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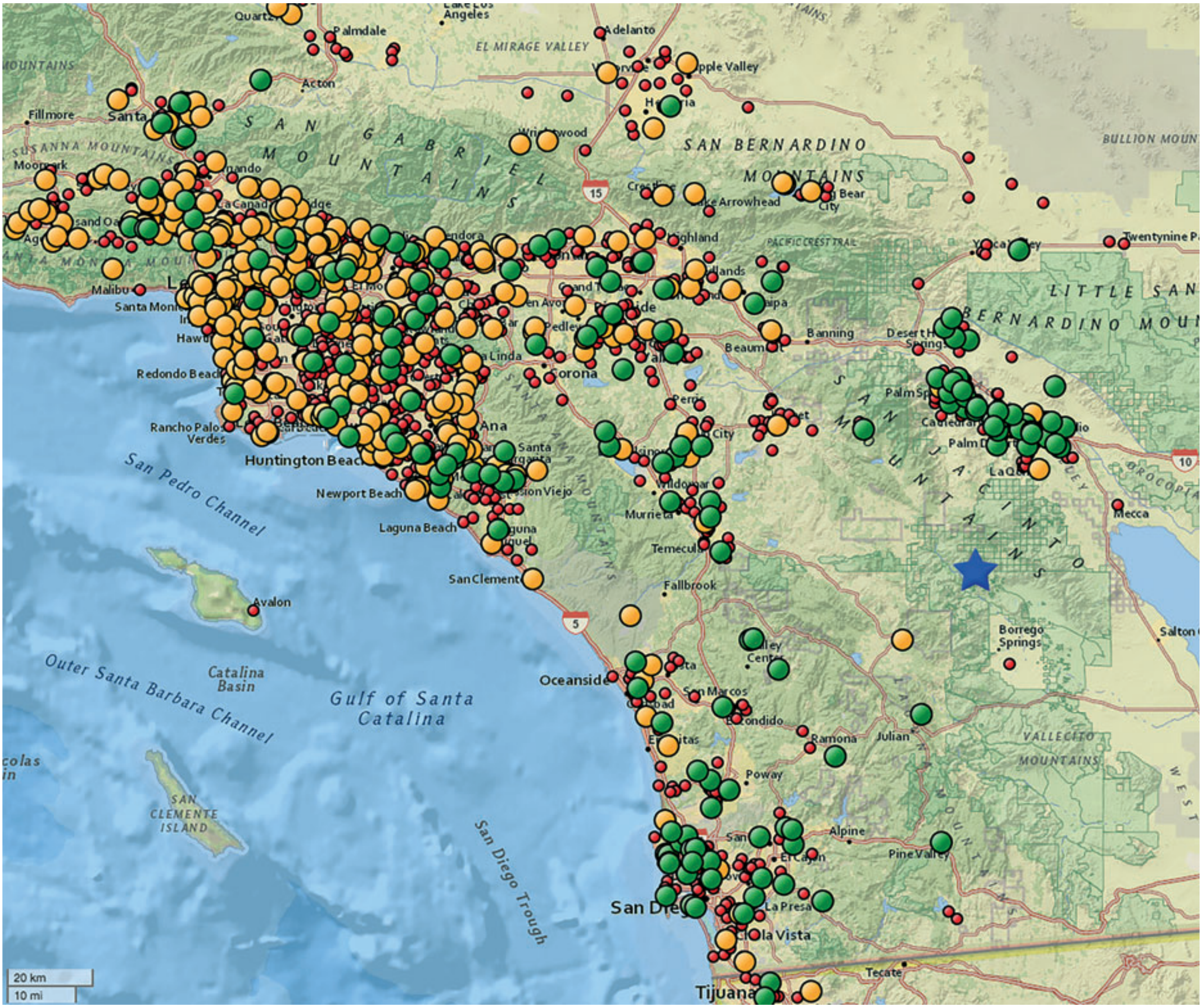

