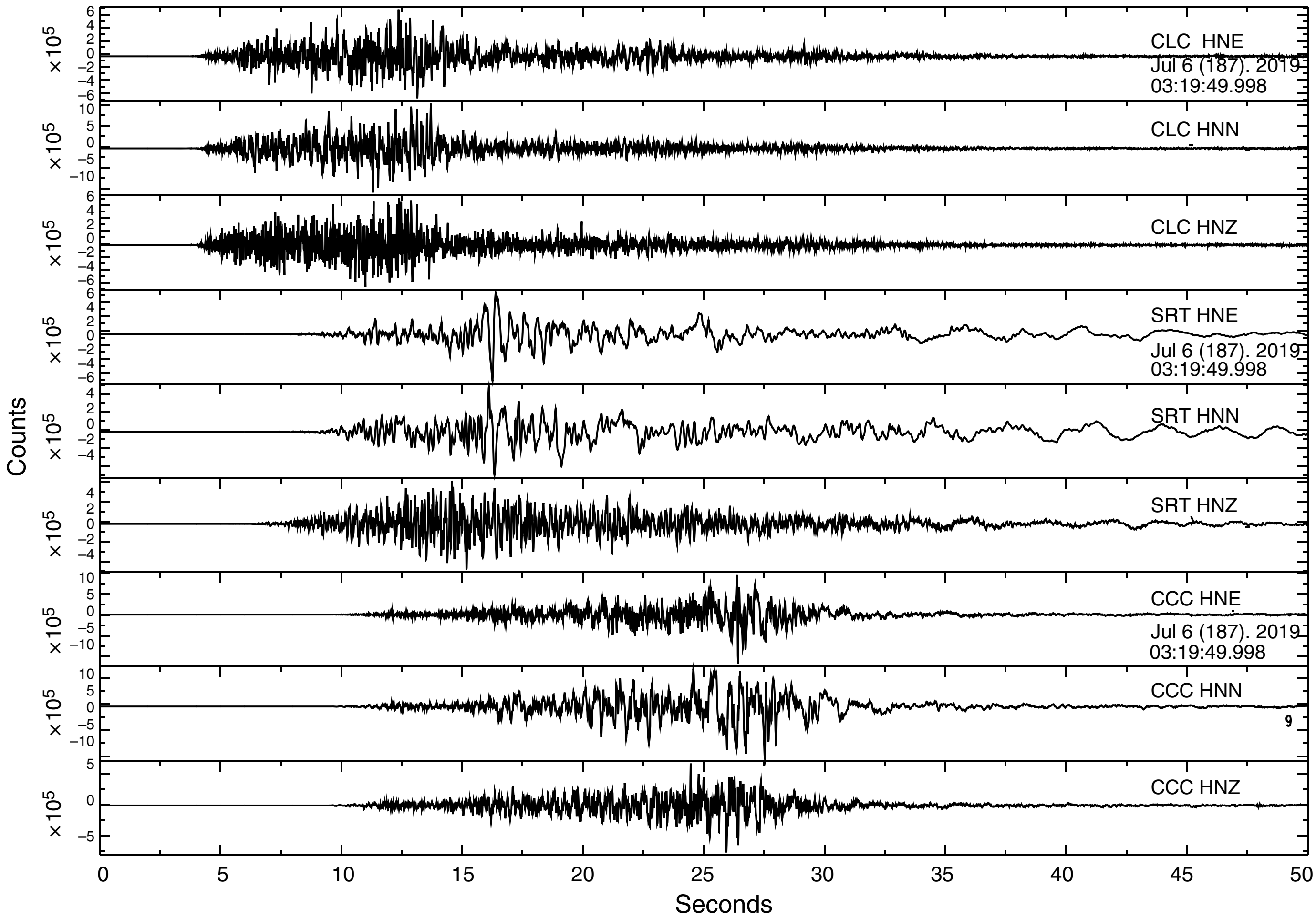


Figure 4. Three-component strong-motion accelerograms of M_w 7.1 mainshock for stations CI.CLC, CI.SRT, and CI.CCC located near both the M_w 6.4 and M_w 7.1 earthquakes close to Ridgecrest.

