Earthquake Response Planning for the Southern California Earthquake Center

Workshop Report:
Post-Earthquake Rapid Scientific Response

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Introduction

Rapid scientific response to strong (M≥6), damaging earthquakes, especially in southern California, is central to the mission of SCEC. Each such event presents valuable opportunities to improve physics-based understanding of earthquake phenomena. Response efforts mobilize the core earth-science disciplines of SCEC--seismology, geodesy, and geology--to gather and preserve ephemeral earthquake data. These efforts must occur as quickly as possible, while aftershocks, transient motions, and surface rupture are strongest and best expressed. Thus earthquake response demands experimental design in real time, with information shared freely and efficiently between disciplines, and guided by hypotheses from the cutting edge of earthquake science.

SCEC serves three roles that guide a more effective rapid scientific response to earthquakes:

1. ***Intellectual leadership*** spanning the breadth of earthquake system science.
2. ***Coordination*** of the response of the earthquake science community.
3. ***Communication*** of knowledge to the world at large.

It is important to differentiate the role of SCEC from that of state and federal agencies. The U.S. Geological Survey is charged with the responsibility for recording and reporting earthquake activity nationwide and providing seismic hazard assessment. Similarly, the California Geological Survey is responsible for mapping active faults and defining hazard zones within the state. The SCEC community, which includes many members of these agencies, responds to earthquakes driven by the imperative of scientific inquiry. Its role complements that of the agencies, in particular by fostering partnership with the academic science community.

This document summarizes planning efforts for the SCEC scientific response to the next major earthquake in southern California. It is the outcome of the *Post-Earthquake Rapid Scientific Response Workshop* held on September 7, 2014, just prior to the SCEC annual meeting in Palm Springs, California. There were approximately 100 workshop attendees. Presenters focused on the science questions motivating post-earthquake response, data-gathering and instrument deployment, inputs from other disciplines, and timeframes for response activities. Presenters were also asked to consider how response would adjust to three example earthquake events: A M~7 rural event, much like the large earthquakes that have occurred in southern California during the lifetime of SCEC, a San Andreas event similar to the 1812 or 1857 ruptures, and an urban earthquake with surface rupture. The occurrence of the M6.0 South Napa earthquake two weeks prior to the workshop introduced a fourth, quasi-real time case study that was much discussed during the workshop.

The format of this report follows that of the workshop schedule, focusing first on the fundamental problems of understanding the seismic source and the radiation of seismic energy to produce ground motions. This is followed by the emerging science of earthquake forecasting, for which the cascade of aftershocks is a fruitful testing ground, and an update to the topic of post-earthquake scientific drilling. We then turn to the core disciplines of seismology, geodesy, and geology. These sections are followed by discussion of post-earthquake imaging, which has become an increasingly coordinated activity spanning the fields of geodesy and geology. We conclude with a discussion of earthquake response coordination facilitated by the SCEC response web site and via interactions with other entities -- especially the California Earthquake Clearinghouse.

Source Modeling

Characterizing the seismic source is an interdisciplinary problem. The source represents the entire earthquake rupture process, beginning with the earthquake hypocenter and first-motion tensor, and synthesizing knowledge from seismology, geology and geodesy to model fault rupture time, surface rupture extent, and finite displacement. Source modeling is an important component of earthquake early warning, where the source is determined in real-time, as the earthquake unfolds (e.g., Allen and Kanamori, 2003). The distribution of slip with depth and along strike leads to coulomb stress change on nearby faults and serves as input for predictive models of aftershock locations and post-seismic deformation. Geodetic information is needed from a range of distances from the rupture plane (up to three times the locking depth). This requires knowledge of the full rupture extent, usually from surface-rupture observations by geologists. Separating post-seismic phenomena from coseismic rupture motivates rapid (within 1 day) reoccupation of geodetic benchmarks after an event, prior to the accrual of significant afterslip.

