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Surface rupture database for Seismic Hazard Assessment

2015 Report of the Kick-Off Meeting of the "SURE Database" Working Group

RT/PRP-DGE/2016-00022

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SURFACE RUPTURE DATABASE FOR SEISMIC HAZARD ASSESSMENT

2015 REPORT OF THE KICK-OFF MEETING OF THE "SURE DATABASE" WORKING GROUP

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ABSTRACT

The goal of the fault displacement hazard assessment is to describe and quantify the permanent displacement that can occur during an earthquake at the ground surface. One of the methods to do so is probabilistic (PFDHA: Probabilistic Fault Displacement Hazard Analysis) and is basically based on empirical approaches which allows predicting the possible displacement on the earthquake fault (« on-fault » displacement) and off this major fault on other fault segments (« off-fault » displacement). Predictive relationships (also called “regressions”) were published in the last 15 years (e.g. Youngs et al., 2003; Petersen et al., 2011; Takao et al., 2013) and they are based on data catalogs limited in case numbers and in magnitude ranges.

Because there are practical applications of PFDHA in terms of engineering, there is concern in the geologists and engineers communities, for instance in the INQUA and the IAEA-ISSC groups, to improve the methodology.

A first and critical step is to build up a community-sourced, worldwide, unified database of surface rupturing earthquakes to include a large number of earthquake cases in various seismotectonic contexts. This is the core task of the SURE (Surface Rupture Earthquake) Working Group which is growing with the support of INQUA and IAEA-ISSC. During the kick-off meeting held in Paris (October 2015) and sponsored by the *Institut de Radioprotection et Sûreté Nucléaire* (IRSN), earthquake geology experts from the USA, Europe (France, Italy, UK, Germany), Japan, New Zealand, South America (Argentina) formed this group and exchanged their experience in surface rupturing events during 3 days. The US and Japanese colleagues presented the existing datasets and the whole group proposed a structure for the future unified database, also suggesting a list of new parameters to be included (e.g. soil conditions).

The attendance underlined that one of the challenges will be to aggregate “historical” cases (events back to the 50’s or even older in the Japanese dataset) with scarce data and recent events with huge number and accurate measurement of displacements from modern techniques (high-resolution elevation maps with LiDAR, 3D imaging with SfM photogrammetry, deformation maps with InSAR).

KEYWORDS

Seismic hazard; Surface displacement hazard; Worldwide database; PFDHA

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Outline

1 EXECUTIVE SUMMARY

The workshop, sponsored by IRSN, was held in the framework of the INQUA and IAEA projects which aim at building an International database of surface ruptures associated with earthquakes. The final goal of such a database is to feed the empirical relationships and attenuation equations of displacement with distance, which are used in probabilistic approaches in seismic hazard assessment. The attendance was constituted of 20 worldwide experts in earthquake geology belonging to 16 different institutes (California Geological Survey and Geo-Haz consulting, USA, Tokyo Electrical Power Company and University of Hiroshima, Japan, ISPRA and Istituto Nazionale Geofisica Vulcanologia, Italy; GNS Science, New Zealand; University of San Luis, Argentina; NERC-COMET, UK; IAEA; University of Aachen, Germany; Ecole Normale Supérieure, CEA and IRSN, France).

Each participant expressed his interest and will in continuing the collaboration for the implementation of this unified database. By this, they agree in sharing their expertise and published/available datasets. This interest will also be materialized through the implementation of the database in the next months. In addition to the Paris attendance, many other scientists from the earthquake geology community are willing to join the effort and the Paris attendance agree in accepting them, both as data providers and users.

With respect to existing databases, the group decided to incorporate new parameters to describe surface rupture data, such as surface geology, focal depth, and structural pattern or fault complexity, because they are potential controlling factors on surface rupture patterns. The attendees agreed on a preliminary list of fields to fill in order to build the databases. These fields are split in three spreadsheets (see Appendix): observation point, fault section, earthquake. In the observation point sheet, the crucial information is the assignment of each point to a primary/secondary/triggered class: the group agreed on distinguishing two fields, one for the original author opinion, one for the compiler.

Attendance agreed the proposed structure of the database by submitting a few test examples before the end of 2016. This deadline is selected to comply with the next AGU Fall Meeting in San Francisco (december 2016), where advancement and preliminary results will be discussed between some of the Paris meeting attendance.
The test examples are listed below:

1. 1944 San Juan and 1977 Caucete (Argentina), by Carlos Costa
2. 1987 Edgecumbe and 2010 Darfield (New Zealand), by Pilar Villamor and IRSN
3. 1992 Landers and 1999 Hector Mine (California), by Tim Dawson
4. 1980 Irpinia, 1997 Colfiorito and 2009 L'Aquila (Italy), by Francesca Cinti and Luca Guerrieri
5. 1968 Dasht-E-Bayaz (Iran) and a second case to be determined, by Richard Walker and Austin Elliott
6. 1995 Kobé and a second case to be determined (Japan), by Makoto Takao
7. 2014 Nagano (Japan) and 1999 Koaceli (Turkey), by Koji Okumura (and IRSN if any help needed)
8. 1959 Hebgen Lake and 1983 Borah Peak (Basin and Range), by James McCalpin (and IRSN if any help needed)

Besides this preliminary working plan, IRSN is setting up a collaboration with Institut de Physique du Globe Paris (IPGP) to develop an innovative approach to investigate historical and recent cases and to start implementing the database for the existing datasets. Ideally, this database would have a completely open on-line access with a free implementation platform which needs to be designed and set up.
All the providers and users of the database will need to comply with the copyright requirements of TEPCO, if they use the Japanese data in their final database.

2 INTRODUCTION

In the framework of IAEA/ISSC-EBP and INQUA working groups on the earthquake surface rupture databases, the kick-off meeting of the SUrface Rupture Earthquake hazard (SURE) working group was held at IRSN in Fontenay-aux-Roses, France on the 28 to 30 october 2015.

IRSN sponsored the meeting, including the costs of air tickets and accommodation of extra-European attendees.

The objectives of the SURE working group are to compile a "Surface Rupture Database" and to generate a standardized method to describe surface rupture on the main fault (primary rupture) and on other fault segments off this main fault (distributed ruptures). In a second phase the homogenized database will be used to feed calculations used for Probabilistic Fault Displacement Hazard Analysis (PFDHA). Another crucial outcome will concern the empirical relationships between magnitude and fault parameters that could be updated.

The aim of this kick-off meeting was to initiate this long lasting project by joining a "task force" of worldwide experts, in order to set up an efficient group, to discuss the methodology to implement the database, to elaborate a first draft of database structure and to identify/gather the first datasets from various regions of the world.

The following persons attended[1] this kick-off workshop:

- Stéphane Baize (IRSN, France)
- Giovanni Bruna (Head of research programs IRSN, France)
- Francesca Cinti (Istituto Nazionale Geofisica Vulcanologia, Italy)
- Johann Champenois (CEA, France)
- Thomas Chartier (IRSN, France)
- Christophe Clément (IRSN, France)
- Carlos Costa (University of San Luis, Argentina)
- Marc Cushing (IRSN, France)
- Tim Dawson (California Geological Survey, USA)
- Austin Elliott (NERC COMET, UK)
- Yoshi Fukushima (IAEA)
- Luca Guerrieri (ISPRA, Italy)
- Jochen Huertgen (University of Aachen, Germany)
- Hervé Jomard (IRSN, France)
- Jim McCalpin (Geo-Haz consulting, USA)
- Koji Okumura (University of Hiroshima, Japan)
- Eugénie Pérouse (Ecole Normale Supérieure, France)
- Oona Scotti (IRSN, France)
- Makoto Takao (Tokyo Electrical Power Company, Japan)
- Pilar Villamor (GNS Science, New Zealand)
- Richard Walker (NERC-COMET, UK)

The workshop was prepared with e-mails exchanges and the completion of a shared Google Doc. Some attendees provided an abstract on their expectation, thoughts and available data relative to the future unified database. These documents were distributed at the beginning of the workshop and are reported in section 3. The workshop included 14 slideshows over 2 days and an open discussion during the last day (section 4), leading to the

[1] Excused: Alessandro Michetti (University of Insubria, Como, Italy); Ray Weldon (University of Oregon, USA); Yann Klinger (Institut de Physique du Globe Paris, France)

proposition of a unified database in the form of three spreadsheets to date (section 5). The attendance decided to test the structure of the database by implementing some earthquake cases for which data are easily available (section 6). Section 7 presents the initiative plan for the on-going year (2016). After the references (section 8), we present a summary of the content of the slideshows in section 9 (appendix).

3 WORKSHOP CONTRIBUTIONS

This section presents the questions and ideas put forward by the attendees for the purpose of the workshop.

3.1 STÉPHANE BAIZE AND OONA SCOTTI (IRSN, FRANCE)

It is not IRSN's role to collect systematically fault rupture data. However, IRSN does collect such data when the occasion arises through specific projects (Ecuador, Italy, USA, Mexico, Spain,..). Clearly, today the main source of data for this database comes from Japan and the USA and from the people around the table that are willing to provide their own individual data sets. One of the objectives today is to clarify what is the format of the existing databases and which data each one of us is willing to feed into the worldwide database.