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Key Points:
- First global seismic network harnessing personal smartphones now providing acceleration waveforms
- On-phone earthquake detection algorithm is triggering on magnitude 2.5 and greater earthquakes
- Two hundred thousand phones have downloaded the MyShake app providing seismic waveform data from six continents

Supporting Information:
- Supporting Information S1

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MyShake: Initial observations from a global smartphone seismic network

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Abstract MyShake is a global smartphone seismic network that harnesses the power of crowdsourcing. In the first 6 months since the release of the MyShake app, there were almost 200,000 downloads. On a typical day about 8000 phones provide acceleration waveform data to the MyShake archive. The on-phone app can detect and trigger on *P* waves and is capable of recording magnitude 2.5 and larger events. More than 200 seismic events have been recorded so far, including events in Chile, Argentina, Mexico, Morocco, Nepal, New Zealand, Taiwan, Japan, and across North America. The largest number of waveforms from a single earthquake to date comes from the *M*5.2 Borrego Springs earthquake in Southern California, for which MyShake collected 103 useful three-component waveforms. The network continues to grow with new downloads from the Google Play store everyday and expands rapidly when public interest in earthquakes peaks such as during an earthquake sequence.

1. Introduction

Since the introduction of low-cost accelerometers in consumer devices such as cars and computers, seismologists have been experimenting with how these sensors might contribute to the science of seismology and hazard reduction [*Allen*, 2007; *Cochran et al.*, 2009b; *Fleming et al.*, 2009; *Chung et al.*, 2011; *Clayton et al.*, 2011, 2015; *Wu et al.*, 2016, 2013; *Evans et al.*, 2014; *Wu and Lin*, 2014; *Wu*, 2015]. While these devices have significantly lower price tags than traditional seismic stations, the data are of lower quality and the operation of networks of low-cost devices is complex and not necessarily low cost. Various types of lower cost sensor networks have been explored with varying degrees of success [e.g., *Allen*, 2012]. At the higher-quality end of the spectrum, the U.S. Geological Survey NetQuakes devices include a high-quality microelectromechanical system (MEMS) accelerometer in a station package that is installed by engineers in household basements and makes use of the in-home WiFi [*Luetgert et al.*, 2009, 2010]. Other efforts have made use of USB accelerometers attached to personal computers or low-cost computers as with the Community Seismic Network [*Clayton et al.*, 2011, 2015; *Kohler et al.*, 2013] and Quake Catcher Network [*Cochran et al.*, 2009a, 2009b; *Chung et al.*, 2011; *Lawrence et al.*, 2014]. In all these cases hardware must be transported from the network operator to a station host. Both hardware and software must then be installed and maintained for the station and network to continue to function.

The advantage of using smartphones is that all the hardware is already packaged in a device that is ubiquitous in urban environments around the world. In addition, convenient software distribution and maintenance platforms exist in the form of the Google Play and iTunes stores and the associated software development kits. The disadvantages of smartphones as seismic sensors are also obvious: the phones are not fixed, phone resources are not tailored for seismology, recording earthquakes is not typically a priority for owners, the phones experience all kinds of motions that have nothing to do with earthquakes, and rapid full waveform data recovery may present challenges.

Multiple efforts are underway using smartphones to detect earthquakes. *Bossu et al.* [2015, 2016] describe the collection of quick eye-witness reports from people within a few tens of minutes after a felt-earthquake occurrence. Multiple efforts make use of the accelerometer. In some cases, a “trigger” message is generated and sent to a central server when a phone moves [*Faulkner et al.*, 2011; *Olson et al.*, 2011; *Finazzi*, 2016]; in others phones are used in a dedicated way to record earthquake shaking by attaching them to walls or other structures and recording continuously [*Naito et al.*, 2013]. The GPS/Global Navigation Satellite Systems sensor on the phone can also be used to detect ground motion when the motion is sufficiently large [*Minson et al.*, 2015]. MyShake attempts to combine all of these elements by turning a typical personal smartphone into a seismometer. The MyShake app has a filter to distinguish earthquakes from other human activities; it uploads earthquake triggers to a real-time server for analysis and also uploads the acceleration time series data to a server for further research analysis [*Kong et al.*, 2016].

