Evaluation of Seismic Hazard Models with Fragile

Geologic Features

by Mark W. Stirling, Michael E. Oskin, J. Ramon Arrowsmith, Anna H. Caklais, Christine A. Goulet, Lisa Grant Ludwig, Albert Kottke, Tamarah R. King, Julian C. Lozos, Chris M. Madugo, Devin McPhillips, Veronica B. Prush, Dylan H. Rood, Norman H. Sleep, and Christine E. Wittich

ABSTRACT

We provide an overview of a 2019 workshop on the use of fragile geologic features (FGFs) to evaluate seismic hazard models. FGFs have been scarcely utilized in the evaluation of seismic hazard models, despite nearly 30 years passing since the first recognition of their potential value. Several studies have recently begun to focus on implementation of FGFs in seismic hazard modelling. The workshop was held in order to capture a “snapshot” of the state of the art in FGF work, and to define key research areas that would increase confidence in FGF-based evaluation of seismic hazard models. It was held at the annual meeting of the Southern California Earthquake Center (SCEC) on 8 September 2019, and the conveners were Mark Stirling (University of Otago, New Zealand) and Michael Oskin (University of California, Davis). The workshop attracted 44 participants from a wide range of disciplines. The main topics of discussion were: FGF fragility age estimation (age at which a FGF achieved its current fragile geometry); fragility estimation; FGF-based evaluation of seismic hazard models; and ethical considerations relating to documentation and preservation of FGFs. There are now

many scientists working on, or motivated to work on, FGFs, and more types of FGFs being worked on than just the precariously-balanced rock (PBR) variety. One of the ideas presented at the workshop is that fragility ages for FGFs should be treated stochastically rather than assuming all share a common age. In a similar vein, new studies propose more comprehensive methods of fragility assessment beyond peak ground acceleration and peak ground velocity-based approaches. Two recent studies that apply PBRs to evaluate probabilistic seismic hazard models use significantly different methods of evaluation. Key research needs identified from the workshop will guide future, focused efforts that will ultimately facilitate the uptake of FGFs in seismic hazard analysis.

INTRODUCTION

This paper summarizes the results of a workshop held in conjunction with the annual meeting of the Southern California Earthquake Center (SCEC) on 8 September 2019 (SCEC, 2019). The half-day workshop was held in recognition of the growing body of work focused on the use of fragile geologic features (FGFs) to evaluate probabilistic seismic hazard (PSH) models, and emergence of different methods of application and evaluation. FGFs are delicate natural features such as paleoseastacks, tufa towers, hoodoos, badlands, and unstable regolith that can potentially be used to provide constraints on past ground motions. The workshop goal was to determine the state of the art of FGF-PSH model evaluation, and identify the work and resources needed in order to achieve defensible evaluation methods for future industry application. While FGF research has long sat at the edge of practical hazards science, recent industry-funded efforts in New Zealand and California (Stirling et al., 2019; Caklais et al., 2020; Caklais et al., in press) have been focused on developing defensible methods for using FGFs to evaluate and modify PSH models.

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50 For our workshop we assembled a group of 44 scientists either possessing experience in studies
51 of FGFs, or not currently involved in FGF work but possessing relevant expertise (Table 1).
52 The main areas of expertise include: geology and surficial processes relevant to the formation
53 and identification of FGFs; methods for fragility and fragility age estimation; statistical
54 approaches for PSH model evaluation; and consideration of ethical guidelines for study of these
55 rare, irreplaceable landforms. The workshop was consequently subdivided into the following
56 sessions: (1) geomorphology and fragility age estimation; (2) fragility estimation; (3)
57 evaluation of seismic hazard models; and (4) ethical considerations.

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59 In order to provide context for our workshop, the history of key milestones in FGF work are
60 summarised as follows:

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- 62 • Recognition of PBRs as paleo-indicators of unexceeded ground motions, and use of
63 rock varnish to develop age constraints (Brune and Whitney, 1992).
- 64 • Southern California-wide comparison of unexceeded peak ground accelerations
65 (PGAs) estimated from PBR geometries to PGAs from PSH maps for long return
66 periods. This simple comparison was the first clear revelation of a large discrepancy
67 between the two (Brune, 1996).
- 68 • Examination of the failure of natural rock columns showed that column heights would
69 be <50 m because their vibrational mode matches typical seismic shaking (Hall, 1996).
- 70 • First use of cosmogenic isotope exposure dating methods to constrain the fragility age
71 of PBRs (Bell et al., 1998).