The ground motion prediction equations (GMPEs) have increased the number of predictive parameters in the past years (e.g. example below from Abrahamson et al. 2008) with the aim to fit the regressions of ground motion attenuation with distance. Probably the surface displacement should also need to be parametrized by accounting for more than just the classical earthquake predictor parameters (magnitude, fault kinematics) by adding focal depth or parameters such as "local" subsurface conditions (surficial geology, Vs30), geometrical and structural parameters (fault dip with respect to surface topography, hanging wall effect). These predictor parameters may also have significant impact and control on the deformation pattern at the ground surface.
In the recent publication by Teran et al. (2015) in Geosphere, there is an interesting synthesis of the factors controlling the rupture zone fabric and pattern. This study documents how these factors affect the fault zone width, the fracture arrangement and connectivity, the slip distribution of surface faulting associated with the El Mayor-Cucapah earthquake (Mexico, 2010, Mw=7.2). According to them, the factors influencing the surface faulting can be summarized as follow:

- Rheology of faulted material (bedrock, consolidated sediments, saturated sediments), and nature of bedrock, are primary controlling parameters;
- With increasing thickness of surficial and loose sediments above bedrock fault, the width of ruptured zone increases. However, when the amount of coseismic slip is sufficient, slip tends to concentrate on specific strands and form a principal scarp;
- Fault dip: rupture propagates into the hanging wall block above dipping faults and creates distributed faulting;
- Master fault changes in strike or continuity (bends, step-over) induce slip transfer across these discontinuities and then rupture complexity;
- The occurrence of paleo-ruptures can control the location of future ruptures;
- Other parameters control the fault zone fabric, such as kinematic partitioning on parallel segments or "regional" tectonic loading influence the surface slip pattern.

Thus from the conceptual point of view, it would be useful to gain from previous experiences and improve, if necessary, the database structure for the new worldwide database by discussing today

- What are the relevant parameters that each one of us would like to see in this Surface rupture database.

- Based on the rich experience that the attendance has, how can we implement an upgraded database? What is possible? What is irrelevant?

3.2 TIM DAWSON (CALIFORNIA GEOLOGICAL SURVEY, USA)

Strike-slip surface rupture database for Probabilistic Fault Displacement Hazard Analysis (PFDHA)

Following the methodology proposed by Youngs et al. (2003), a GIS-based database of strike-slip surface rupturing earthquakes was assembled in order to develop regression equations for strike-slip faults using PFDHA (Petersen et al., 2011). On and off-fault displacement data was collected for nine global strike-slip earthquakes where detailed (> 1:50,000) maps and displacement data were available. On-fault displacement data was also supplemented with additional data published by Wesnousky (2008). Petersen et al. (2011) expanded the methodology by including a "mapping accuracy component" to the analysis, by comparing maps of fault rupture to fault maps published prior to the earthquake. The intent of this component of the analysis was to quantify the variability between previous mapped faults to the location of fault ruptures in an effort to understand the uncertainties of mapping (which includes both epistemic and aleatory uncertainty). The intent of this component of the analysis is for use as a screening tool for fault rupture hazard related to existing infrastructure, where site investigations may not exist, or are inconclusive.

The existing database is limited in scope (n = 9 earthquakes) and because the data was originally compiled in the early 2000's, is in need of being updated with more recent surface ruptures. The database also consists of some earthquakes that occurred several decades ago, and may suffer from completeness issues. Because post-earthquake investigations typically focus on the primary causative fault, secondary faults of concern in PFDHA may not be fully accounted for in these older earthquakes. Recent earthquakes (e.g. 2010 El Mayor-Cucapah, 2014 South Napa) have shown that modern data collection techniques such as the use of LiDAR, InSAR, and optical differencing techniques show that ruptures can have complicated zones of distributed faulting, some of which is minor and easily missed by field surveys unless informed by these types of data. These new techniques may also be employed in analyzing near-field (10's of meters away from the principal fault trace) patterns of deformation, a subject that the current PFDHA approach does not address, but is a topic of engineering significance. Clearly, adding additional earthquakes into the database, particularly earthquakes mapped using these new techniques, is a task that will improve the database and derived regressions. The goal of this Working Group should be to outline a unified database structure such that past and future earthquake ruptures can easily be added to the database.

3.3 MAKOTO TAKAO (TOKYO ELECTRIC POWER COMPANY, JAPAN)

According to a safety standard related to seismic hazards for nuclear installations (No.SSG-9) established by the IAEA in 2010, it is recommended that probabilistic fault displacement hazard analysis (PFDHA) is performed for existing nuclear power plants.

PFDHA, which was proposed by Youngs et al. (2003), is a methodology that assesses the annual rate/probability of exceedance that an amount of displacement of a surface earthquake fault exceeds a certain quantity.

However, as no study on PFDHA has been done in Japan, Takao et al. (2013) proposed evaluation formulae in terms of both principal and distributed faults based on data from surface earthquake faults generated by reverse and strike-slip faults in Japan.

For principal faults, an abundance of data is accumulated by making use of the past surface earthquake faults in Japan, while for distributed faults, the data are not necessarily sufficient in reality.

Therefore, Takao et al. (2014) conducted model experiments and numerical analyses based on the discrete element method (DEM) to compensate for the lack of data regarding distributed faults.

Furthermore, Takao et al. (2014) described a logic tree methodology that can consider epistemic uncertainties and demonstrated an example of its application.
As a result of model case analyses, the proposed evaluation formulae gave the prospect of applicability of PFDHA in Japan and future tasks to be addressed are described.

3.4 CARLOS COSTA (UNIVERSIDAD NACIONAL DE SAN LUIS, ARGENTINA)

Surface ruptures in South America; some case studies and challenges

Crustal faults in South America have hosted many destructive earthquakes, as also underlined by paleoseismic studies. However, just few historical primary coseismic ruptures related to primary sources have been reported.
Near 1500 Quaternary-active structures have so far been inventoried, although their characterization as input sources for seismic hazard models is not a straightforward task.
Structures located in the North Andean block (north of 4°S), show dominant strike-slip movements in the major faults, as also reported or interpreted for historical ruptures in Venezuela and Ecuador.
Hazardous structures along the Central Andes (4°S-46°S) lie within the plate interior where most slip rates are considered to be lower (< 1 mm/a) than those characterizing major structures at the Northern Andes. Historical ruptures are related with normal faults (mainly in Perú) and thrusts in Argentina, with the only mention of a strike-slip rupture at the southern tip (Tierra del Fuego).
Several cases studies in compressive settings in Argentina are here discussed, derived from historical ruptures and from insights of paleoseismic trenches and terrain analysis. They usually challenge a straightforward application of the empirical relationships because in most cases, rupture length and coseismic slip seem to underestimate the predicted earthquake size.
It is intended to promote debate about the factors controlling the surface manifestation of these deformation; structural style, uppermost fault geometry and rheology of deformed materials among them.
It is also underlined that the studied faults can host shallow earthquakes M > 7 without noticeable primary ruptures. Paleoseismological studies are crucial in these settings for constraining the threshold earthquake magnitude which may induce surface deformation and to provide a more realistic assessment on the seismogenic potential. It is interesting to discuss the contribution of innovative techniques (LiDAR, InSAR) to these situations.

3.5 RICHARD WALKER (NERC – COMET, UNITED KINGDOM)

InSAR technique is useful in earthquake geology for the following reasons:

1) InSAR can image ground displacements even on non-obvious faults with subtle geomorphic expression and situated at a distance from the known active faults. Examples include the 2003 Bam earthquake in Iran, and the recent Napa and Nepal earthquakes where the Sentinel satellite provided detailed maps of ground deformation..
2) InSAR is sensitive to fault motions at depth. Inversion of the surface displacement yield constraints on down-dip width, and on uneven slip distribution across the fault plane. InSAR slip-distributions can hence show the existence of enhanced slip patches at depth, and shed light on discrepancy between seismic moments and observed slip/ length measurements. Constraint on the depth extent of rupture is usual in estimating the seismogenic thickness in the source zones.
3) InSAR yields a map of the far-field displacements. Usually there is no coherence close to the fault rupture itself, and so the InSAR maps are complementary to near-field and field observations, rather than repeats of the same observation.
4) Modelling of InSAR-derived surface deformation yields constraint on sub-surface structure. Transient post-seismic fault creep events can be imaged, and yield additional insight into structure. Recent examples include the 2011 Van earthquake fault in eastern Turkey, and the 1978 Tabas earthquake in Iran, which is still undergoing postseismic slip more than 30 years after the mainshock.

Far-field deformation measurements from InSAR are complemented in the near-field by pixel offset measurements, performed either with the RADAR amplitude images, or with optical satellite images. Such techniques give correlation closer to the rupture itself, but are blurred close to the fault as the matching algorithms operate over a window of pixels, and also are not sensitive to the vertical component of motion. DEM to DEM matching techniques offer a potential to yield full 3D displacements, but few earthquakes have yet occurred with suitable 'before' imagery. Near-field measurements of displacement are best derived from optical imagery. The recent generation of sub-metre-resolution optical satellites (e.g. Worldview, Pleiades) offer along-track stereo acquisition from which ~1-2 m DEMs can be extracted, and measurements of rupture displacement made remotely. Examples from the 2013 Balochistan (Pakistan) earthquake highlight the substantial off-fault deformation, which is larger in places where young sediments have accumulated, which are also the most suitable sites (in terms of sedimentation) for slip-rate measurement and trenching.