The size of an event, its remoteness, and the density of pre-existing benchmarks all affect the scope of response. Large earthquakes with lengthy surface ruptures are likely to produce a strong signal of coseismic displacement across the permanent geodetic network in southern California. In such cases, post-earthquake data gathering may be focussed on particular experiments to investigate anomalous features of the rupture and to capture post-seismic deformation. For smaller and remote events, re-occupation of existing benchmarks becomes a proportionally more important need for characterizing the source. A coordinated plan to periodic re occupation of existing benchmarks will improve the quality of post-earthquake data.

Ground Motions

The severity of ground motions depends upon characteristics of the seismic source, the path of radiated energy, and properties at a site. Strong earthquakes offer an important opportunity to validate and improve models for ground motion prediction. It is a high priority to identify sites of anomalously strong or especially damaging ground motions during post-earthquake scientific response. Quick deployment of instrumentation in these areas, while aftershock productivity is high, can help to disentangle path versus site effects, and better inform which ground-motion metrics are most correlated with damage. Training field responders to make better observations of structural damage and ground failure could improve this response, especially in areas of poor seismic station coverage. Assessing the effectiveness of ground motion prediction also relies on knowledge of the source, which benefits from timely input from geodesy and geology, including locations of surface rupture and its relationship to previously mapped fault traces.

For characterizing anomalous ground motions, assessment and design of instrument deployment should take place within one to two days of the earthquake origin time. Instruments need to be matched to the setting (urban vs. rural, telecommunications access).

Initially the response plan will consist of targets on a map with a radius of interest and ranked priority. Teams of trained personnel scout sites, secure permits, and deploy instruments. It is important to assess whether adequate trained personnel are available to respond to a large event (Steidl and Cochran SCEC report). The emergence of large-N / wavefield imaging using thousands of small, portable instruments could revolutionize understanding of how the details of earth structure affect ground motions (e.g., Lin et al., 2013), but also presents new logistical challenges.

Both the size of the event and its situation within existing seismic networks determines the scope of the response. A rural event in an area with a sparse seismic network increases reliance on other observations of surface rupture and damage. Issues of site accessibility, population density, and the availability and cell and internet connectivity all affect the style of instrument deployment and thus the effort required. Field response teams from other disciplines can contribute by identifying landowners willing to host instruments in secure locations with existing communications connectivity.

Operational Earthquake Forecasting

Operational earthquake forecasting is the timely dissemination of authoritative information about time dependence of seismic hazard. This is a frontier research-area where earthquakes and their aftershocks provide critical opportunities to validate and improve forecasting techniques. Much effort remains to incorporate existing earthquake forecasts, such as paleoseismologic data and fault maps compiled for the UCERF3 project, into an operational framework before the next large earthquake in California. Also important is to understand the social science and tracking the success of forecasting time-dependence, relative changes in probability for events with very small absolute probabilities of occurrence. For these reasons it is unwise to attempt to roll out a forecasting system during an event sequence. The groundwork must be laid ahead of time.

Operational earthquake forecasting places challenging demands on post-event data gathering. Rapid and detailed knowledge of the mainshock rupture is needed as soon as possible from geology and source modeling. Timely aftershock locations are critical, with magnitude completeness to M0 or lower, and focal mechanisms for as many events as possible. Any time-dependent post-seismic phenomena may impact crustal and fault properties should be incorporated, such as afterslip, post-seismic visco-elastic deformation, and fault-zone healing.

Because any earthquake has the potential to be a foreshock, operational earthquake forecasting is concerned with events of all sizes. In the context of other post-earthquake response efforts, the data needs of operational earthquake forecasting align well with goals of geodesy, source-modeling, earthquake geology. The greatest challenges are in seismology. Achieving a desirable level of magnitude completeness and density of focal mechanisms requires a dense and rapid deployment of seismometers around the rupture. This could be challenging after a major urban event with substantial damage to infrastructure, or for a rural event with sparse station coverage.