- 72 • Studies of the site conditions of PBR sites in southern California to assess whether
73 unusual site conditions could be controlling the distribution of PBRs. No such site
74 conditions were shown to exist (Abbott et al. 2001; Stirling et al. 2002).
- 75 • Development of a deterministic method for testing PSH hazard curves with PBRs
76 (Anderson and Brune, 1999). This method came out of the recognition that the ergodic
77 assumption used routinely in probabilistic seismic hazard analysis (PSHA) may lead to
78 ground motions that exceed the fragility of the PBRs.
- 79 • First study of PBRs outside of North America, which was an application of cosmogenic
80 dating methods and the Anderson and Brune (1999) method to evaluate national seismic
81 hazard maps in New Zealand (Stirling and Anooshehpour, 2006).
- 82 • The multidisciplinary Yucca Mountain Extreme Ground Motion project (Abrahamson
83 and Hanks, 2008; Hanks and Abrahamson, 2008; Hanks et al., 2013) applied the
84 Anderson and Brune method (which was named the “Points in Hazardspace” method
85 in those papers) to a range of FGFs. The method tested the very high ground motions
86 estimated for the Yucca Mountain site for long return periods. The project supported a
87 wide variety of work on probabilistic fragility estimation and dating of FGFs with
88 cosmogenic ^{36}Cl exposure ages (Balco et al., 2011; Purvance et al., 2012; Hanks et al.,
89 2013).
- 90 • A workshop was held to bring together relevant scientists to review the work done to
91 date on PBRs, and to assess whether PBRs could be used to test the national seismic
92 hazard maps for the USA (Anderson et al., 2011).
- 93 • Recognition of the trade-off between making detailed 3D measures of fragility for a
94 few PBRs versus making 2D fragility measures for many PBRs in a landscape (Haddad,
95 et al., 2012a). The latter approach was found to be the most informative for

development of a PBR fragility distribution, and for investigating the geomorphic controls on PBR development and preservation (Haddad, et al., 2012b)

- Development of a fully probabilistic method to test PSH models with PBRs (Baker, et al., 2013).
- Application of the fully probabilistic method (Baker, et al., 2013) to the Clyde Dam site in New Zealand, representing the first-ever use of PBRs to inform design ground motions for a major engineered structure (Stirling et al., 2019).
- Application of the fully probabilistic method (Baker, et al., 2013) to the Double Rock site of coastal central California (Caklais et al., 2020; Caklais et al. in press).
- The very recent work documented in this paper.

GEOMORPHOLOGY AND FRAGILITY AGE ESTIMATION

A number of focused studies of FGF geomorphology and fragility age dating have taken place over the last decade. These studies focus on characterizing a group of FGFs in detail to understand their fragility age and resistance to earthquake shaking. Studies of granitic precariously-balanced rocks (PBRs) in the Mojave Desert (Rood's presentation; Fig. 1) use cosmogenic exposure age dating techniques to date the PBRs through modeling the observed radionuclide concentrations according to a simple vertical exhumation model (Balco et al., 2011). The exhumation model is well suited to describing the progressive vertical exhumation of granitic corestones. The key end result is to establish the fragility age, which is the age at which the surrounding weathered rockmass is removed and the PBR achieves the present unstable shape. The fragility age distribution for PBRs in the Mojave Desert seems to range from the thousands to tens of thousands of years (e.g. Balco et al., 2011), which is interpreted to be indicative of a stochastic process of PBR formation and destruction over time. This

contrasts with the early studies which suggested the PBRs to have a singular, common fragility age of early Holocene (e.g. Brune, 2002), and gives support to constraining the age of each PBR on a case by case basis. A possible alternative solution for addressing the uncertainties of FGF fragility age was by way of a probabilistic fragility age, which could be assessed from a FGF landscape through an understanding of the balance of background and episodic surficial processes in landscape evolution (e.g. Oskin's presentation; Prush and Oskin, 2020).

Cosmogenic exposure age dating methods have also been applied to constrain the fragility age of seven PBRs at the Double Rock site, situated in a high seismicity, plate boundary setting in coastal central California (Caklais et al., 2020; Caklais et al. in press; Fig. 2). Here, modest uplift rates preserve ancient coastal landforms as FGFs, and these have formed by weathering and removal of blocks formed along the fractures and steeply-dipping bedding planes of chert paleo-sea stacks. Cosmogenic exposure ages of rock surfaces on all sides of the FGFs exposed by block removal have yielded fragility ages in the tens of thousands of years (Caklais et al., 2020).