Earthquake surface rupture: examples from Asia

Diffuse secondary rupturing was widespread following the Mw7.4 1978 Tabas earthquake in eastern Iran. Co-seismic fold growth was accommodated by slip on multiple bedding planes and possibly by tensional fissuring near the fold axis. Post-seismic slip (and fold growth) has continued at Tabas for decades after the earthquake at measured rates of 5 mm/yr. In another recent example from Iran, the 1998 Fandoqa strike-slip earthquake triggered aseismic slip event on adjacent thrusts. The 2003 Bam earthquake ruptured a previously unmapped strike-slip fault, 5 km west of a known thrust that runs parallel to it. The strike-slip rupture extended into Bam city, and contributed to the large damage and death toll.

In some parts of Asia (e.g. Iran, China) a rich written history extends the catalogue of major earthquakes back several thousands of years. We show the importance of re-examining historical earthquakes in China through analysis of the remnants of surface ruptures. For instance, the 1739 Yinchuan earthquake, with a magnitude of 8 assigned from historical intensities, had a rupture length of ~80 km and a maximum slip of ~5.5 m, and so the magnitude assigned from the geological evidence is closer to ~7.5. However, the 1556 Huaxian earthquake in China (the most deadly in history) appears to have involved slip of ~10 m over a length of ~80 km, with a penultimate event that involved similar amount of slip ~6 ka ago. Both Huaxian events would have been M7.8+. We are currently undertaking a similar study to reevaluate a historic (1932 M 7.6 Changma) rupture in the same region using Pleiades optical satellite imagery-derived topography to measure the size and kinematics of this 100+ km long earthquake rupture and evaluate how it relates to longer term fault recurrence rates and kinematics.

Not all of Asia has such a long historical record, but the arid and cold environment of much of its interior leads to excellent preservation of the landscape. The steppe and mountains of central Asia and Mongolia preserve individual surface ruptures for periods of >1000 years. For instance, the Egiin Davaa normal faulting palaeo-rupture in Mongolia is ~5,000 years old. The earthquake involved slip of ~8 m for ~80 km length. A trench excavation through the Bartogai thrust palaeo-rupture in Kazakhstan yields an age of ~4 ka, and surface evidence for the penultimate event (which occurred >20 ka) was removed by a regionally extensive period of alluvial fan aggradation at ~15 ka. This result suggests that the recurrence interval between successive earthquakes in central Asia may be longer than the timescale of landscape preservation. The most recent rupture of the 1800 km long left-lateral Altyn Tagh fault in western China took place between ca. 1270 and 1500 AD. Our results show a 330 km long rupture with an average of at least 5.6 to 2.2 m sinistral slip, consistent with physics-based models of rupture propagation and extent along this fault system.

Finally, the 1990 Suusamyr reverse earthquake in Kyrgyzstan Mw 7.3 has a surface rupture that is variable along strike. Up to 2 m of displacement was observed, but only along two short sections. Secondary fissuring was observed at the apex of an anticlinal ridge for much of the fault length. Despite the absence of rupturing in the recent earthquake, we show that a discrete scarp is present that is a composite of two past earthquakes, with the most recent ~3 ka ago. The Suusamyr fault appears to have shown very different rupture characteristics in successive earthquake cycles.

3.6 AUSTIN ELLIOTT (NERC COMET, UNITED KINGDOM)

Quantifying rupture offset uncertainties with high-resolution surveys

The increasing availability of high-resolution remote sensing and surveying products enables unprecedented analysis of offsets in past earthquakes via preservation and digitization. In particular, high resolution digital elevation models allow us to not only measure offsets but to quantify uncertainties more precisely and rigorously than has been historically possible. Using the ideal case of extremely high-resolution (103 pts/sq m) terrestrial lidar scans of a <2 week old coseismic surface rupture, Gold et al. (2013) repeated measurements of a set of offset features up to 15 times in order to assess uncertainties associated with the subjective selection of geomorphic piercing points. The consistent 11% standard deviations of measurements on individual features show that uncertainties in relative displacement are commonly underreported. Underreporting of displacement uncertainties commonly leads to the overestimation of slip gradients along strike, in turn leading to exaggerated and unwarranted interpretation of along strike and off-fault strains. Scharer et al., (2014) conducted a similar validation exercise among the SCEC (Southern California Earthquake Center) community, analysing the results of 27 earthquake geologists measuring the same set of 32 offset features along the southern San Andreas Fault. Differences in reporting methodology among the researches inhibited, to some degree, comparison and analysis of the results, revealing a fundamental methodological problem that is important to address in the compilation of offset measurements from known earthquake ruptures. To the extent that measurements could be compared, large variability among them relative to reported uncertainties reveal underestimation of measurement and interpretive errors. Scharer et al. (2014) recommend combining field work with remote sensing analysis on digital terrain, and including both qualitative assessments of measurement confidence as well as quantitative constraints on measurement uncertainty.

3.7 PILAR VILLAMOR (GNS, NEW ZEALAND)

New Zealand does not have a database of historic surface ruptures as such. We have an active fault database (NZAFD) and the historic surface ruptures are included. However, the NZAFD does not have the detailed (in line work and in attributes) that I suspect will be needed for a database of surface ruptures that will help assessing Probabilistic fault displacement hazard.

You can access the NZAFD in http://www.gns.cri.nz/Home/Products/Databases/Active-Faults-Database-of-New-Zealand. This DB is about to be updated.

We are working on creating a more detailed active fault database because we have produced some reports for Regional and City Councils on fault avoidance zones (for land use planning), which required more detail. So we want to create a parallel database as high resolution. It is possible that such a database can be populated in a way that is useful for the purpose of PFDHA. However, it will be great to discuss how paleo-ruptures could be used to assess PFD, I can see how the paleo-events can inform on fault PFD but not sure how the paleo-events can inform secondary or off main fault ruptures.

We have not incorporated NZ historic surface data (1987 Edgecumbe, normal faults in the Taupo Rift; 2010 Greendale Fault, strike-slip with some reverse) into any surface rupture database. Some data is available to be incorporated into an international one and the rest of data will be available soon. At the moment we are not planning to create a database for historic surface rupture but we are putting the information into GIS platform for publication.

Other aspects for discussion

Secondary/Triggered rupture on nearby active faults:

The Edgecumbe experience showed that several faults of the rift underwent secondary/triggered fault rupture (Beanland et al. 1989) at quite large distances. This is something that may need to be incorporated into post event reconnaissance, that is reconnaissance farther away that the close vicinity of the fault, targeting nearby faults (how good will INSAR pick up these small displacements?).

There are some other examples worldwide.

Variability if fault displacement at a single point on a fault-Taupo Rift faults.

We have documented large variability in single event displacement at point locations on faults (together with Recurrence interval variability). This is because faults in the area are very close to each other and rupture on a single faults is easily promoted or inhibited by faulting (stress transfer). I wonder if there needs to be a factor that takes into account non-characteristic behavior (Nicol et al 2006 and 2010).

Greendale – broad deformation is granular materials, fault growth, fault displacement versus folding.

Rupture of the Greendale is an example of an early evolutionary stage of strike-slip fault through almost homogenous granular materials (Quaternary gravels), a natural sand box model. We have information of how deformation was distributed across the fault for most of the fault trace that is how much accommodated by faulting and how much by folding and how far deformation extended away from the main fault trace. Some fault sections with steps over compared with section of straight fault had also different distribution patterns. While this is a great data set, it will be useful to discuss how this type of dataset can be useful for PFD. They are complex zones and they evolve into a narrower fault zone with time and they contain faulting as well as folding.

Key references are Villamor et al (2012), Quigley et al. (2012), Van Dissen et al. (2013)

Greendale – Capturing all information needed (new technology: LiDAR, INSAR drones)

We have information from Greendale fault surface rupture that is good for PFD studies but we struggled to get to the detailed that will be fully useful for PFD. I can comment on the issues we had to collect data at that level and great to hear about your experiences and suggestions from improvement.

Magnitude vs displacement - The use of the right scaling relationships in different tectonic regimes

In NZ we have developed a new fault scaling relationship for slow moving strike-slip and reverse faults and another one of fault in the Taupo Rift because typically used ones (e.g, Wells & Coppersmith) did not reconcile surface rupture displacement, rupture length and Mw (see discussion on Stirling et al. 2013). Greendale proved that this indeed happens (Greendale has part of complex rupture). It will be useful to hear your thoughts on this at the workshop .

Inversion tectonics - distribution of SED along the fault

The 1968 Murchision earthquake ruptured a reverse fault that was reactivated from a normal fault (Anderson et al., 1994). Because these faults are difficult to rupture they tend to present a complex SED distribution pattern. 1968 is not the best example to work with because densely vegetated areas could not be explored (only a trace of 4 km with 4 m displacement was documented). Can other examples tell us something about “anomalous” variability or SED along reactivated faults? (well, most fault are reactivated …but I mean those with clear inversion tectonics or complex inversion tectonics)

3.8 JAMES McCALPIN (GEOHAZARDS, USA)

We are trying to predict what will be the surface displacement (VD, HD) on a fault (or near a fault), at various points along the strike of the fault, in its next surface-rupturing earthquake.