This paper presents initial observations from the seismic data recorded by MyShake since the public release in February 2016. We detail the rapid expansion to a global seismic network recording earthquakes across six continents and show that smartphone sensors are capable of recording seismic events with magnitude 2.5 and larger. For larger earthquakes, these sensors can record the entire wave train starting from *P* wave. Previous shake-table tests have assessed the quality of the smartphone waveform data [*Dashti et al.*, 2011, 2012; *Reilly et al.*, 2013; *D'Alessandro and D'Anna*, 2013; *Kong et al.*, 2016]; here we compare smartphone recordings in the field to nearby traditional seismic stations. Finally, we examine the potential for MyShake to provide seismic data in many regions where there are little or no traditional seismic stations such as Nepal and Ecuador and where seismicity is a relatively new phenomenon like Oklahoma.

2. MyShake Methodology

MyShake was developed on the android platform as an application to monitor the accelerometers inside the smartphones. The motion of the smartphones is summarized into three key parameters that feed into an Artificial Neural Network (ANN), which has been trained to distinguish earthquakes from human activities. Once the ANN algorithm detects an earthquake-like motion, the app will send a message in real time to the server. This message, which contains location, time, and amplitude of the trigger, can be used for earthquake early warning or other types of rapid detection applications. At the same time, the app collects three-component acceleration time series data, at 25 Hz. The waveform data have a duration of 5 min, including 1 min before and 4 min after the trigger. The 1 min of data before the trigger ensures that the entire earthquake waveform is recorded even when the phone only triggers on a later phase of the ground motion. When the phone is connected to WiFi and power, the waveform recordings are uploaded to the server for further analysis. For more details about the app and methodology, see *Kong et al.* [2016].

Since MyShake was released publicly on 12 February 2016 in the Google Play store, there have been almost 200,000 downloads and the app is presently installed on 36,000 phones distributed across six continents (numbers from Google Play Store). Figure 1a shows the global distribution of all phones registered with the system. The number of phones contributing shows peaks in North America and some other places where earthquake hazard is high including Nepal and India. On a typical day between 8000 and 10,000 phones provide data to the system (see Figure S1 in the supporting information).

3. Seismic Data Recorded by MyShake

As of 11 August 2016, MyShake has recorded 237 earthquakes from *M*2.5 to *M*7.8 around the globe since released to the public ("recorded earthquakes" are defined as having at least one good smartphone-recorded earthquake waveform sent back to the server and confirmed by a seismologist). Figure 1b shows the distribution of the recorded earthquakes and includes regions with good seismic network coverage like the U.S., Taiwan, Japan, and Chile and also areas without dense networks, such as Nepal and Ecuador. Not surprisingly, locations with higher density of MyShake users, like California, have a larger number of earthquake detections. This is due to the higher density of users closer to the epicenter. Example waveforms from around the world are included in Figure S2. Not only shallow but also large deep earthquakes have been detected by MyShake. These are shown by the warmer color circles in the Figure 1b. The distribution of the magnitude and depth of the recorded earthquakes can be found in Figure S3.

The earthquake which has generated the most waveforms to date is the *M*5.2 earthquake that occurred near Borrego Springs in Southern California on 10 June 2016 at 08:04:38 UTC. Figure 2a shows the status and performance of the MyShake network at the time of the event. The green dots show the locations of the phones that triggered on the earthquake ground motion using the ANN algorithm on each phone. The orange dots are the phones that were "ready"; i.e., they were monitoring the accelerometer to detect an earthquake but did not trigger on this event. The red dots show other MyShake phones that were in communication with the network but were not monitoring for an earthquake at the time of the event. Not surprisingly, the percentage of phones that triggered on the event decreases with increasing epicentral distance as the amplitude of the ground motion decreases.