The variety of fragility ages found in previous studies suggests that a probabilistic approach to age and fragility may be warranted. In a study of a subset of about 50 schist PBRs and damaged outcrops in the low seismicity Otago region of New Zealand, Stirling et al. (2019) utilized cosmogenic dating methods to determine a wide range of fragility ages of up to tens of thousands of years (Fig. 3; Stirling et al. 2019). Furthermore, damaged outcrop ages show consistency with PBR fragility ages, suggesting that landscape modification events can lead to the simultaneous creation or destruction of FGFs.

Recent studies of fragile sea-stacks in Oregon (McPhillips's presentation) have been at the reconnaissance level, in that features have been documented (Fig. 4), but no detailed fragility age dating studies have been conducted as yet. FGF ages have only been broadly inferred from estimates of coastal retreat rates. More work on these features is warranted, given that these FGFs hold the potential to provide ground motion constraints on great Cascadia subduction interface earthquakes. Also, sea stacks will be more abundant than other types of FGFs along rocky coastlines. Sea stack fragilities generally agree with scenario-based estimates of Cascadia megathrust earthquake motions (Fig. 5; Abrahamson et al., 2016; McPhillips and Scharer, submitted), but future work must better understand the evolving fragilities of coastal FGFs.

FRAGILITY

The workshop offered a number of presentations on FGF fragility, and some observations of toppled FGFs during the M7.1 2019 Ridgecrest earthquake. One study (Arrowsmith's presentation) showed the use of machine learning methods and physics-based rigid-body dynamics simulations to examine whether the observed size-frequency distributions of fields of PBRs could be a consequence of strong ground motions (Erez et al., 2015; Hamano et al., 2016). The concept of PBRs being produced as well as destroyed by strong ground motions has also been suggested by the Stirling et al. (2019) study in New Zealand.

More than one method now exists for estimating FGF fragility, and this is mainly the result of ongoing efforts at the Double Rock site. Caklais et al. (in press) apply both PGA and peak ground velocity/PGA (PGV/PGA)-based probabilistic fragilities for the FGFs at the Double

Rock site using the method of Purvance et al. (2008). The most recent work at the site (Wittich's presentation) shows PBRs to be sensitive to several factors, including pedestal interface geometry (shape and roughness), and the type of motion induced at this interface (rocking, sliding, and twisting). Peak horizontal velocity proves to be the most important parameter for causing overturning (Wittich et al., 2018; Wittich and Hutchinson, 2019).

Stirling et al. (2019) have developed a distribution of PGA-based deterministic fragilities for a group of PBRs at the Clyde site from the PBR geometries (e.g. Brune, 2002; Stirling and Anooshehpour, 2006; Stirling et al., 2019). The fragilities are widely varying, with one of the PBRs able to be rocked by hand (Fig. 3), and clearly representing the extreme lower bound of the fragility distribution. The composite fragility distribution represents the collective fragility signal of the population of PBRs at the site, which is effectively equivalent to the fragility distribution of a random PBR (Abrahamson, written communication, in Stirling et al., 2019).

While no fragility studies have been carried out on FGFs in the vicinity of the M7.1 2019 Ridgecrest earthquake, reconnaissance observations show that the earthquake did shake some FGFs down at the Trona Pinnacles site, located 15 km from the earthquake surface rupture. Though the event toppled some features (Fig. 6a), it also left some precarious features standing (Fig. 6b). Ongoing work at the Trona Pinnacles site (Goulet's presentation) will model the changes produced by the earthquake from differential photogrammetry, and track the paths of toppled blocks. This could eventually serve as a calibration for past major earthquakes which may have produced more significant damage at the site in the last 2000 years. Nearby earthquake sources include the Garlock fault (Dawson et al., 2003) and Panamint Valley-Searles Valley low-angle normal fault system (Walker et al., 2005).

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193 The concept of what represents a FGF has broadened somewhat in recent years from those of
194 PBRs and fragile outcrops, and future efforts will need to be focused on understanding the
195 fragility and associated fragility age of the additional FGF categories. Recent studies in the
196 Parkfield and Whittier Narrows areas of California (Sleep's presentation) suggest that the near-
197 surface rock mass in hilly terrain shows a reduction in shear modulus over time, which is in
198 essence equivalent to an increase in fragility (Sleep and Nakata, 2019). The likelihood of
199 gravitational failure during strong earthquake shaking would therefore increase as a function
200 of time. This abundant category of FGF is potentially useful as a regional shaking hazard
201 constraint.