The SCEDC also archives triggered waveform data and amplitudes from SCSN stations equipped with NetQuakes dataloggers. These amplitudes are also being used in ShakeMaps and exchanged to other CISN partners. Analysts can also use the archived NetQuakes waveforms in postprocessing to further locate earthquakes.

Since the inception of the World Wide Web and the introduction of webpages hosting seismological data, public internet traffic following almost every major earthquake in the western United States has overwhelmed these systems. To alleviate this problem, we have hosted the SCEDC and SCSN webpages in the Amazon Web Services (AWS) cloud for the past 4 yr. The performance of the SCEDC website during the M_w 6.4 and M_w 7.1 events is shown in Figure 7. The website remained fully functional and kept providing up-to-date information to users through the entire sequence. However, immediately following the M_w 7.1 earthquake, the web traffic exceeded the resources that we were able to request from AWS, and thus some customers probably did not get an immediate response. The SCSN website showed similar performance while also serving up real-time videos of seismic waveform streams and playbacks of significant events via Facebook Live. It is noteworthy that the websites stayed up and we were able to disseminate vital information to interested decision makers as well as the general public at a critical time. In addition, from a public relations perspective, we were able to provide this information at the very point in time when people were most interested in seismicity and when they most appreciated the importance of a seismic network.

Open Dataset Available at AWS

We have also deployed our data into the AWS cloud to make large-scale processing easier (Yu *et al.*, 2019). The entire SCSN continuous waveform archive (~100 TB of data) from 2008 to present-day 2019, including waveforms of the Ridgecrest earthquake sequence, is now freely available as an AWS Public Dataset at this Registry of Open Data page. These data can be accessed in the AWS Public Dataset website (see Data and Resources). Each file is one day for a single seismic channel. The format is miniSEED. The data archive is being updated