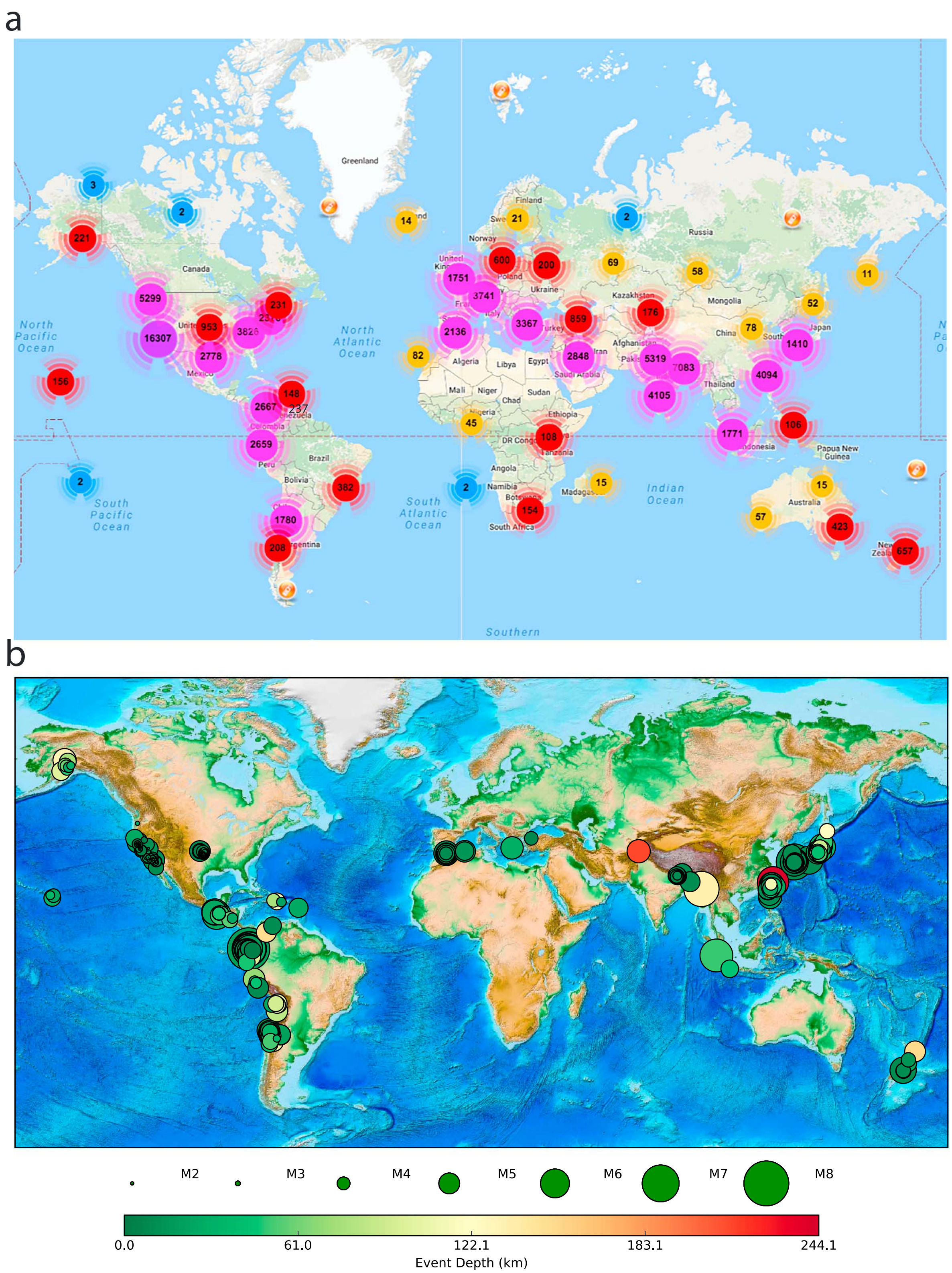

Figure 1. Distribution of MyShake registered users and detected earthquakes. (a) Registered MyShake users are shown in clusters. The number in each circle indicates the number of registered users in the cluster, and the color of the circle shows the order of the number of phones; i.e., a purple circle indicates that the number of phones is of order tens of thousands, magenta is thousands, red is hundreds, yellow is tens, and blue for less than 10. (b) The 237 earthquakes recorded by MyShake users since 12 February 2016. The locations of the earthquakes are shown as circles, which are color coded by the depth and whose sizes are scaled by the magnitude of the earthquake. Figures are generated on 11 August 2016.