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203 **SEISMIC HAZARD MODEL EVALUATION**

204

205 A range of studies have addressed ways of evaluating PSH models, predicted ground motions,
206 and fault rupture models. The use of PBRs to evaluate PSH models at the Double Rock and
207 Clyde sites (Stirling et al. 2019; Caklais et al., 2020; Caklais et al. in press) applied the best-
208 estimate fragility age of PBRs to evaluate the seismic hazard. Specifically, the minimum
209 fragility age ranges for the two sites (20 to 30 kyr age) were used with the adapted versions of
210 the method of Baker et al. (2013). The Baker et al. (2013) method was originally developed to
211 test site-specific hazard estimates at Yucca Mountain using PBR fragility functions (Hanks et
212 al., 2013). The adapted Baker et al. (2013) approach requires selecting a probability of survival
213 of the PBR, and then evaluating the hazard curves produced from logic trees according to the
214 survival probability. For the Caklais et al. (in press) study a 5% probability of survival was
215 used, but a 1% probability was also considered. In the Stirling et al. (2019) study, a probability
216 of survival of 5% was used. A fragility defines the probability of failure as a function of the

input motion parameters, and the annual failure (overturning) rate can be calculated by convolving the fragility and hazard curves. In the Caklais et al. (in press) study, each PBR was considered independently, and then detailed analyses were performed using the most fragile PBR (the PBR that most significantly reduced the hazard). In the Stirling et al. (2019) study, fragility curves from multiple PBRs were combined and used to test each branch of the Clyde logic tree. Individual branches found to overturn the PBRs with greater than 95% probability (survival probability of <5%) were eliminated from the PSH model. Both studies showed significant reductions in PSH. For example, a 20% reduction in 10 kyr hazard was noted at the Clyde site (Stirling et al., 2019), and 30% reduction in 10 kyr hazard at the Double Rock site (Caklais et al., 2020; Caklais et al., in press). The two approaches (using each PBR probabilistic fragility individually vs. combined deterministic fragility distribution for a population of PBRs) were briefly debated at the workshop. Clearly, future PBR-PSH model evaluation methods will require expert judgement based on the quality and quantity of available data. To this end, recent efforts by Abrahamson and Kottke (in review) have focused on using the Double Rock PBR data to examine the Caklais et al. (in press) logic tree branches for the site and outline a process for incorporating the presence of the PBRs into the weighting of logic-tree branches for specific fault sources (Hosgri and Shoreline faults; Fig. 7).

Studies of FGFs within the intraplate setting of interior Australia focus on identifying features, understanding their age and genesis, and assessing their utility for constraining PSH models in regions of low earthquake probability. Findings indicate that the slow surficial processes still effectively outpace the recurrence of earthquakes, rendering FGFs only marginally useful for constraining past earthquake motions (King's presentation). Conversely, when intraplate earthquakes do occur, field observations indicate that strong motions are sufficient to topple PBRs. Observations made following the M6.1 2016 Petermann Ranges earthquake in Northern

Territory include flipped, tossed and rotated rocks near the epicentre. These observations are effectively the compliment of PBR studies, as they provide information on ground motion exceedance, as well as on rupture dynamics. The observations suggest there was a systematic change in ground motion directivity along the rupture, and as such provide valuable constraints on ground motions at the source.

Rupture and ground motion modeling of San Andreas system faults in Southern California have compared factors such as rupture segmentation and directivity to the presence of PBRs close to the ruptures (Lozos's presentation). The survival of the PBRs in these situations imply that ground motions close to major active strike-slip faults are consistently low from event to event, given that the PBRs are old enough to have survived multiple large near-field earthquakes (Grant Ludwig et al., 2015).