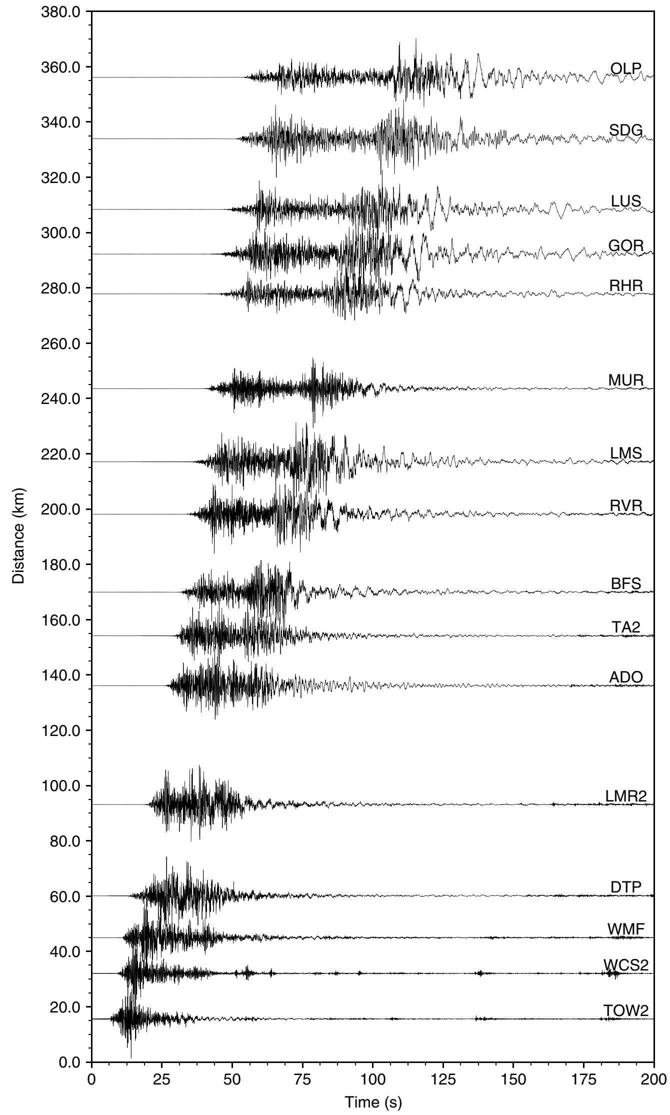


Figure 5. Acceleration record section of the M_w 7.1 mainshock on HNZ channels across the SCSN network at a range of epicentral distances, extending from CI.TOW2 near the epicenter to the station CI.OLP, which is located near the U.S.–Mexican border more than 350 km away.

and improved as resources are available. The SCEDC AWS Public Dataset allows users to process GB- to TB-size waveform datasets in the cloud without having to first download the data to a local server and enables the development of cloud computing workflows for analyzing large seismological datasets.

Initial Observations

The SCSN real-time systems have cataloged >55,400 earthquakes automatically from 1 January to 14 November 2019 and distributed more than 358 ShakeMaps (Fig. 8). Using template matching for the first four weeks of the Ridgecrest foreshock–mainshock sequence, Ross *et al.* (2019) identified >110,000 earthquakes along orthogonal southwest and northwest trends. Initially, an L-shaped pattern was formed by an M_w 4 foreshock that preceded the M_w 6.4 event by 30 min and subsequent aftershocks of the M_w 6.4. About 34 hr later, an M_w 5.0 foreshock occurred followed within 3 min by the M_w 7.1 event. The M_w 7.1 event formed a bilateral aftershock distribution extending from the M_w 7.1 epicenter 20 km northwest and 40 km southeast. The depths of the aftershocks extended to 10–12 km. The focal mechanisms are mostly strike slip with a few dip-slip events, consistent with the regional north–south $S_{H\,max}$ tectonic stress field. The earthquake sequence's statistical parameters (*a*-, *b*-, and *p*-values) that remained fairly constant with time have similar values as expected for average southern California sequences. However, the *b*-value was ~0.74, suggesting lower detection or productivity of smaller events compared with an average *b*-value for southern California of ~1.0 (Hutton *et al.*, 2010).