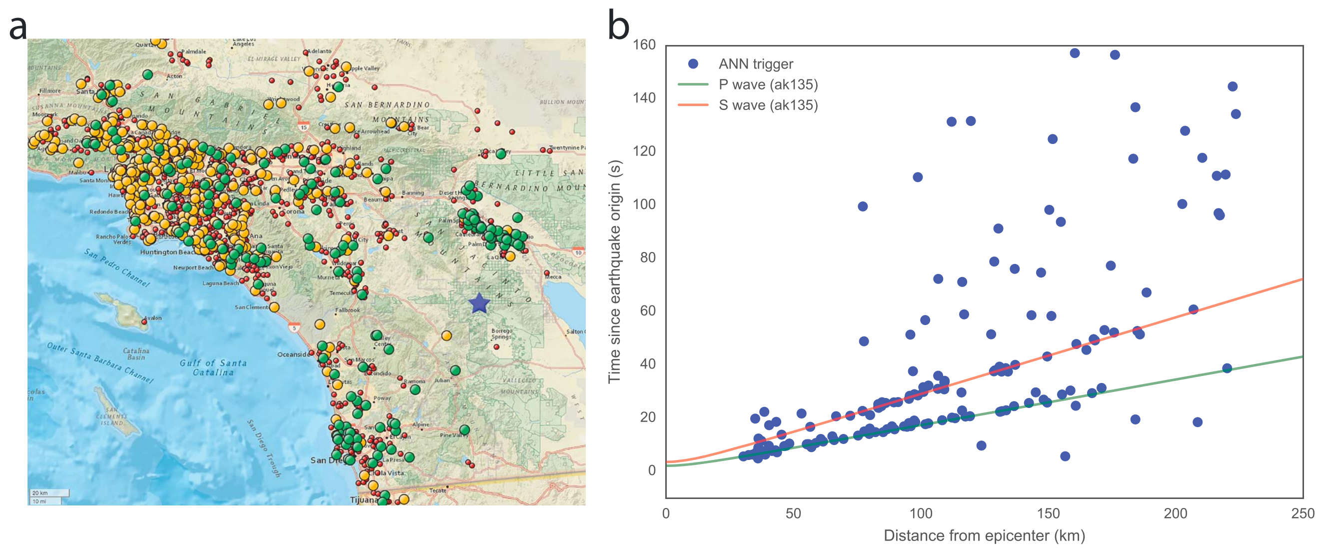

Figure 2. (a) Location of the *M*5.2 Borrego Springs earthquake and the MyShake phones at the time of the event. Blue star is the epicenter of the earthquake. Green dots are phones that triggered using the ANN algorithm. The red dots are phones that were not ready to detect earthquakes (likely due to human activities), and the orange dots show the phones that were ready to detect the earthquakes but did not. (b) MyShake trigger time versus distance. Blue dots are the phones' trigger times, and the green and red curves are the estimated *P* and *S* wave traveltime based on Model ak135 [*Kennett et al.*, 1995].

The trigger times of the phones is shown in Figure 2b along with the expected *P* and *S* wave arrival times. Most phones are triggered on the *P* or *S* waves, as would be expected, and it is encouraging to see that the ANN detection algorithm is still recognizing the earthquake out to distances of ~200 km.

Figure 3a is the record section showing horizontal component waveform data from phones out to 200 km from the epicenter. The *S* wave energy is clearly recorded by the smartphone sensors out to 200 km, and the *P* wave energy is also visible on some phones at these distances. The *P* wave signal is clearer on the vertical component record section (Figure S4).