ETHICAL CONSIDERATIONS

With the growing interest in FGF research, the workshop provided an opportunity to discuss issues relating to the management and protection of FGFs as delicate, spectacular, and scientifically important landforms. Related to this is the appropriate management and publication of FGF results (Grant Ludwig's presentation). FGFs can have aesthetic value (e.g., FGFs within Arches National Park, Utah), cultural value (e.g., Monument Valley), and scientific value (e.g., Mojave Desert, Double Rock and Otago PBRs). The challenges of managing these features in order to preserve them from destruction comes down to land use and property ownership considerations. FGFs within national parks, national monuments, scientific reserves, and the like are obviously in the best land management situation with respect to preservation, but FGFs in public or private lands are at risk of damage through

vandalism or human development (housing developments, industrial projects, and roading). In situations where it is not possible to preserve the FGFs, then archiving of comprehensive records of the FGF is of critical importance. A SCEC PBR database was initiated by James Brune around 15 years ago, but never completed and made public. The workshop participants concluded that the database could be rejuvenated in order to comprehensively document all FGFs, and be a primary resource for facilitating the preservation of FGFs and the associated records. The workshop discussions used the example of archaeological sites as a model for the management of FGFs. The archaeology profession has formal policies and procedures in place to ensure the careful documentation, and where possible, preservation of important sites (Beaudry, 2009; Chartered Institute for Archaeologists, 2014). Table 2 shows how the conditions applied to archaeological sites could be readily transferred to FGF research:

DISCUSSION

Our workshop demonstrates that there has been a range of work on the use of FGFs to constrain seismic hazard models in recent years. It is now clear that PBRs are no longer the only focus of FGF research. Studies of the non-PBR FGFs identified to date (e.g. Hall, 1996; Anooshehpour et al., 2013; Moore, et al., 2019; Finzi, et al., in review) will greatly enhance the opportunity for using FGFs to evaluate PSH models. The estimation of fragility for these FGFs will be a significant challenge, given that they have not seen the same focused efforts that have gone into PBRs. Similarly, only limited efforts have gone into constraining ground motion exceedance through observations of rocks displaced by earthquake motions. Another significant challenge will be to constrain the fragility age of FGFs, a topic that has stimulated significant research to understand both FGF evolution, and the age distribution of multiple FGFs.

Two detailed studies summarised at the workshop use adaptations of the Baker et al. (2013) method to evaluate PSH models using PBRs. One stands as the first-ever use of PBRs to modify design spectra for a major engineered structure (N. Abrahamson written communication; Stirling et al. 2019). These studies continue to show the hazard estimates to be overestimated with respect to the age and fragility of PBRs, a suggestion originally made by Brune (2002), and later quantified during the Yucca Mountain investigations (Hanks et al. 2013).

An important, largely overlooked issue raised at the workshop is that of ethical considerations. This is a recognition of the importance of documenting and preservation of FGFs as important non-renewable features, and using the management of archaeological sites and data being seen as a useful analog.

Looking to the future, the workshop discussions recognised that FGF fragility age dating methods have contributed hugely to our understanding of the timescale of PBR formation and preservation, but are expensive, time-consuming, and require special expertise. For FGFs to be readily useable in the evaluation of PSH models, the community might consider continuing to undertake case studies that require these specialist age dating methods, but also develop more time and cost-efficient methods to provide useful fragility age constraints. However, the results of these fragility age studies in the Mojave Desert show that populations of PBRs are produced by a stochastic process, with the implication that the fragility ages should not all be treated as a single value. Instead, a probabilistic FGF age may be able to be assessed for a population of PBRs through an understanding of the balance of background and episodic surficial processes in landscape evolution (e.g., Prush and Oskin, 2020).

The case studies in New Zealand (Stirling et al., 2019) and central California (Caklais et al., in press) also effectively address a frequently-voiced concern; that the surviving PBRs may be the remnants of a former larger population that has been mostly obliterated by strong earthquake shaking. While this may be a valid concern for areas where PBRs are extremely rare, the case study areas were chosen because of the abundance of PBRs in each. The Stirling et al. (2019) study identified > 20 PBRs and about 50 FGFs in an area less than 25 km², and around 20 FGFs were observed in the much-smaller Double Rock area (Caklais et al., in press). Furthermore, the observations of the distribution and age of damaged outcrops, toppled boulders, soils and sediments in the case studies also provide a wider understanding of the rates of surficial processes that would lead to destruction of the PBRs. The bottom line from the case studies is that non-trivial populations of PBRs have collectively survived multiple large near-field earthquakes.