If the surface rupture pattern at a point is mainly controlled by time-invariant factors (depth to bedrock, Vs30, rheology of surface materials, distance to major fault discontinuities such as bends and stepovers, distance from the end of the mapped fault), our job is simplified. We can measure those factors at points of interest along our fault, and know that the factors will have the same value when the next surface rupture occurs. So if we develop an empirical equation that relates future surface displacement to Magnitude, as affected by (say) depth to bedrock, we at least know that depth to bedrock in the future earthquake at a given point will be exactly the same as it is today. If there is scatter in the data and uncertainty in the empirical equation, at least we know that the uncertainty does not result because depth to bedrock changes from seismic cycle to seismic cycle.

Conversely, some other factors are time-variant. For example, say we develop an equation that relates surface displacement to distance from the end of the surface rupture. We can easily make such an equation based on historic surface ruptures. But for a future earthquake on a fault, we don't know where the ends of its future surface rupture will be. In some ruptures the end may coincide with the end of the mapped fault, but in other ruptures the rupture may start several km closer to your point of interest than the end of the mapped fault. Or the surface rupture may start beyond the end of the mapped fault. So there is a time-varying uncertainty in the value of this factor. We can perhaps describe this uncertainty statistically, if we have enough data, but we can't simply assume that the factor is constant, like we can for depth to bedrock.

So perhaps we need to consider whether the variability in surface displacement as a function of (say) magnitude in data sets of historic earthquakes comes from intrinsic variability of how the fault operates from seismic cycle to seismic cycle, or from measurement error on a factor that should be constant from cycle to cycle. Because these two types of variability are fundamentally different.

3.9 KOJI OKUMURA (UNIVERSITY HIROSHIMA, JAPAN)

Surface Ruptures and Deformation Associated with 3 Recent Earthquakes of 2004, 2007, and 2014 in Central Japan

Three recent Mw 6.2 to Mw 6.6 earthquakes in central Japan generated surface ruptures and deformation in different manners. The variety of the surface phenomena associated with these earthquakes gives us ideas about how we expect fault displacement and deformation during relatively small earthquakes with surface ruptures.

During the 22 November 2014 Nagano, Central Japan earthquake of Mw 6.2, 9 km long clear surface faulting occurred along the previously mapped Kamishiro fault in the northern Itoigawa-Shizuoka tectonic line active fault system (ISTL). In the 100-km-long central and northern ISTL, Mw ~8.3 earthquake was forecasted with 30 year probability of 14%. This very high probability was based on 500 to 800 year recurrence intervals and 1174 year elapsed time since the last event in 841 AD, and 3 to 9 m slip in the last event. The 26 km long Kamishiro fault by itself was supposed to generate M 7.2 earthquake. But the 2014 ISTL earthquake was only Mw 6.2 and 9 km long with a maximum vertical slip about 1 m.

Though the rupture is short and the offset was small, such clear surface faulting is rather unusual for earthquakes less than Mw 6.5 in Japan. The shallow slip with epicentral depth at 4 km on a mature fault plane might explain these unusual ruptures.

The 2014 ruptures mostly coincided with previously mapped Kamishiro fault. However, unmapped ruptures occurred in the northern termination and the middle portion on active river beds and on flood plains, where there was no possibility for past offsets to survive severe erosion. Some secondary ruptures appeared also on steep hill slopes but, again, preservation of past offsets there is not likely. The southern 2 km of the 2014 ruptures appeared within back marshes and a footwall subsiding area. The area along the ruptures is artificially modified severely to build wider rice paddies by cutting and filling older small paddies following tectonic and eroded slopes. 2014 ruptures are away from fault-like topographic steps after modification. However, old air photos indicate that they appeared around the bottom of pre-modification gentle flexure-like slopes. When we study surface ruptures on artificially modified ground, we need to examine the location of fault line in natural conditions.

During the 24 October 2004, Mw 6.6 Niigataken Chuetsu earthquakes faulting occurred at a depth of 4 to 15 km below thick Neogene sediments. 3 km long discontinuous surface ruptures with 10 to 20 cm offset appeared on the surface east of a Neogene anticlinorium that grew coseismically. It is not clear if that minor offset was the upper end of a continuous rupture from the seismic depth or secondary induced slip at surface. The surface ruptures occurred at the foot of 1 to 2 meter high fault scarp and trenching into the scarp showed ~1.5 m slip by the penultimate event. This indicates the fault does continue from hypocentral depth to surface. However, there is no evidence of significant slip on the fault plane in 2004.

The 16 July 2007 Niigataken Chuetsu-Oki (NCO) earthquake occurred under the seafloor offshore Kashiwazaki. There was no surface rupture detected on the seafloor and above the aftershock area, but coastal uplift caused by land-ward dipping reverse fault was detected by GPS and InSAR. At the same time, InSAR analyses revealed a narrow zone on a Neogene anticline was uplifted during the earthquake. The zone is parallel to the source fault, but located a few kilometers in southeast of the source area. There is no connection between the deformed zone of the source fault. The 22 km long and 1 to 2 km wide zone on the west flank of a Neogene fold was upheaved up to 10 cm. Asymmetric deformation indicates an east-dipping blind reverse fault caused the deformation. This deformation is very likely an induced deformation by the shaking of the NCO main shock.

3.10 FRANCESCA CINTI (INGV, ROME) & LUCA GUERRIERI (ISPRA, ROME)

Building a worldwide Surface Rupture Database for probabilistic analysis

In order to build a worldwide Surface Rupture Database (SRD), we propose to take advantage from our experience in designing and implementing the EEE Catalog – a worldwide database collecting information about the characteristics and size of Earthquake Environmental Effects, i.e. the geological effects triggered by earthquakes.

The EEE Catalog was built in the frame of INQUA TERPRO PALACTE Focus Group, and is focused on the primary effects including surface faulting and coseismic tectonic uplift/subsidence, besides the secondary effects caused by seismic shaking (i.e. like slope movements, ground cracks, liquefactions, tsunami, etc.). Data sources are survey reports for modern earthquakes, and historical documents and paleoseismic studies for past earthquakes.

The database infrastructure is developed into three main levels: the “Earthquake” level provides general information about the seismic event and summarizes the wealth of information about EEEs (extent of surface faulting; total area of secondary effects). The “Locality” level summarize the information on EEEs occurred within a single locality for local intensity assessment. The “Site” level provides more details on individual recorded EEE, with some quantitative parameters and pictures, when available.

Although the EEE Catalog collects information about coseismic surface ruptures, it cannot be used for probabilistic analysis, mainly for three reasons: i) the target is just data collection; ii) mapping scale and data reliability are not homogeneous; iii) for historical and paleoearthquakes the degree of completeness can be very low.

Nevertheless, the EEE Catalog structure is valid and, similarly to that, we propose three levels for the SRD (Fig. 1): the “Earthquake” level to be linked to several “SR Descriptions”, according to different references and methods of collection. Each “SR description” related to more than one “Ruptures”, describing the rupture in terms of type, geometry, with associated uncertainties. Ruptures should be associated to a list of seismic events (modern, historical and paleo) that caused the previous reactivation of the same rupture.

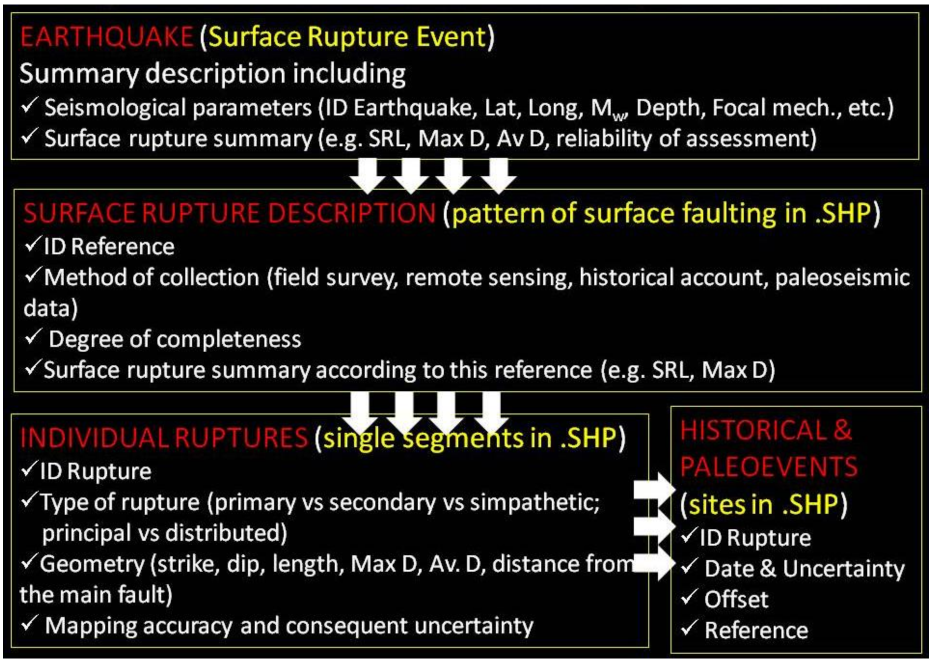

Fig. 1 – Proposal of structure for the Surface Rupture Database

In order to summarize SR information at earthquake level, we suggest to "weight" different SR descriptions through a logic tree. A more challenging issue will be the evaluation of the maximum displacement when data are not complete (for historical and paleoearthquakes).