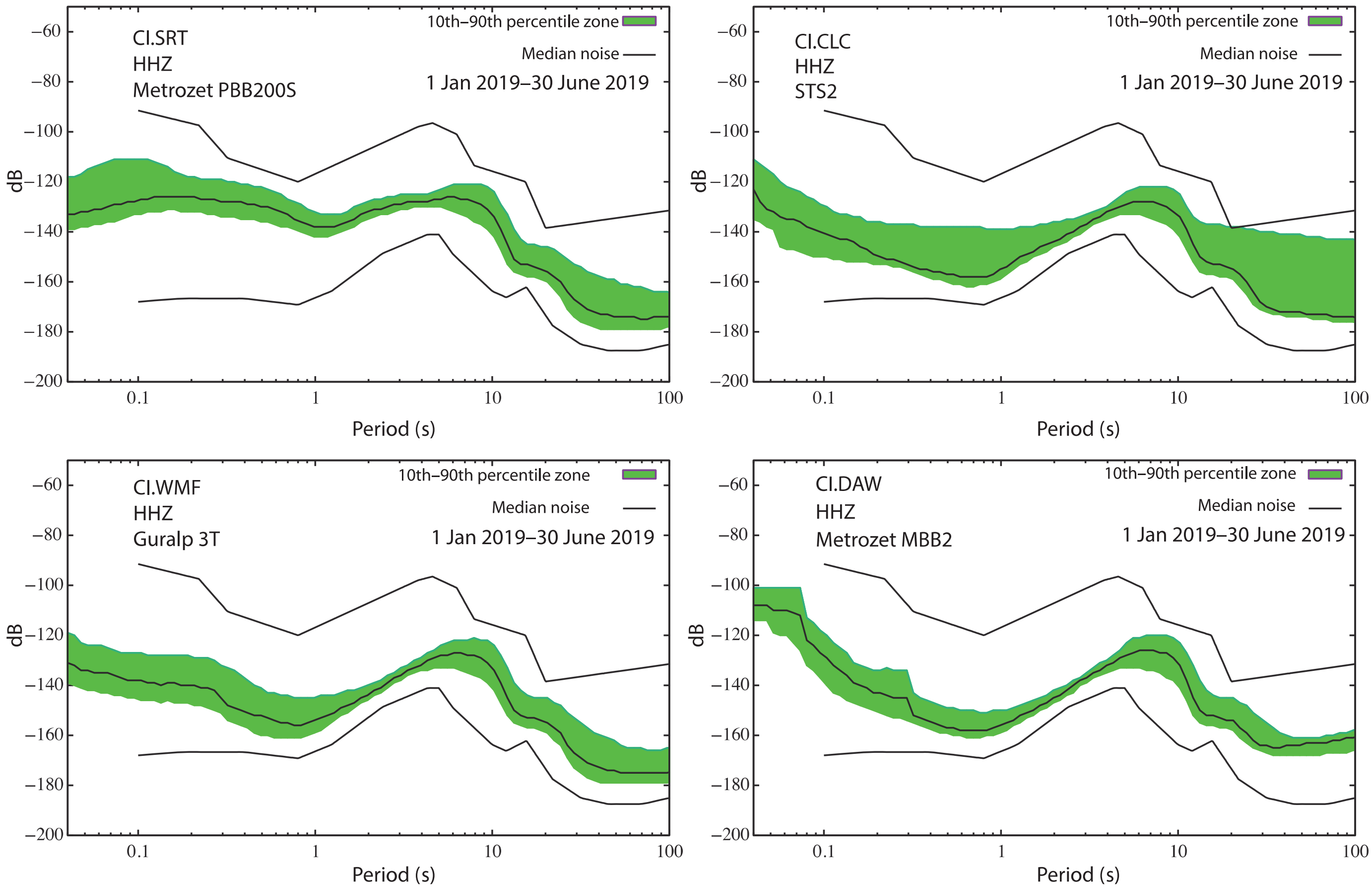
These data will be used for detailed analysis of tectonics, source physics, and ground motion as well as analyzing detailed fault structure, velocity structure modeling, testing theories of earthquake interaction, and other studies. The high quality and spatial density of the SCSN data, because of investments that have been made in improving the SCSN, have captured the largest major southern California earthquake in 20 yr with higher spatial and temporal resolution than ever before. In future studies, these observations can facilitate new developments in our understanding of earthquake behavior, especially when used in concert with other geophysical datasets of the Ridgecrest earthquake sequence such as mapped surface rupture (Brandenberg *et al.*, 2019), drone images, light detection and ranging (lidar), Interferometric Synthetic Aperture Radar (InSAR), and Global Navigation Satellite System (GNSS). The goals of such lidar, InSAR, and GNSS studies are to improve the understanding of the region and improve future earthquake hazard estimates.

Summary

The SCSN, partner networks, and SCEDC provide the most comprehensive seismic datasets available for the 2019 Ridgecrest earthquake sequence. This includes waveform data from both permanent networks such as CI and temporary seismic stations deployed as GS or ZY networks. These waveform data are also being made available at SCEDC in Pasadena as well as through AWS Open Data program (Yu *et al.*, 2019). The SCSN and SCEDC also provide products such as the earthquake catalog, phase picks, moment tensors, focal mechanisms, and ShakeMaps.