One of the key parameters for earthquake hazard studies is the Peak Ground Acceleration (PGA). Figure 3b presents a comparison of the PGA values observed by MyShake phones and traditional seismic stations.

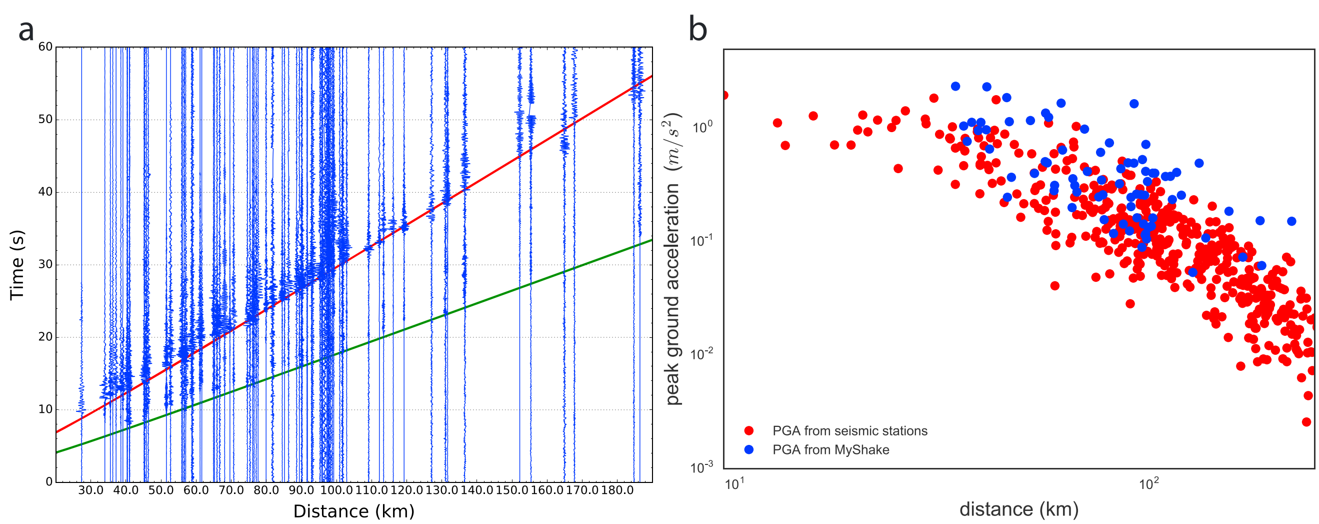

Figure 3. (a) Record section plot for phones within 200 km. Each blue trace is one horizontal recording from MyShake user, and the green and red curves are the estimated *P* and *S* waves based on ak135. Amplitudes of the recordings are normalized in each trace. (b) PGA value observations with distance. PGA values from MyShake (blue) and traditional seismic stations (red) are shown as observed on the largest horizontal component. The seismic station data are from Southern California Earthquake Data Center.