Among the Italian earthquakes, we have data collected on the 1980 Irpinia, the 1997 Umbria-Marche, and the 2009 L'Aquila earthquakes, that are the three earthquakes that produced surface faulting in the last thirty-five years. We propose to start the implementation of the SRD database with these cases, having the information about surface breaks distribution and slip characteristics quite well documented. These data have been collected during the post-seismic phase by teams of experts on active tectonics and paleoseismology from numerous italian research and academic institutes, that will keep the ownership of these data.

A second more challenging step will be to include into the SRD, historical earthquakes whose information of surface faulting has been well described by contemporary eye-witnesses (e.g. the 1915 Fucino and the 1783 Calabria earthquakes). We also aim at revisiting the historic and pre-historic cases through present scientific learning and modern technologies and tools (GPS, LiDAR, etc).

4 GENERAL DISCUSSION

4.1 STATE-OF-THE-ART

4.1.1 JAPANESE DATABASE

Makoto Takao presented the Japanese dataset which includes 17 surface ruptures from earthquakes between 1891 and 2008. Faults traces are included in a georeferenced file.

The database has a "Point data table". The criterion for secondary and distributed assignment to an observation of fault offset is based on the "process zone" idea, as it was defined by Vermilye and Scholz (1998).

In this model, the master fault growth (during earthquakes) is associated with a related population of lesser order fractures, which are concentrated in the so-called "process zone". The width of this zone scales linearly with the master fault length, in the 1% proportion factor. In the Japanese database, the fractures/faults that are outside this process zone are considered secondary/triggered ruptures. Points are deleted if the author of publication is claiming that the process is non-tectonic.

The fields of the “Point data table” are the following:

1. loc # in a referred paper
2. N lat; E lon
3. min and max horizontal displacement (m)
4. min and max vertical displacement (m)
5. dummy index (for mapping)
6. principal or distributed deformation (p or d)
7. reference
8. description in a referred paper
9. reliability (1 high / 2 low / 3 ignore)
10. classification # (separate description)

The “Line data table” describes the fault traces.

1. Fault trace data fields (line data)
2. Different mesh sizes (500 – 250 – 100 – 50 m) were used.
3. Principal (p)/Distributed (d)?
    1. If existing, “p” or “d” classification in the reference paper is reported in DB;
    2. If not, the “process zone” criterion (cf Vermilye and Scholz) is used;
    3. Principal Fault trace is mapped by digitizing data from published papers

4.1.2 US DATABASES

The US database for strike-slip faults (Petersen et al., 2011) has a similar structure, in GIS format; uncertainties are included. This database includes the 1995 Kobe earthquake surface rupture, like the Japanese database. Tables are available in Petersen et al. (2011). It would be interesting to compare their content and choices, because data compilation processes follow a different approach: the US one is more “geological”, accounting for continuity of rupture, amount of offset and morphological criteria.
The normal fault database processed by Youngs et al. (2003) includes statistics on distributed faulting, based on 13 US cases. These cases are described in Pezzopane and Dawson (1996) report which includes paper maps of fault traces and offset information.

4.2 IMPROVEMENTS

Seismic hazard assessment relies on empirical relationships between magnitude and fault parameters and probabilistic relationships between expected surface rupture displacement and distance to the primary fault. These two elements require databases which are presently insufficient in terms of available cases and predictor parameters. The attendance agreed that present-day regressions and relationships are not robust.
The first issue that SURE working group will address is the completeness of the database (e.g. there is a need to complete the magnitude range with moderate events) (section 4.2.1). The database will have to cope with handling both modern examples with very detailed data (e.g. LiDAR) (section 4.2.2) and old cases with incomplete data and aggregate them in a unified database. A general opinion in the attendance is that the unified database will have to include new relevant parameters which control the nature, the amount, and the distribution of faulting at the surface (i.e. soil conditions, earthquake focal depth) (section 4.2.3). Finally, the unified database will have to include each kind of surface faulting, including the triggered ones, and will propose one (or several) mode(s) to define master and distributed ruptures (section 4.2.4). A standardized database structure is therefore presented in section 4.3.

4.2.1 INCREASING THE NUMBER OF CASES & THE MAGNITUDE RANGE

There is a completeness issue in the existing databases.

- There are only a limited number of cases, especially in the moderate magnitude range, say below magnitude 6.5.
- The second completeness issue refers to the content of “distributed” features in historical events, because they were (and in some cases they are still today) neglected compared to the primary fault trace.

During the meeting, it has also been emphasized that the conspicuous discrepancy between the Japanese and US primary surface rupture probability vs magnitude is most likely the result of a different level of detection of surface faulting (desert context in the US vs dense forest environment in Japan).

The US database of strike-slip cases contains only 7 cases (M≥6.5) with distributed deformation data. The US reverse cases do not have any, whereas the US normal fault database is more populated, with 13 cases in the M5.5 to M7.4 magnitude range. The Japanese database contains 17 earthquakes with distributed faulting, covering the 1891 – 2008 time-window and the M5.8 to M7.4 magnitude range (exclusively strike-slip and reverse faults).

The Japanese database has been increased with values from simulations, for distributed faulting at large distances from the primary fault. As a group, we tend to favor a purely empirical approach and would avoid this kind of data. With an increased worldwide dataset including modern cases, the objective is to get significant amount of remote data in order to build robust statistics.

4.2.2 ADDING INFO FROM MODERN TECHNIQUES

4.2.2.1 LiDAR & other high-resolution Digital Elevation Models

This technique delivers high resolution picture of fault pattern. Software tools allow handling the amount of information (series of topographic profiles, calculation of vertical/horizontal displacements, etc). This (these) technique(s) yield not only a high-resolution image of topography and fault offsets but also an access to rigorous uncertainties on measurements.

With airborne LiDAR, we have the opportunity to skip the problems of dense vegetation. Sweden and Finland post-glacial faults in forest areas were revealed thanks to LiDAR, as well as Alaska faults (J. McCalpin).

LiDAR is an appropriate tool to capture the fault complexity, especially in the near-primary fault area where InSAR (often) saturates.

The challenge in some case will be how to handle the great amount of data that this method can provide. The key issue is to set up a “mapping scale” that is relevant for implementing statistics on a 100 to 500 m grid size (the size of studied facilities and sites).

4.2.2.2 Radar interferometry

SAR interferometry (InSAR) can image ground displacements including along primary and distributed fault strands (see Napa case, T. Dawson’s talk; or Iranian cases, R. Walker’s talk). It is also sensitive to fault motion at depth and inversion of ground displacement provides constraints on down-dip width, sub-surface length, slip distribution on fault plane etc. This technique offers the opportunity to capture the entire large-scale and continuous surface deformation field associated with an earthquake, starting from moderate magnitudes (M>5).

However, this technique has some limitations. There may be no coherence close to the fault rupture itself when relative displacements are high. In addition, resolution may not be sufficient for mapping details required for the database purposes (but this depends on the used SAR data). Also, displacement values are provided in “line-of-sight” (LOS) and several interferograms with different LOS are needed to convert LOS components to the actual displacement values.
InSAR also gives access to the possibility of quantifying afterslip and creeping displacement along faults.

4.2.3 ADDING PARAMETERS TO IMPROVE REGRESSIONS

The attendees regularly underlined during their talks and during the open discussions that the unified database require including relevant parameters that control surface rupture pattern. Up to now, regressions were proposed only based on the magnitude and on the earthquake mechanism. However, geological surveys of historical events clearly showed that other parameters control the surface faulting pattern. The most obvious parameters, and the most mentioned ones during the meeting, are the following.
At the level of the displacement description,

- **Surface geology** (see P. Villamor for Darfield quake, C. Costa for South-American paleoevents, etc). The large spectrum of cases - in terms of quality and quantity of data, as well as in terms of diversity of natural environment- could result in an unmanageable situation and non-representative statistical populations. We therefore propose a basic classification (cover beds vs basement; basic sediment lithology). We could also add a rough classification of sedimentary thickness, for instance using the morphological location: points within large valleys could be assigned with a “thick cover bed” flag, whereas points on proximal alluvial fan with “thin alluvium” and points on hillslopes with “basement”. When available, the database could include a thickness value. **Water table** relative elevation (to ground surface) could also be considered;
- **Along-strike location**: close to fault tips, secondary ruptures are more numerous (fault growth) (e.g. Perrin et al., 2015);
- **Fault dip and azimuth** @ station: as shown by recent examples (e.g. Balochistan earthquake, Vallage et al. 2015), the fault dip influences the fault pattern at the surface;

At the level of the fault portion/segment,

- **Mapping accuracy** (e.g. concealed; inferred; accurate location), which can help in quantifying the variability between previously mapped faults and surface ruptures has been used in the Strike-slip US database;
- **Paleoseismological information** has been mentioned by several attendees to be a potential interesting parameter: it could help in some cases to distinguish between primary and distributed fault segments; it can also be a “marker of **fault maturity**”;
- **Fault complexity**: Several attendees (e.g. J. McCalpin, P. Villamor) emphasized that distributing faulting (nature of faulting, length of fault portions, amount of displacement) is controlled by the fault complexity: step-over jog, fault sinuosity, position relative to fault tip, etc;
- **Hanging wall effect** is commonly observed, especially during reverse faulting (El Asnam earthquake in 1980);
- **Width of accommodation zone**: P. Villamor introduced this problem when presenting the 2010 Darfield case, where surface faulting is accommodated in a volume 10 to 100 m wide across the fault line;
- How do we handle (aseismic) **afterslip** in the database? Do we include in total slip the aseismic part of slip that occurs sometimes after the quake (e.g. cf T. Dawson: 2014 Napa)?;

- Do we account for time-variant factors (i.e. fault growth)? See Abstract of J. McCalpin.