The recent adaptations of the Baker et al. (2013) method of PSHA-PBR evaluation have differed in the way the PBR fragilities have been developed to evaluate the respective PSH models. The development of a probabilistic fragility function for each individual PBR as the basis for PSHA model evaluation (Caklais et al., in press) differs from the combination of deterministic PBR fragilities into a singular theoretical fragility distribution (Stirling et al. 2019). The PSHA model for the Double Rock site was evaluated based on the vector hazard PGA and PGV/PGA-based probability of toppling of the most fragile PBR at the site (Caklais et al., in press). In contrast, the fragility distribution for the Clyde site was constructed by combining the deterministic PGA-based fragilities of the multiple PBRs near the site in order to estimate the probability of toppling effectively equivalent to that of a theoretical random PBR at the site (Stirling et al., 2019). The former approach places high importance on the individual PBRs, whereas the latter approach places importance on the center, body and range

of a PBR fragility population. In application of both of these methods, a threshold probability of survival must be selected, and guidance as to how this decision should be made needs to be investigated. There are alternative interpretations of what information a collection of PBRs at a site provides.

The observations of damaged and undamaged FGFs at the Trona Pinnacles site near the M7.1 2019 Ridgecrest, California earthquake, and displaced rocks at the M6.1 2016 Petermann Ranges, Australia earthquake site reinforce the learning opportunities to be gained from careful field observations following the occurrence of major events. These observations provide information on both non-exceedance and exceedance of ground motions. Future studies at the Trona Pinnacles may be focused on using remote sensing imagery pre and post-earthquake to assess total damage, and examining the considerable damage to the pinnacles that has been caused by prehistoric large earthquakes on nearby faults.

Recent work on PBR fragility has shown that the Brune (2002) and Purvance et al. (2008) fragility assessment methods do not completely account for important parameters such as the frequency dependence of PBR toppling (e.g. Purvance, 2008). Large PBRs may be more sensitive to long period motions than shorter PBRs, but no research has formally addressed this topic to date.

Southern California-based studies have suggested that fault segmentation and rupture directivity scenarios can be tested with PBRs along the San Andreas fault (Grant Ludwig et al., 2015). The use of PBRs in this context is innovative, and promises to contribute to rupture simulation modeling in the future. An interesting aspect of this work is that the spatial distribution and fragility of PBRs in relation to the San Andreas and San Jacinto faults requires

the ruptures to propagate in specific ways across repeated earthquake cycles (Grant Ludwig et al., 2015; Lozos, 2015; Lozos et al., 2016). Such constraints on segmentation behavior could greatly reduce the number of computations required in rupture simulation models.

Specific research needs arising from the workshop are summarised in Table 3. These needs, along with the associated benefits (also in Table 3) could be used as a basis for justifying and directing FGF research into the future. Ultimately FGFs could have utility in constraining of PSH models at all scales, from detailed site-specific engineering applications, to national-scale seismic hazard models. The former applications have already commenced in New Zealand (Stirling et al., 2019), and the current update of the New Zealand national seismic hazard model will consider historical and PBR evaluation criteria (Stirling and Anooshehpour, 2006; Stirling and Petersen, 2006; Stirling and Gerstenberger, 2010). However, a significant challenge influencing the more widespread use of such evaluation criteria will be an acceptance of the value of the criteria by PSHA practitioners, engineers, and strong motion seismologists. We will have to come up with strategies for bringing these professionals along with us while we are conducting the actual research.

CONCLUSIONS

We have provided an overview of our recent workshop on the use of FGFs to evaluate seismic hazard models. There is significant community interest in the topic, despite formerly being a focus of just a small cadre of scientists. Support from the industry in recent years has resulted in two major site-specific studies that used PBRs to evaluate PSH models, and these have stimulated awareness and built a track record of rigorous analysis. FGFs now include many more types of features than just PBRs, which means that future PSH model evaluations will be

less limited by the availability of PBRs. Enriched understanding of the parameters that control FGF fragility, and the stochastic nature of fragility age are also being explored. Fragility age assessment remains a valuable, but specialized area that is very time consuming and expensive, so future efforts could be focused on both increasing the application of modern exposure dating methods to a broad range of FGFs, and also finding more cost-effective and time-effective ways of providing these age assessments. Effort could also be put into working out how best to use FGF data in PSH model evaluation. Because of their rarity and irreplaceable nature, FGFs could be formally classed as non-renewable features of high scientific value, and the associated datasets comprehensively developed and managed.

DATA AND RESOURCES

This paper is constructed from notes taken at the workshop by the conveners Mark Stirling and Mike Oskin, along with presentations, abstracts and edits provided by the other co-authors. The sources of images are as follows: Fig. 1 from Balco et al. (2011); Figs. 2, 3 and 5 from Mark Stirling; and Fig. 4 from Kate Scharer.