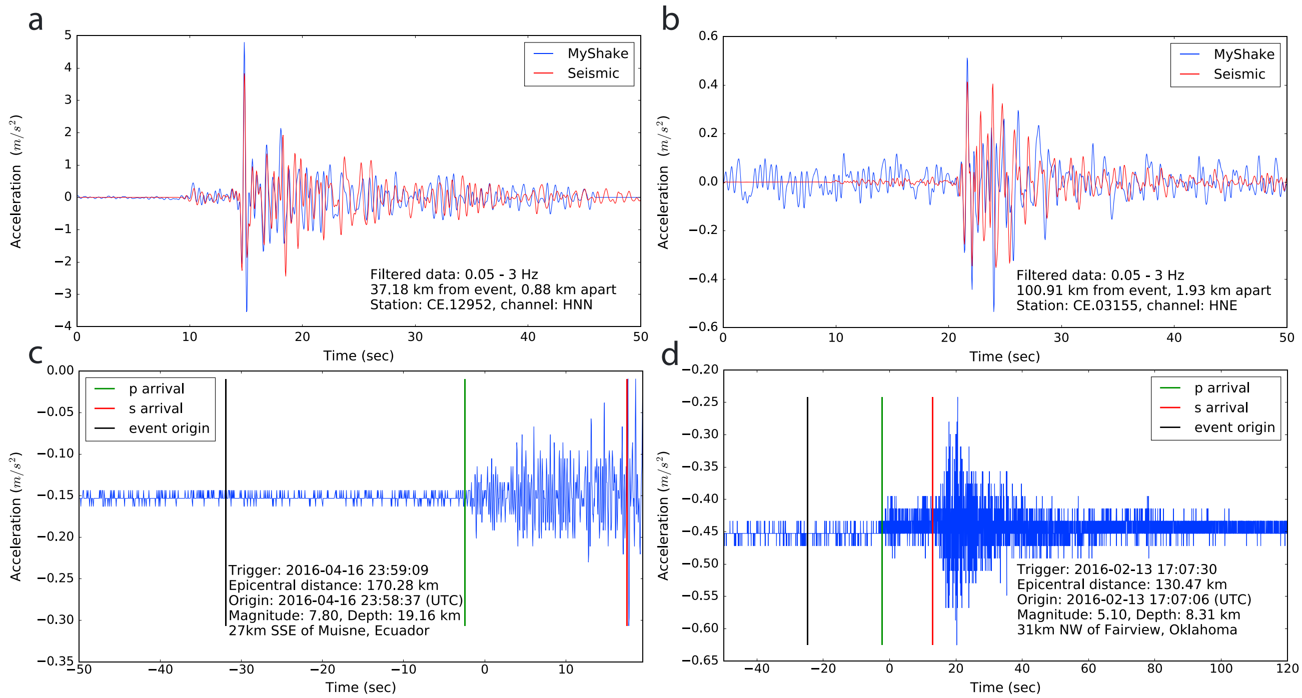

Figure 4. Example MyShake waveforms. (a and b) Comparison of the waveforms recorded by MyShake and a nearby traditional seismic station (horizontal component) for the *M*5.2 Borrego Springs earthquake. Figure 4a shows MyShake waveform recorded 37.2 km from the epicenter and a traditional seismic station 0.88 km from the smartphone. Figure 4b shows MyShake waveform recorded at 100.9 km from the epicenter and a traditional seismic station 1.93 km from the smartphone. See Figures S6 and S7 for the comparison of other components. (c) *M*7.8 Ecuador earthquake recorded at 170 km away from epicenter. (d) *M*5.1 Oklahoma earthquake recorded by a phone at 130 km from epicenter. For Figures 4c and 4d the zero time is the phone trigger time. The vertical black, green, and red lines are the origin time and predicted *P* and *S* wave arrival times, respectively (estimated using ak135 model).

While the values are similar and show the same trend with epicentral distance, the ratio of the PGA values from the phones to that of the nearest seismic station is 2.0. Figure S5a shows a histogram of PGA difference between MyShake recordings and the closest traditional seismic station. This may reflect the fact that the phones are in buildings and on tables rather than being free field sites as with most traditional stations. It may also reflect the fact that most people (and their phones) live in basin locations and on sediments leading to amplification effects. Figure S5b shows a comparison of the occurrence time of the PGA value on MyShake recordings and traditional seismic stations showing correlation with the *S* wave arrivals. Figures 4a and 4b show comparisons of the waveforms recorded on a smartphone and a nearby traditional seismic station. It shows good agreement between the waveforms (they are separated by 1–2 km) but also shows that the PGA is greater on the phone records. For other components comparisons see Figures S6 and S7.

The other recorded earthquakes typically have far fewer waveforms than the Borrego Springs earthquakes, because of lower density of MyShake phones. The largest earthquake recorded to date is the *M*7.8 16 April 2016 Ecuador earthquake. In this event two phones triggered at distances of 170 and 200 km (the location of the phones and earthquake is shown in Figure S8a). Figure 4c is the waveform record at 170 km and shows that the phone triggered on the *P* wave arrival even at this great distance. Shortly following the *S* wave arrival, there is a very large acceleration likely due to the phone owner picking up the phone (see the whole waveform in Figure S8b).