Rapid Response Fault-Zone Drilling

After a large earthquake, the potential to gain considerable information about the earthquake process is available through rapid response drilling (Brodsky et al., 2009; 2010). Rapid response drilling into a fault after an earthquake provides important insight into the conditions within a fault that supports earthquake rupture, the stresses on the fault during and after the earthquake, the process by which the fault heals and rebuilds stress, and how the fault zone is affected by other earthquakes and aftershocks. The timescale of rapid response drilling differs from other likely rapid response efforts, but complement each other and ideally entails drilling across the fault slip zone at ~ 1 km depth within ~1-2 years of a large surface rupture. Previous rapid response drilling projects have been successfully completed following the 1995 Kobe, Japan; the 1999 Chi-Chi, Taiwan; the 2008 Wenchuan, China; and the 2011 Tohoku-oki, Japan earthquakes.

Drilling into a fault provides access to fault rocks from depth and allows the structure of the fault zone to be determined and the physical properties to be measured on multiple scales through analysis of core samples and geophysical logging (e.g., Ma et al., 2006; Zoback et al., 2010; Chester et al., 2013; Li et al., 2013; Ujiie et al., 2013). Fault zone drilling also provides the opportunity to measure and monitor conditions within the fault zone and perform in situ borehole experiments (Doan et al., 2006; Kitagawa et al., 2002). Geophysical logging within the borehole contributes to understanding the subsurface geology and fault zone architecture and also allows for determinations of the stress state at the time of drilling through borehole breakout analysis (e.g., Hickman and Zoback, 2004; Lin et al., 2013). If drilling is completed soon enough after an earthquake (within 1-2 years at ~1km depth considering a fault slip of ~5 m or more), there is potential to measure the frictional heat signal and determine the amount of stress that was on the fault during the earthquake (Kano et al., 2006; Tanaka et al., 2006; Fulton et al., 2010; Fulton et al., 2013). A fault-crossing borehole provides an ideal environment for monitoring near-field fault zone processes and access to processes that are otherwise difficult to observe or infer from afar. Installation of downhole monitoring instrumentation can provide a unique insight in the fault healing process and other processes within the active fault zone (Xue et al., 2013; Fulton et al., 2013; Ma et al., 2012). Downhole instrumentation of existing wells and boreholes within the earthquake-affected region, even if they do not cross the fault zone, can also provide useful information on earthquake damage, healing processes, and earthquake interactions and should also be pursued both before a large event and in the immediate aftermath of very large and intermediate-sized earthquakes.

Seismology

Science objectives in source modeling, ground-motion prediction, and operational earthquake forecasting present seismology with an abundance of targets after a major event. The challenge of planning a seismology response is how to balance these targets with limited resources. Instruments deployed for understanding damage and ground motion prediction compete for coverage of aftershocks and examining changing fault-zone properties. There are also trade-offs between quick deployments of standalone instruments versus setting up telemetered stations for real-time data analysis. Prior to an event, it is important to have an up-to-date record of available instruments, and to have trained sufficient personnel for instrument deployment. In a response situation, coordination is crucial in order to avoid redundant instrumentation and balance competing priorities. It is also important that post-earthquake deployments not jeopardize existing agreements for hosting permanent instrumentation. As described above for ground motions, both the size of the event and its situation within existing seismic networks determines the scope of the response. Induced [or suspect of having been induced] seismicity could lead to unconventional political problems in planning a response, as well as land- and data-access issues with private entities.

Distributed sensor networks present new opportunities in seismology response. MEMS sensors and even smartphones can be harnessed to provide widely distributed shaking intensity information. However the data from these instruments are not currently useful for measuring strong ground motions. Vast, 100s to 1000s of instrument-arrays of short-period instruments, known as large-N or wavefield imaging, present exciting new opportunities for understanding the propagation of seismic energy and recording aftershocks (Lin et al., 2013). Instruments such as these are fully three component, self-contained, and can record for over a month. Due to battery-life constraints the current generation of instruments are not suitable for forecasting applications because the data are not telemetered or otherwise available until the instrument is recovered.

Time frames for response are most rapid for recording aftershocks and for understanding fault-zone properties, as these properties change quickly. Knowledge of surface rupture locations is vital for strategizing instrument deployment. Ideally instruments can be deployed within one day of the event, with telemetered data for those instruments that supplement existing station networks for aftershock locations for use in operational earthquake forecasting. Quick deployment also increases the chances of capturing the nucleation process of a large aftershock. Characterizing anomalous ground motions may move at a slightly slower pace, with instrument deployment within 2 to 4 days after an event, or later depending on the productivity of the aftershock sequence.