Data and Resources

If you use Southern California Seismic Network (SCSN) data or the Southern California Earthquake Data Center (SCEDC), please acknowledge use of waveforms and parametric data from the California Institute of Technology & U.S. Geological Survey (Caltech/USGS)



SCSN (http://www.scsn.org; doi: 10.7914/SN/CI); stored at the SCEDC (doi: 10.7909/C3WD3xH1). All SCSN recorded data and products are available through the SCEDC at https://scedc.caltech.edu and the Amazon Web Services (AWS) Open Data program (Yu *et al.*, 2019). Data from the Ridgecrest earthquake sequence are now freely available as an AWS Public Dataset at this Registry of Open Data page: https://registry.opendata.aws/southern-california-earthquakes. The AWS bucket name is: s3://scedc-pds and is stored in the us-west-2 AWS region. The data archive is being updated as needed and documentation is found at https://scedc.caltech.edu/cloud. SCEDC data access tools can be found at https://scedc.caltech.edu/research-tools/downloads.html. SCEDC also provides webservices, such as (1) earthquake parametric data in QuakeML (service.scedc.caltech.edu/fdsnws/event/1); (2) station metadata in StationXML (service.scedc.caltech.edu/fdsnws/station/1); (3) continuous waveforms in miniSEED (service.scedc.caltech.edu/fdsnws/dataselect/1); (4) triggered waveforms in miniSEED, Seismic Analysis Code (SAC), ASCII (service.scedc.caltech.edu/webstp); (5) poles and zeros in SAC ASCII (service.scedc.caltech.edu/scedcws/sacpz/1); (6) instrument response in RESP format (service.scedc.caltech.edu/scedcws/resp/1); and (7) waveform availability in ASCII (service.scedc.caltech.edu/scedcws/availability/1). SCSN time-series data from ~60 CI stations are also available from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) at http://ds.iris.edu/ds/nodes/dmc. Strong-motion records from CI stations for events of magnitude ≥3.5 are available from the Center for Engineering Strong Motion Data (CESMD) at www.strongmotioncenter.org. Advanced National Seismic System (ANSS) performance standards are from https://www.usgs.gov/media/files/anss-performance-standards. Technical information about NetQuakes stations is available from https://earthquake.usgs.gov/monitoring/netquakes. The real-time SCSN waveform videos are available at http://www.scsn.org/index.php/earthquakes/live-seismogram-feed/index.html. The specific SCSN waveform videos for the M_w 6.4 and M_w 7.1 Ridgecrest events are available at http://www.scsn.org/index.php/2019/07/04/07-2019-ridgecrest-sequence/index.html. Other relevant data are from the CISN website (http://www.cisn.org). All of these websites were last accessed in November 2019.

Figure 6. Median values of probability density functions for the HHZ channel bounded by the 10th and 90th percentiles for stations CI.SRT, CI.CLC, CI.WMF, and CI.DAW. The continuous data is from 1 January through 30 June 2019. Because of site conditions, noise levels are elevated for stations near Ridgecrest (CI.SRT) for frequencies between 1 and 100 Hz, stations 40 km away (CI.DAW) have lower overall noise levels. The upper and lower black lines are new high noise model and new low noise model from McNamara and Buland (2004).

Acknowledgments

The Southern California Seismic Network (SCSN) is partially funded by U.S. Geological Survey (USGS) Cooperative Agreements G15AC00023, G19AS00034, and California Office of Emergency Services (CalOES) Agreement 6012-2017 with California Institute of Technology