For "causative earthquake table"

- **Focal depth**: this is a crucial criterion which can be computed from seismological data
- **Seismogenic depth**, referring to regional studies (seismicity; tomography)
- **Rupture length at depth**, inverted from seismological data
- **Regional deformation from InSAR data,** which opens the door to Probabilistic Tectonic Deformation Hazard Assessment (PTDHA) (see ANS, 2015). How could be raster or volumetric data be taken into account?
- Structural background**: the surface rupture pattern depends a lot on the geometrical relation between the fault at depth and the ground surface**. For instance, flat and low dip thrusts earthquakes often lead to faint (or null) surface deformation in spite of their large magnitudes (see 2015 Gorkha earthquake in Nepal; 1977 San Juan quake in Argentina). In addition, the **structural history (inversion)** can also partly control the surface deformation, as shown by Pilar for reverse-kin earthquakes on previously normal faults in New Zealand.

4.2.4 DISTINGUISHING PRIMARY FROM SECONDARY AND TRIGGERED DISPLACEMENTS

To generate statistics on the database, it is necessary to decide whether each displacement observation point belongs to a primary or a secondary, distributed fault. Unlike the US strike-slip database, but in accordance with the US normal database and the Japanese database, the unified database will account for all evidences of faulting, including the "triggered" ones.

There are several ways to assign a "primary" (or master faulting) or a "distributed" (or secondary + triggered) character and we suggest testing the different criteria and present them in the database:

- The longest fault with the largest displacement defines the primary fault; in normal cases, the antithetic fault will be considered as distributed; this "geological" approach is more "expert-dependent".
- Process criterion, used in the Japanese dataset to define secondary faulting: fault evidences located at distances greater than 1% of the primary fault length are considered distributed; this is a convenient approach which can be automated once the primary fault is defined.
- Seismological/geodetical inversion results can be considered to define the primary fault at depth according to slip distribution and then constrain the primary fault geometry at the surface.

C. Costa has introduced – but also Richard (Gorkha quake) and K. Okumura (2004-2007 Niigata earthquakes) in a certain manner - the issue of distributed faulting evidences that does not match with surface primary faults. In Argentina and Nepal, where large earthquakes are generated at depth by low dip faults, these primary faults often don't reach the surface, while distributed faulting can occur due to flexural slip or moment-bending faulting on fault-related folds for instance. How to handle these cases? How to determine the distance between distributed observation point and the primary fault? In the Japanese database presented by M. Takao, two such earthquake cases (1939 and 1984) are included and the definition of distances (between "secondary evidence" and "primary evidence") was approached as follows (e-mail exchange between M. Takao, S. Baize and O. Scotti, after the meeting):

1. The most appropriate source fault model was selected among the source fault models proposed for the earthquake.

2. The intersecting line between the upper extension of the source fault plane and the surface was estimated.

3. The intersecting line was regarded as the trace of the surface earthquake fault on the surface.

4. The shortest distance from the intersecting line to the distributed fault was measured.

4.3 CONTENT AND STRUCTURE OF THE FUTURE UNIFIED DATABASE

4.3.1 SOURCES OF INFORMATION AND DATA

The database must include the archives of the publications, at least as an external link. Choices that may appear in the DB (e.g. author opinion) need to be traced and accessible. The DB should include a minimal level of interpretation. However, we propose to include fields where the author opinion (when existing) can be presented, as well as the name of the compiler.

How to handle a case when there is more than one reference for one displacement/fault? A logic tree approach can be suggested, but in most cases the most appropriate paper will be chosen. Choice will be justified.

Different rows related to archive/authorship issues must be included:

- author's opinion,
- compiler’s opinion
- general derived method/criteria for calculating displacement
- etc

4.3.2 BASIC STRUCTURE

The fault map (including primary, secondary, triggered fractures) can be in the form of a GIS Shapefile of points (for offset measurements) and segments (for fault traces), and associated attribute tables, in its first stage.

Based on the EEE catalogue experience (cf L. Guerrieri’s talk) and on the outcomes of the discussions, we decided to implement 3 levels of data:

- At the level of the displacement observation point
- At the level of the fault portion (primary or distributed)
- At the level of the causative earthquake

The database should also include a minimum accuracy of measured elements (i.e. minimum mapping scale), a minimum degree of completeness and of data quality (e.g. Good-Mean-Bad quality indices? Or ABC).

In addition, we should define standard criteria for summarizing the Surface Rupture parameters (Surface Rupture Length, Maximum Displacement, etc).

The last issue is linked to the potential existence of different descriptions. The EEE database defines a Table for each interpretation.

4.3.3 COMPLETENESS

The idea is to aggregate as many case studies as possible. Some are “old” cases, say before the 1980’s, and they are suspected to be relatively “incomplete”; others will be recent cases characterized thanks to precise and accurate techniques (e.g. LiDAR, remote sensing). The SURE Working Group suggests adopting quality ranking at different levels and especially in the causative earthquake table where we can rank its completeness, in particular based on the date of its occurrence and survey.

A future action of the group could be to screen historical cases with existing LiDAR data and test their completeness: this could probably be done in the western US (California, Nevada, Idaho) where some places are

covered by free LiDAR data.
Scale of mapping is a significant parameter: modern techniques, together with field checks, allow reaching a high level of detail in fault mapping. For instance, LiDAR-generated DEM have a pixel resolution lower than the meter. This scale is probably not relevant for compiling rupture data to generate probabilities in an engineering perspective (or is it? for instance in lifelines issues?).
The map scale for which we generate the probability function of surface faulting with distance to the primary fault has to be discussed, because the resulting function is grid-size dependent.
According to Makoto, it is necessary to estimate the probability functions at the same (or similar) grid size as the facility dimension. According to US experience, 1:25,000 scale of mapping is the appropriate one.

4.3.4 UNCERTAINTIES

Modern techniques drastically increase the accuracy of offset measurements. They also significantly improve our capacity to assess uncertainties on measurements, which were largely under-reported leading often to overestimation of slip gradients along fault strike (Gold et al., 2013). A similar study (Scharer et al., 2014) suggests that in the database, we have also to address the methodological issue (i.e. how and with which marker was evaluated the offset?) because this choice often controls the result. Finally, Salisbury et al. (2015) formulate best-practice and report recommendations for remote sensing studies of earthquake faults from the analysis of a rich catalog of nearly 5000 earthquake offsets which provided insight into quality rating and uncertainty trends.
For the database, we suggest to include maximum and minimum values of measured displacements as well as preferred value and its uncertainty in continuity with previous US and Japan methods.

4.4 OTHER ISSUES

4.4.1 COPYRIGHT

The Japanese database is under copyright: not only the judgment about principal/distributed faulting but also the evaluation about reliability (credibility) of the data is TEPCO's intellectual property. However, raw data (with only indication of location and displacement) are freely available. For other contributors, there is no problem of copyright, because data are published and in the public domain (US).
IAEA suggests sharing an agreement stating that the interpreted data from the Japanese dataset can only be used in the framework of the IAEA. In any publication involving these interpreted data, the acknowledgments will include a reference to the owner of the data (TEPCO) and indicate, for instance, that “this article was developed in the framework of Work Area I (Seismic Hazard of IAEA)".
The SURE WG should anticipate on distribution issues concerning the finalized DB; should distribution occur in real-time or only once the SURE WG has published?

4.5 MANPOWER

The compilation of data is a time-consuming task. The attendees decided to start the implementation with a few cases, first to test the database structure.
The preliminary workplan concerns the following list of earthquakes:

1. 1944 San Juan and 1977 Caucete (Argentina), by C. Costa
2. 1987 Edgecumbe and 2010 Darfield (New Zealand), by P. Villamor (and IRSN staff)
3. 1992 Landers and 1999 Hector Mine (California), by T. Dawson (and IRSN staff if any help needed)
4. 1980 Irpinia, 1997 Colfiorito and 2009 L'Aquila (Italy), by F. Cinti and L. Guerrieri
5. 1968 Dasht-E-Bayaz (Iran) and a second case to be determined, by R. Walker and A. Elliott
6. 1995 Kobé and a second case to be determined (Japon), by M. Takao

7. 2014 Nagano (Japan) and 1999 Koaceli (Turkey), by K. Okumura (and IRSN staff if any help needed)

8. 1959 Hebgen Lake and 1983 Borah Peak (Basin and Range), by J. McCalpin (and IRSN if any help needed)

In a second step, IRSN plans a 6 month- to 1 year self-funded contract to start implementing the database. Ideally, this database would have a completely open on-line access with a free implementation platform which needs to be designed and set up.