MyShake has also recorded multiple earthquakes in Oklahoma. Figure 4d is one example from the 13 February 2016 *M*5.1 event recorded at a phone 130.5 km away. While the individual counts are clearly visible in the record, the phone still triggered on the *P* wave arrival. Figure S9 shows the map of this earthquake and the waveforms for the three components. Additional examples of *P* wave recordings are shown in Figure S10 illustrating that *P* wave arrivals are typically recorded out to ~100 km for *M*5 and larger events. Figure S2 shows some more examples of recordings from other regions.

4. Discussion and Conclusions

Based on the data recorded by the MyShake network during the first 6 months of operation, the MyShake approach of using personal smartphones has the clear potential to provide data useful for multiple seismological studies and hazard reduction efforts. It is remarkable how quickly the network has grown, primarily driven by news media and citizen scientist interest in the project. While technical challenges still remain, and there are opportunities to improve the data quality through further improvements in the on-phone app, the network is already collecting a substantial volume of earthquake time series. MyShake has already provided data from many earthquake-prone areas, including the U.S., Nepal, Chile, Japan, Taiwan, and New Zealand.

The MyShake data are of sufficient quality to be useful in many types of scientific and hazard reduction projects. The data collected show that the full seismic waveform (*P* wave, *S* wave, and surface waves) can be recorded with a high signal-to-noise ratio at distances in excess of 100 km for earthquakes of magnitude 5 and larger (see examples in Figures S11 and S12). It can also provide peak ground motion information for much smaller earthquakes; a *M*2.5 earthquake is the smallest detected to date. The network can provide a very dense array of stations across urban centers if deployed on enough phones, providing a perhaps unprecedented opportunity for full wavefield analysis. The network can also be used for more traditional seismic studies as it can be used to detect, locate, and estimate the magnitude of earthquakes in regions that have few or no seismic stations. Microzonation peak ground motion maps can also easily be generated from the data. These maps may also have a third dimension when arrays of phones also provide observations on multiple floors of high-rise buildings. More events with large numbers of observations are needed to fully understand the potential uses of these data.

The rapid expansion of the network and the large number of recordings are all possible because we harness a ubiquitous hardware/software package: android smartphones. While the sensor network therefore already exists—it is estimated that there are over 1 billion worldwide—the challenge is in reaching enough sensor owners and persuading them to run MyShake. MyShake must therefore minimize any interference with other phone functions. This means that the applications must run in the background and consume as little power as possible. We must also provide the owner with some value. The current version of the app has a user interface that provides basic information about “recent” (past week) earthquakes as many other apps do. In addition, there is some educational material with information about past earthquakes including videos illustrating the intensity of shaking at the users’ location in those past earthquakes and information on how to be earthquake safe. Finally, users are participating in a citizen science project whereby they are helping to develop and test the MyShake network. Over the coming months and years substantial effort will be needed to maintain and grow the number of users.

One key objective is also to use the network to deliver earthquake alerts as described by *Kong et al*. [2016]. This is not only the right thing to do as it will reduce the impact of earthquakes on MyShake participants, but it is also important for MyShake to provide this service in order to increase that value of the app to phone owners and thereby increase the number of phones running MyShake and recording earthquakes. The fact that we can clearly detect *P* wave arrivals with MyShake will allow the application of *P* wave-based methodologies for early warning as are currently employed by traditional seismic networks running early warning systems [*Allen et al*., 2009].

Perhaps the most important conclusion is that MyShake has demonstrated the potential to collect seismic waveform data of similar density and useful quality to what we are accustomed to in California, Japan, and the few other densely instrumented regions. The network can provide more data in areas with few seismic stations like Nepal, Ecuador, and Haiti, including regions with few stations because significant-risk seismicity is a new phenomenon like Oklahoma and Texas.

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