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Mark W. Stirling
Otago Earthquake Science Group
Department of Geology
University of Otago
PO Box 56
Dunedin
New Zealand

571 Michael E. Oskin
572 Veronica B. Prush
573 Earth and Planetary Sciences
574 UC Davis
575 One Shields Avenue
576 Davis CA 95616
577 USA
578
579 J Ramon Arrowsmith
580 School of Earth and Space Exploration
581 Arizona State University
582 Tempe, AZ 85287-6004,
583 U.S.A.
584
585 Anna H. Caklais
586 Department of Civil and Environmental Engineering
587 Imperial College London
588 SW7 2AZ
589 UK
590
591 Christine A. Goulet
592 Southern California Earthquake Center

593 University of Southern California
594 3651 Trousdale Parkway #169
595 Los Angeles, CA 90089-0742
596 USA
597
598 Lisa Grant Ludwig
599 Department of Population Health and Disease Prevention
600 University of California, Irvine
601 653 E. Peltason Drive,
602 Irvine, CA 92697-3957
603 USA
604
605 Albert Kottke
606 Chris M. Madugo
607 Pacific Gas and Electric Company
608 77 Beale St,
609 San Francisco, CA 94105
610 USA
611
612 Tamarah R. King
613 Department of Earth Sciences
614 University of Oxford

615 Wellington Square
616 Oxford OX1 2JD
617 UK
618
619 Julian C. Lozos
620 Department of Geological Sciences
621 California State University, Northridge
622 18111 Nordhoff Street,
623 Northridge, CA 91330
624 USA
625
626 Devin McPhillips
627 US Geological Survey
628 525 South Wilson Avenue
629 Pasadena, CA 91106
630 USA
631
632 Dylan H. Rood
633 Department of Earth Science and Engineering
634 Royal School of Mines

635 Imperial College London
636 SW7 2AZ
637 UK
638
639 Norman H. Sleep
640 Department of Geophysics
641 Stanford University
642 373A Mitchell Building
643• Stanford, CA 94305-2215
644• USA
645
646 Christine E. Wittich
647 Department of Civil and Environmental Engineering
648 University of Nebraska-Lincoln
649 2200 Vine St.,
650 Lincoln, NE 68583-0855
651 USA
652
653
654

Figure 1

Figure 1: Example of granite PBR from the western San Bernardino Mountains, California. The image shows sample locations for cosmogenic dating, and labels used to develop 3D models from photogrammetry.

Figure 2

Figure 2: PBR from the Double Rock site in coastal central California. The PBR is approximately 2 m tall. The red spots on the PBR are pieces of marker tape used to develop a 3D from photogrammetry.

Figure 3

Figure 3: PBR from the Clyde site in central Otago, New Zealand. Height of the entire feature is approximately 3 m.

Figure 4

Figure 4: Fragile paleo-seastack from Bandon Beach, coastal Oregon. The feature is about 11 m in height.

Figure 5

Figure 5: Graph of 0.2 s spectral acceleration as a function of source-to-site distance in southern Oregon from a Mw9.0 Cascadia megathrust earthquake (solid and dashed sloping lines representing median and 1 sigma, respectively). FGF fragilities are also plotted (black diamonds are FGFs that have likely survived at least one megathrust earthquake, and gray diamonds are FGFs that have likely never experienced one; McPhillips and Scharer, submitted). Distances are plotted relative to the 1 cm/yr locking depth contour (Frankel et al., 2018). Field evidence for recent erosion and shape change suggests that the sea stack MP-01 (labelled) may be an outlier.

(a)

(b)

Figure 6: The Trona Pinnacles site, located approximately 15 km from the epicentre of the 7.1 2019 Ridgecrest, CA earthquake: (a) shows a FGF that was toppled by the earthquake (the large boulder towards the lower left of the image); and (b) shows a FGF still standing after the earthquake, and a large FGF toppled prior to the earthquake. Images from Mark Stirling.

Figure 7

Figure 7: Double Rock site in coastal central California, showing the fractions of Hosgri and Shoreline fault logic tree branches that are consistent with a $\geq 5\%$ PBR survival probability. The fractions are grouped by slip rate, and show that survival of the PBR is strongly influenced by the slip rate of the Hosgri fault, but not sensitive to the slip rate of the Shoreline fault. This information can be used to identify logic tree branches that should be revisited and reassessed.

Table 1. 2019 workshop presenters, titles, and title categories.