5 DATA TABLES

5.1 CAUSATIVE EARTHQUAKE TABLE

Field Name	*Type*	*Required*	*Comment*
ID			*worldwide database? (Mai)
Magnitude	real		*clarify the magnitude scale
Depth	real		
Focal mechanism	real		*1: Reverse; 2: Strike-slip; 3: Normal; 4: Oblique
reference	text		
SRL from Geology	real		*Primary fault
Reference	text		
SRL from Geodesy	real		*Primary fault (ex InSAR)
Reference	text		
Deep Rupture length	real		*Primary fault, from seismology or seismo+geodesy inversion
Fault Width	real		
Average displacement	real		
reference	text		
Seismo layer thickness	real		
reference	text		
Structural context[$]	text		* From a standard (?)
Inversion tectonics	text		* yes/no/unknown
Morphoclimatic context[€]	text		* From a standard (?)
Quality ranking	integer		* 1: high quality; 2: mean quality; 3: poor quality

[$]Undefined; Thick-skinned fold-and-thrust belt; Thin-skinned fold-and-thrust belt; Rift; Basin-and-Range; Intraplate Fault Zones

[€]Climate: glacial, nival/periglacial, humid temperate, semi-arid and arid temperate, semi-humid tropical, semi-arid and arid tropical, and humid tropical.
Vegetation: Forest, steppe, desert
Morphology: Plain, Plateau, Mountains/Hills, High Mountains

5.2 FAULT SECTION TABLE

Field Name	Type	Required	Comment
ID		yes	
Map scale	real		
Length	real	yes	
strike (0-360°)	real	yes	
mean dip	real	yes	
fault tip dip	real		
fault-pattern complexity	text		*step-over -bend/relais - fault tip
Observer/Author ranking			* Primary/Secondary/Triggered
Paleo-events			*Y/N
Slip rate	real		classes (mm/yr): 0.1-1; 1-10; >10
Compiler section			
Origin	text	yes	*tectonic/gravitational/liquefaction
Compiler ranking	text	yes	* Primary/Secondary/Triggered

5.3 OBSERVATION POINT TABLE

Field Name	*Type*	*Required*	*Comment*
ID	integer	yes	Numerical Station ID; primary key
Date	date/time		Date and time (if recorded) of observation
reference	text		
Observer	text	yes	Last name of primary observer
Description	text		Observer's field notes
Latitude	real	yes	Latitude of observation (WGS84) - adjusted to align onto feature of interest
Longitude	real	yes	Longitude of observation (WGS84) - adjusted to align onto feature of interest
Lateral offset	real		Horizontal component of fault slip measured (cm). (positive value is for right-lateral displacement)
uncertainty horizontal (+)	real		* 2 options of uncertainty quantification
uncertainty horizontal (-)	real		
Max horiz measurement	real		
Min horiz measurement	real		
Large-aperture offset	real		* in case separation not accomodated on a single/multiple fracture(s); aperture is width of deformation zone around fault line (example Greendale fault)
Width	real		
Capture 100% deformation? (Y/N)			Y/N
Vertical offset	real		Vertical component of slip (cm)
uncertainty horizontal (+)	real		
uncertainty horizontal (-)	real		
Max vert measurement	real		
Min vert measurement	real		
Large-aperture offset	real		*aperture is width of deformation zone around fault line
Aperture Width	real		
Capture 100% deformation? (Y/N)			Y/N
Upside	text		For vertical slip, relative compass direction of uplifted side (eg. N, S, E, W, NW, etc.)
Net Slip	real		* in case directly given by observer/author
uncertainty (+)	real		
uncertainty (-)	real		
Max measurement	real		
Min measurement	real		
Slip vector inclination (°)	real		* given the fault place (see below)
Shortening	real		Negative when Extensional
Observer/Author ranking	text		* Primary/Secondary/Triggered
FltAz	real		Strike of fault at station (0-360)
uncertainty horizontal (+)	real		
uncertainty horizontal (-)	real		

Max measurement	real		
Min measurement	real		
FltDip	real		
uncertainty horizontal (+)	real		
uncertainty horizontal (-)	real		
Max measurement	real		
Min measurement	real		
Cover bed (Y/N)	boolean		
Cover nature - Lithology	text		* from a predefined list
Thickness	real		
Thickness footwall	real		*difference of cover thickness between two sides of fault
Thickness hanging wall	real		
Local slope (%)	text		* flat - gentle slope (<5%) - hillslope (5-10%) - steep slope (>10%)
Water table depth	real		
Compiler section			
Reliability	text		A: optimal; B: average; C: weak
Section	text		Link to the Fault Line Table
origin	text		Origin of offset inferred by compiler (eg. tectonic, uncertain, etc.)
notes	text		Compiler notes

6 DATA CONTRIBUTION TO THE FUTURE UNIFIED DATABASE

The attendees proposed to contribute to the unified database in providing the following cases data. Some cases are already digitized; others need to be compiled.

Carlos Costa

- 1944 M7 San Juan (Argentina), with secondary but no primary rupture;
- 1977 M7.4 Caucete (Argentina), with secondary but no primary rupture.

Pilar Villamor

- 1987 Edgecumbe (New Zealand), with triggered faulting
- 2010 Darfield earthquake, Greendale Fault (New Zealand), with “distributed primary” faulting

Tim Dawson

- California strike-slip cases: need to exported from GIS to database
- 2014 Napa earthquake (California)

Francesca Cinti

- Two Italian earthquakes (1980 Irpinia and 1989 Umbria-Marche) need to be digitize, with several triggered faults and breaks within the epicentral area; some far away
- 2009 L’Aquila (Italy)

Austin Elliott

- 2-3 ruptures to contribute, already digital format; secondary faulting incomplete/not present

Richard Walker

- Dasht-e-Bayaz quake (Iran): lots of digitizing + detailed papermaps exit
- Other Iranian earthquakes would need to compile ruptures. Most have some element of secondary faulting.

Makoto Takao

- 19 earthquakes from Japan, digitizing already done

Koji Okumura

- 2014 Nagano (Japan) earthquake (with Japanese colleagues)
- 1999 Kocaeli (Turkey) earthquake (with GST and USGS colleagues)

James McCalpin

- Around 20 earthquakes in USA Basin-and-Range Province; Plates 1-20 Pezzopane and Dawson, 1996. These earthquake ruptures are the basis of PFDHA equations for normal faults (Youngs et al. 2003).

7 ON-GOING INITIATIVES

- The first one is to implement the identified 2-3 cases per contributor (see above), by the end of 2016;
- Second, Tim Dawson, Stéphane Baize, Katsunori Sugaya (from the Nuclear Regulatory Authority of Japan) and Makoto Takao will convene a session at the AGU Fall Meeting 2016. The idea is to join the US and overseas community of earthquake geologists who potentially can contribute by providing case studies with surface ruptures;
- Third, a pre-AGU Fall Meeting workshop will be held in Menlo Park (USA). Organization is performed by Tim Dawson, Stéphane Baize and Francesca Cinti, in collaboration with USGS (D. Schwartz).

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9 APPENDICES

9.1 SCHEDULE

Wednesday 28/10/2015 PM

14.00 Welcome (Giovanni Bruna, IRSN representative)

14.10 Workshop Introduction (Oona/Stéphane)

14.30 PFDHA method and Strike-slip database in the USA (Tim)

15.15 PFDHA method and database in Japan (Makoto)

16.00 Coffee break

16:30 New tools to be used to feed the database

- LiDAR methodology (Jim)
- InSAR methodology (Richard)

Thursday 29/10/2015

9:00 Case studies in New Zealand (Pilar)

9.45 Case studies in Latin America (Carlos)

10.30 Coffee break

11.00 Case studies in Asia (Austin)

11.45 Case studies in Italy (Francesca)

12.30 Lunch

14.00 The EEE INQUA catalogue and its potential contribution to the surface database (Luca)

14:45 Case studies in the US: Normal faulting events and their use (Jim)

15.30 Coffee break

16.00 Case studies in Japan (Koji): focus on the Niigata earthquakes in 2004, 2007 and 2014

16.30 The Napa earthquake (M6; 2014); contribution of modern techniques to surface displacement mapping (Tim)

16.30 Open discussion

19.30 Social Dinner “Le Barbezingue”, Châtillon

Friday 29/10/2015

9.00 Detailed presentation of the Japanese DB and approach (Makoto)

10.00 Open discussion

- Selection of relevant parameters and database structure drafting

10.30 Coffee break

- Practical exercise on Napa earthquake dataset
- Planning the future actions

12.30 Lunch

PM: Writing down the conclusions and preparing the executive summary

9.2 SUMMARIES OF THE SLIDE SHOWS

This section presents a summary of each presentation, according to personal notes from Stéphane Baize and Jochen Hürtgen. A picture representative of the content of each presentation has been extracted and added to this summary. The full content of the slideshows is available on a shared dropbox (stephane.baize@irsn.fr).