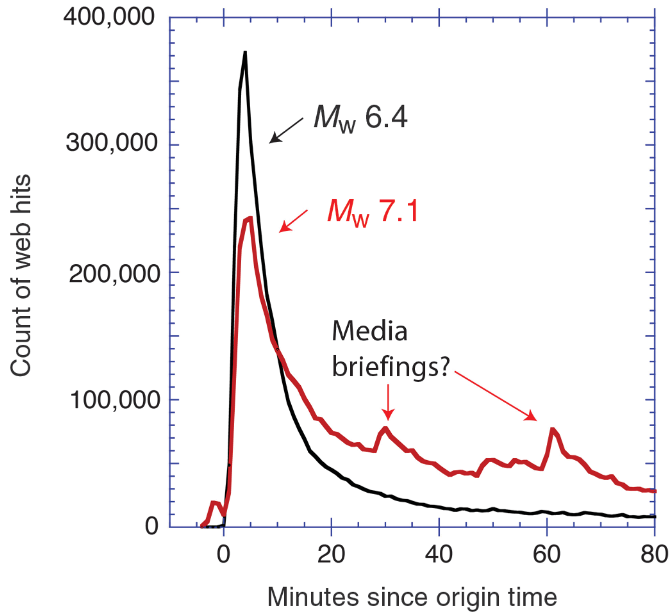


Figure 7. Web traffic on the Southern California Earthquake Data Center (SCEDC) website (see Data and Resources) in 1 min intervals following the M_w 6.4 and M_w 7.1 earthquakes, centered on the origin time. The peak of the distribution is reached within several minutes. The M_w 7.1 had less web traffic than the M_w 6.4 in part because of technical limitations; the later secondary peaks may be related to media briefings that took place at the California Institute of Technology Seismo Lab in Pasadena during a similar time period.

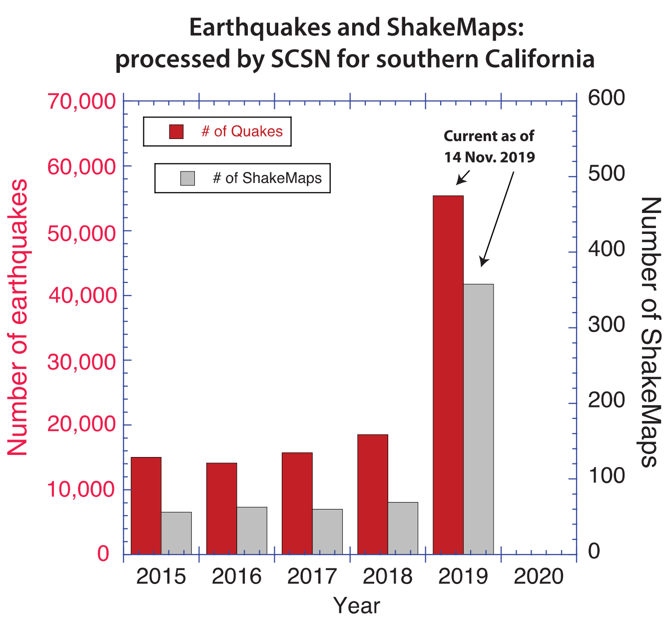


Figure 8. SCSN data availability for the SCEDC archives from 2015 to 2019, showing the number of recorded events (red bars, left vertical axis) and the number of ShakeMaps distributed to users (gray bars, right vertical axis).

(Caltech). The SCEDC was also supported by the Southern California Earthquake Center (SCEC; Contribution No. 10006). SCEC is funded by National Science Foundation (NSF) Cooperative Agreement EAR-1600087 & USGS Cooperative Agreement G17AC00047. The authors appreciate the support provided by more than 20 SCSN and Southern California Earthquake Data Center (SCEDC) staff members who maintain stations and communications systems, as well as data flow, processing, and archiving. The authors also thank National Earthquake Information Center (NEIC), Albuquerque Seismic Lab (ASL), and The Geothermal Program Office at the Naval Air Weapons Station China Lake staff for their collaboration, especially during the 2019 Ridgecrest sequence. Reviews were provided by two external reviewers, and *SRL* Associate Editor. E. Cochran and R. Graves provided internal USGS reviews of this article.

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Manuscript received 1 October 2019
Published online 22 January 2020