Presenter	Title	Category
Dylan Rood	Exposure dating of precariously-balanced rocks	Geomorphology and fragility age estimation
Devin McPhillips	Fragile sea-stacks in the Pacific Northwest	Geomorphology and fragility age estimation
Mike Oskin and Veronica Prush	A Probabilistic Approach to Dating Fragile Geomorphic Features?	Geomorphology and fragility age estimation
Ramon Arrowsmith	2D traits and 3D models	Fragility estimation
Christine Wittich	Geometry data acquisition and fragility	Fragility estimation
Norman Sleep	Shallow ambient rock stress, topography, and non-traditional FGFs	Fragility estimation
Albert Kottke	Using FGFs to inform ground motion hazard	Evaluation of seismic hazard models
Mark Stirling	Clyde Dam, New Zealand case study	Evaluation of seismic hazard models
Anna Caklais	Hazard evaluation with PBRs: example from central CA	Evaluation of seismic hazard models
Tamarah King	Australian FGFs and past ground motions	Evaluation of seismic hazard models
Julian Lozos	Application of FGFs to dynamic rupture modeling	Evaluation of seismic hazard models
Lisa Grant Ludwig	Ethical considerations for FGF research	Ethical considerations

Table 2. Archaeology research guidelines applicable to FGF research

Investigators must know and comply with all laws of the land.
Conservation of sites and material as resources for study and enjoyment. Where such conservation is not possible, the sites need to be thoroughly archived.
Adequate justification needs to be given prior to the destruction of scientifically important sites.
Research needs to be conducted in such a way that valuable and reliable information about the past is provided.
Results should be published and made available to the public in a timely manner, including depositing data in an appropriate repository.
Appropriate credit for work done by others should be provided.

Table 3. Research needs for FGF work according to the categories of: (1) geomorphology and fragility age estimation; (2) fragility estimation; (3) evaluation of seismic hazard models; and (4) ethical considerations.

Topic	Research needs	Gaps in data and knowledge	Benefits
Geomorphology and age estimation	<p>Additional detailed case studies of the fragility age of various categories of FGFs using state-of-the-art and new exposure dating methods</p> <p>Cost and time-effective dating of the fragility age of FGFs</p>	<p>Age control for FGFs limited to four well-studied PBR areas (Mojave, Double Rock, Clyde, and Yucca Mountain)</p> <p>Time and cost-effective geomorphic interpretation-based methods for quantifying fragility age of individual features as well as an ensemble of features</p>	<p>Greater uptake of FGF data for constraining seismic hazard models</p>
Fragility estimation	<p>Case studies of the fragility of various categories of FGFs</p> <p>Cost and time effective methods for quantifying fragility that accounts for frequency content of ground motions</p> <p>Methods for quantifying uncertainty in FGF fragility</p>	<p>Quantification of frequency-content-dependent fragility</p> <p>Cost and time-effective field-based fragility assessment</p> <p>Methods for quantifying FGF fragility uncertainty</p>	<p>Greater confidence in fragility assessment</p> <p>Greater uptake of FGF data for constraining seismic hazard models</p>
Evaluation of seismic hazard models	<p>Resolving why ultra-fragile FGFs exist in fields of less fragile FGFs, and whether they should be considered in the evaluation of seismic hazard models</p> <p>Influence of slip type and rupture directivity on near-fault FGF distributions</p>	<p>The spatial distribution of site response within a field of FGFs</p> <p>Whether seismic events can haphazardly enhance fragilities and produce ultra-fragile FGFs</p> <p>Whether repeating rupture</p>	<p>Enhanced treatment of the range of FGF fragilities in the evaluation seismic hazard models</p> <p>Greater uptake of FGF data for constraining</p>

	Alternative methods for using FGF data to constrain seismic hazard models	<p>characteristics can influence near-fault FGF distributions</p> <p>Direct use of FGF data in source and ground motion logic trees</p>	seismic hazard models
Ethical considerations	Update of the UNR/SCEC FGF database, development of guidelines for the management and preservation of FGFs as features of scientific value, and of minimum requirements for data capture if FGF destruction is imminent.	<p>Up to date FGF database with open access</p> <p>Guidelines for FGF management and preservation</p> <p>Rapid data mining procedure for FGFs in areas of imminent land development</p>	<p>Up to date FGF database</p> <p>Greater appreciation of the scientific and practical value of FGFs</p> <p>Ability to capture valuable FGF data before it is forever lost</p>