Geodesy

Earthquakes are natural experiments for probing the rheology of the lithosphere with tectonic geodesy. Coseismic displacements characterize the earthquake source, and are important for modeling three-dimensional elastic strain of the surrounding rock volume, as well as distributed inelastic deformation (Barbot et al., 2009). Quick assessment of displacements is important for operational earthquake forecasting, because stress changes that result may increase hazard on nearby faults (Dieterich, 1992; Stein, 1999), and affect the distribution and rate of aftershocks (Perfettini and Avouac, 2004; Savage et al., 2007). Stress changes also reveal rheological contrasts such as zones of damage surrounding active faults (Fialko et al., 2002). Time-dependent, post-seismic deformation occurs due to afterslip, both within and below the rupture zone, as well as deeper, visco-elastic deformation of the lower crust and upper mantle (Burgmann and Dresen, 2008). Characterizing this transient deformation helps to test deformation models for the base of the seismogenic zone, which is important for understanding the loading of faults during the interseismic period. Post-seismic transient deformation also contributes to earthquake clustering by reloading the source fault (Kenner and Simons, 2005) as well as other, nearby faults (Chery et al., 2001; Freed and Lin., 2002). Rupture end points are particularly important for discriminating models lithospheric rheology (Hearn, 2003).

Earthquake response for geodesy depends upon where the rupture lies within the existing geodetic network. If permanent GPS station coverage is insufficient to characterize the source, more effort must be expended to fill in gaps by resurveying existing campaign GPS benchmarks. Though campaign GPS has been largely superseded by permanent networks, periodic resurveying of campaign benchmarks is a relatively low-cost insurance of getting the best possible pre-earthquake deformation signal and coseismic offset measurement. Radar interferometry also provides continuous coverage if images are sufficiently correlated. Recent and planned missions (Sentinel, NISAR) with shorter repeat-pass intervals will play an important role in source characterization in future earthquakes in California, as will the NASA airborne SAR platform (UAVSAR). Both Sentinel and UAVSAR were employed after the South Napa earthquake to characterize rupture traces and coseismic displacement. UAVSAR proved especially valuable for discovery of secondary traces with very small slips (<5 cm). With adequate resources and access, GPS deployments may be tailored to test mechanisms of post-seismic deformation (Hearn, 2003). Because post-seismic deformation decays rapidly, the sooner that the rupture trace and its endpoints are defined, and the sooner that instruments are deployed, the better the results will be from post-seismic deformation studies. As with seismometer deployments, a pre-event inventory of available GPS instruments, and community coordination immediately after an event, are both needed to in order to avoid redundant instrumentation and balance competing priorities.

Earthquake Geology

The primary goal of geology earthquake response is to capture data that relate ground deformation to the seismologic or geodetic character of the earthquake. Such data can be ephemeral and poorly captured by remote sensing techniques, requiring rapid field deployment and repeat visits to the rupture. Geologists focus much effort on defining the slip distribution of the fault and as it evolves with time. Distinguishing between coseismic and post-seismic (afterslip) displacements, the character of distributed slip and small slip triggered on secondary faults, and later, the rate and character of scarp degradation are all relevant for understanding the temporal evolution of the surface rupture and for developing empirical relationships that are used with paleoseismic data. Related to this, geologists are also concerned with biases in the slip distribution that arise due to variations in the width of the deformation zone. Existing studies show that the type of surface materials (e.g., bedrock versus alluvium, Milliner et al., in press) and the energetics of the rupture itself can impact the distribution of surface slip along strike and with depth. Detailed, quantitative measures of fault slip, distributed deformation, and the geologic materials surrounding the fault zone, are needed to tease out the contributions from each. This is relevant for understanding why some step overs are breached, and where the rupture terminates. Data collection should also extend to regions where no surface slip is observable, but where remotely-sensed data suggest distributed slip occurred.

Understanding rupture direction from geological information could provide powerful new constraints for seismic hazard estimation. A fresh earthquake rupture, where the directivity of slip is known, provides an opportunity to identify features that record the propagation direction. The symmetry of distributed deformation, and damage within the fault zone rocks or sediment have the potential to record such data; its preservation and evolution through time are important metrics.

Geological observations after an earthquake also contribute to understanding strong ground motions, and could better characterize long-term constraints on strong ground motions from fragile geomorphic features and precarious rocks. The distribution of landslides, liquefaction, and rockfalls provide a coupled measure of local site geology and path effects. Detailed mapping of the distribution, magnitude and variability of these effects are needed, so that areas that did experience higher intensity shaking can be distinguished from those with similar geologic materials that did not have the same intensity. Rapid dissemination of this information is desirable to in order to deploy seismometers to better characterize anomalous areas of ground failure.

Immediately following an earthquake, a team of geologists must conduct aerial reconnaissance of the rupture in a helicopter, known as an overflight. This establishes the location and general characteristics of the rupture, and provides critical data for subsequent imagery capture. Following this, the types of data gathering needed to address the geologic questions takes two forms. The first is point data, largely collected by teams of geologists working on the ground using cameras to capture field imagery of the deformation and measuring tapes to document the magnitude of surface slip. The second, newer to geology, are spatially dense data, such as lidar (whether terrestrial, mobile, or aerial) and high-resolution photogrammetry for structure from motion techniques. Both approaches are required, and deployment of people and technology is strongly influenced by remotely sensed data on the deformation field (interferograms and optical correlation mapping), as these data can highlight areas of subtle deformation, motion on secondary faults, or deformation obscured in rugged terrain. For secondary deformation (e.g. liquefaction), maps of peak ground acceleration and data from utilities (broken pipes, etc.) guide the search when the region is large. Mapping of deformation can be slow, and repeat measurements are needed to differentiate coseismic versus post-seismic signals, as well as to densify the original measurements. Sequential, recurring data collection efforts should be expected.

The location and setting of the earthquake will have significant impacts on the geologic response, yet one of the most challenging aspects of any scenario is communication and logistics. If the event is rural, where cellular coverage is limited by geography, of in the case of a large urban event that is also likely to impair cellular coverage, organization of field teams must be facilitated at base camps where satellite phones and/or BGAN (broadband global area network) units can be used to communicate with other scientists and relate relevant data between disciplines. Access challenges will be increased when the earthquake is urban, but logistics such as water and power will be more complicated for a rural event.

Post-Event Imaging

The number of imaging types and platforms available for post-earthquake response has mushroomed over the past decade: Satellite: High-resolution (sub-meter) optical, and synthetic aperture radar (SAR); Airborne: Lidar, SAR, multispectral sensors, digital photography and video; Terrestrial/Near-surface: Lidar (tripod, mobile, balloon), structure-from-motion photogrammetry (ground, drone-based), tripod SAR. Science objectives met from analysis of imagery data include co-seismic deformation (SAR, differential lidar), post-seismic deformation (SAR, terrestrial lidar), fault offset, including time-dependent afterslip, and support for field investigation and mapping of fault rupture.

After an earthquake, the key issues are the timeliness of imagery acquisition, and the dissemination of large data products. In the event of a major disaster, satellite imagery may become freely available for research under the international disaster charter agreement (via the USGS, a charter member, disastercharter.org). Airborne data acquisition requires local coordination with emergency responders, and between agency and academic researchers. This will likely be handled through the California Earthquake Clearinghouse. Generally the USGS leads an initial aerial reconnaissance of surface rupture, which is very valuable for designing other components of response. Agencies (CGS, USGS) also tend to coordinate collection of aerial photography. Small, remotely piloted aircraft (drones) have emerged as a powerful tool for high-resolution data gathering. However there are safety issues that may limit their use in a response situation. The NASA UAVSAR project is emerging as another important resource, especially for revealing very small fault offsets that are not visible to other techniques. Sharing and cataloguing imagery data can be problematic. An automated system is needed to rapidly generate and share image geolocations, browse images, and download links. For imagery collected through the USGS, the HDDS system provides a mechanism for openly sharing data with the community. Google Earth KML format is another accessible way forward to openly sharing imagery data and links among researchers.

Due largely to the costs involved, there is currently no formal approach to post-earthquake airborne lidar data acquisition. It is a high scientific priority to acquire airborne lidar as quickly as possible after an earthquake because of its value for post-earthquake rupture characterization, and, where pre-event data are available, to generate fully three-dimensional near-field deformation fields (Nissen et al., 2012, 2014; Glennie et al., 2014). A coordinated effort is needed to pre-plan a proposal, probably targeting the NSF RAPID grant program or a combination of funding resources. Unlike the case for imagery, there is an established mechanism for lidar data distribution through the OpenTopography portal (opentopography.org).

Terrestrial and near-surface imaging will be primarily investigator driven, but will be most efficient if coordinated among the research community. There will likely be an opportunity to deploy terrestrial lidar from the UNAVCO instrument pool, which requires coordination between operator/engineers, earthquake geologists, and field geodesists. The proliferation of point-cloud data generated from various lidar and structure-from-motion field efforts will require a coordinated mechanism for data archiving and distribution. This could be a merit for expanding the scope of the OpenTopography portal, for example.

Earthquake Response Coordination

Major Southern California earthquakes—1992 Landers (M7.3), 1994 Northridge (M6.7), 1999 Hector Mine (M7.1), 2003 San Simeon (M6.5), 2004 Parkfield (M6.0), and 2010 El Mayor-Cucapah (M7.2)—have been important events for focusing SCEC research and stimulating collaboration. The Center's management structure, as expressed in its working groups, has been able to respond quickly in coordinating field programs with the USGS and other organizations to capture perishable data and conduct post-earthquake studies. Overall post-earthquake scientific response will be managed by the USGS in coordination with the State of California. SCEC has the responsibility for coordinating for the NSF the scientific response to large earthquakes in Southern California (and sometimes elsewhere). Through its cooperative agreements with the NSF and USGS and its contractual arrangements with core and participating institutions, SCEC will provide a well-organized conduit for the funding of scientific investigations in the critical period immediately following a major event. The SCEC components of this response will be managed by the SCEC Director, Co-Director, and staff, and plans will be executed through the SCEC working groups and special teams. SCEC geologists will move quickly to resolve the scope of surface rupture, which will require immediate access to necessary equipment, clearance, and transportation, including helicopters and aerial photography in collaboration with the U.S. Geological Survey, California Geological Survey, and other agencies. SCEC geodesists will quickly install temporary GPS receivers to track post-earthquake slip and coseismic slip during after-shocks, in addition to processing data from PBO. SCEC seismologists will immediately deploy seismometers from SCEC's Portable Broadband Instrument Center into the epicentral region, and request additional instruments from IRIS, to record aftershocks, resolve the properties of the fault rupture, and help assess the potential for additional large events. All these efforts will require coordination with data center seismologists who will be revising real-time information on source properties and ground motions. As observations are reported from the field, the SCEC office of Communication, Education, and Outreach will help coordinate an effective media response with the USGS, State of California, and other organizations.

SCEC has developed an Earthquake Response Site (response.scec.org) to prepare for future earthquakes and to improve post-earthquake communication and coordination capabilities among the SCEC community and its partners. The site has important capabilities including threaded discussions, the ability to post and share files, and to monitor of who is currently online. SCEC scientists, particularly the disciplinary group leaders of the PC have populated the site with an inventory of instrumentation, such as seismometers and campaign GPS instruments. The information includes contact information for SCEC scientists and resources at universities, agencies, and consortia (UNAVCO and IRIS) detailing what's available, where it is, and how to get it. Given that conference calls are critical in coordinating research we have a dedicated 24/7 conference call line (hosted outside California).

Post-earthquake activities will require close coordination among earthquake science and engineering organizations. In 2003, the USGS developed a Plan to Coordinate NEHRP Post-Earthquake Investigations to provide guidance to coordinate post-earthquake investigations supported by the National Earth-quake Hazards Reduction Program (NEHRP) [http://geopubs.wr.usgs.gov/circular/c1242]. The plan addresses coordination of the NEHRP agencies—Federal Emergency Management Agency (FEMA), National Institute of Standards and Technology (NIST), National Science Foundation (NSF), the U.S. Geological Survey (USGS)—and their partners such as SCEC. The State of California has now established a Clearinghouse (www.californiaeqclearinghouse.org) made up of representatives of various agencies and institutions based in the state and is managed by the California Geological Survey, the California Emergency Management Agency, the California Seismic Safety Commission, the U.S. Geological Survey, and the Earthquake Engineering Research Institute. When activated following a significant earthquake, the Clearinghouse is designed to provide official disaster responders with crucial data more efficiently, maximize and expedite data availability to involved agencies and institutions, and effectively utilize the talents of earth scientists, engineers, and others that arrive on the scene wanting to participate in field investigations. There remains work to be done to better integrate the SCEC earthquake response web site, with its aim to coordinating earthquake geoscience response, with the California Earthquake Clearinghouse, which aims to coordinate a broader set of geoscience and engineering response efforts, and to convey findings to emergency responders. Both web sites serve their respective purposes effectively, as demonstrated during recent response efforts (2010 El Mayor-Cucapah, and 2014 Napa). However more interoperability between these sites would be desirable in order to enhance data sharing and coordination.

Scenario exercises to simulate earthquake response should be held annually to prepare the SCEC scientific community. They will be used to practice response and coordination with SCEC and its partners. The exercises will be used to uncover issues we need to resolve, and will enable a more effective response to a real earthquake.

Recommendations and Conclusions

This document highlights current research problems for which rapid scientific response provides one important mechanism for gaining new understanding in earthquake system science. These problems will continue to evolve, and new problems and research opportunities will arise, before the next major earthquake hits southern California. Before then, there are several ways that the SCEC community can increase its preparedness for post-earthquake rapid scientific response:

- Maintain the SCEC response web portal as an easy-to-use, low-overhead forum for coordinating post-earthquake activity, and keep the inventory of locally available seismometers, GPS instruments, and other resources up to date.
- Coordinate planning with IRIS, UNAVCO, and private industry partners for GPS instrumentation, wavefield / large-N seismic array deployment, and terrestrial and mobile lidar surveys after a future earthquake.
- Periodically resurvey campaign GPS benchmarks in southern California to get the best possible pre-earthquake velocity field.
- Train field responders to be broad-based observers of earthquake phenomena, and to identify potential sites for instrument deployment.
- Develop standards for field data collection, transmission, and archiving, mindful of the promising capabilities, as well as the logistical limitations of new technologies.
- Work with the California Earthquake Clearinghouse to become more closely involved in the credential process for access of field responders to disaster sites.
- Continue to practice simulated earthquake response scenarios on an annual basis to prepare the SCEC community for earthquake response.

- Improve ways to share data between SCEC and state and federal agencies (USGS, CGS, and the Earthquake Clearinghouse) through interoperation of response web portals, and by facilitating distributed, open, and timely access to data.
- Develop an instrument deployment plan for aftershock monitoring for Operational Earthquake Forecasting.
- Pre-plan a proposal for post-earthquake airborne lidar survey immediately after an earthquake, aimed at the NSF RAPID grant program, but with anticipated support from other federal agencies (e.g. FEMA).

In closing, the SCEC scientific community draws from wide-ranging expertise in earthquake science, and collectively possesses a deep capacity for effective post-earthquake rapid scientific response. The leadership of the SCEC, and the leaders of the Planning Committee in particular, will be essential to ensuring that post-earthquake response is coordinated among the entire SCEC community. In case lead members of the planning committee are unavailable, co-leaders should serve as backup in order to ensure coordination of response efforts. The roles of the SCEC leadership includes helping to identify leaders of various response activities, linking together efforts from different parts of the earthquake research community, ensuring communication between the SCEC community and NEHRP agencies, and stepping in to fill critical gaps, such as coordinating proposal-writing to fund post-earthquake research activities. As an open collaboration, SCEC is ideally suited to bridge between federal and state agencies with defined response roles, such as the U.S. Geological Survey and the California Earthquake Clearinghouse, and the diverse, entrepreneurial flexibility of academic science.

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