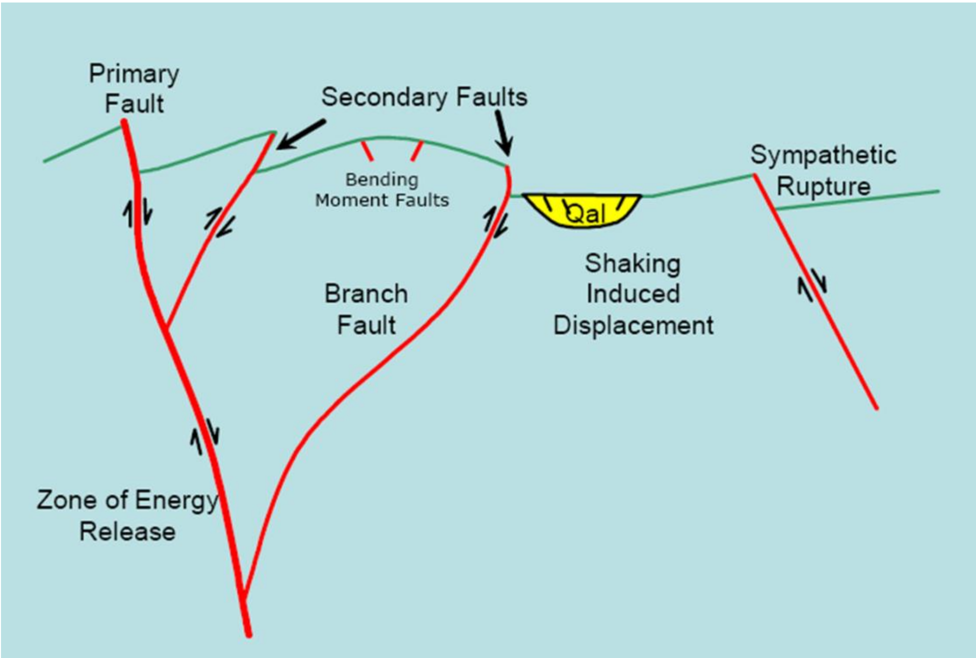
9.2.1 INTRODUCTION TO THE WORKSHOP AND THE PROJECT (O. SCOTTI & S. BAIZE)

The talk emphasized the aims of the workshop and, more generally, the objectives of the group: building a worldwide database of earthquake surface ruptures, including primary, secondary and triggered (sympathetic) ruptures.

This task will have to cope with several issues and difficulties: define (new) relevant parameters to describe/characterize surface rupture (i.e. soil conditions), standardize a database structure, handle both modern examples with very detailed data (LiDAR) and old cases with incomplete data, aggregate these datasets with various levels of completeness, complete the magnitude range to moderate values.

This new database will come out with an updating of the commonly used empirical relationships between magnitude and fault parameters.

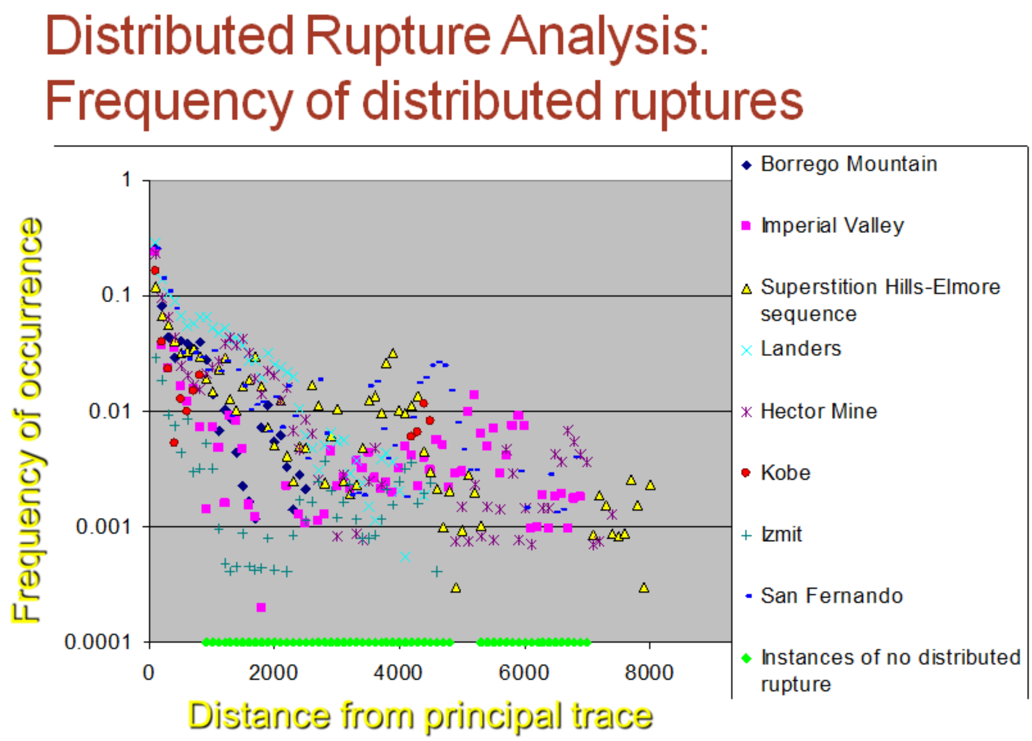
This project is in the framework of INQUA and IAEA.



Definition of surface ruptures and other surface deformation during an earthquake (From Frazier in Treiman, PEER Capable Fault Workshop in 2009)

9.2.2 PROBABILISTIC FAULT DISPLACEMENT HAZARD ANALYSIS (PFDHA) - OVERVIEW OF PFDHA AND PFDHA APPLIED TO STRIKE-SLIP FAULTS (T. DAWSON)

PFDHA provides an estimate of fault rupture hazard at a specific site, with a formulation based on PSHA (see Youngs et al. 2003). Basically, this formulation stands on a probability of surface fault rupture, an “attenuation” function (of displacement with distance along and off the main fault) providing the conditional distribution of the amount of displacement given that slip occurs (in location and magnitude).



Probability of distributed surface faulting during strike-slip events (Petersen et al., 2011 dataset)

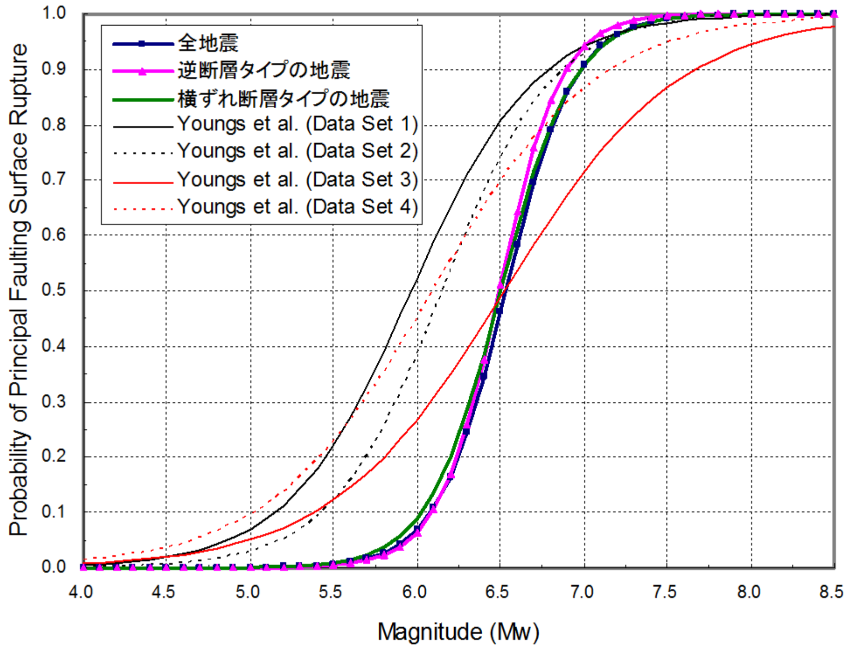
The US database is in a GIS format for Strike-Slip faults, including polylines for faults and points for displacement measurements. This dataset needs to be updated.

The Petersen et al. (2011) paper expanded the methodology by including a “mapping accuracy component” to quantify the variability between previous mapped faults to the actual location of fault ruptures, for use as a screening tool for fault rupture hazard related to existing infrastructure, where site investigations may not exist.

At the end, uncertainties appear to be large at various levels. For instance, data completeness is highly dependent on the date of the EQ and of the investigation of surface rupture. Also, distinguishing between principal and distributed faulting is sometimes equivocal and morphotectonic/surface geology conditions play a role in the shape of rupture displacements.

9.2.3 ESTABLISHMENT OF EVALUATION FORMULA FOR PROBABILISTIC FAULT DISPLACEMENT HAZARD ANALYSIS IN JAPAN (M. TAKAO)

The formulation used in the Japanese approach is similar to the Youngs et al. (2003) one. However, one conditional probability term is added: it concerns the probability of occurrence of displacement at the considered point (on master fault) when principal faulting occurs at the surface (deals with the ratio surface rupture length vs rupture length at depth). During discussion, it appears that the probability of surface faulting (when a quake occurs) is significantly different between the Japanese and US databases.



Comparison of primary faulting statistics from US and Japanese datasets (from Takao et al., 2013)

Japanese database includes 17 earthquakes with primary and distributed displacement values, which have been compiled by TEPCO from the available Japanese bibliography. The distributed faulting database, very poor at distances larger than 5 km, has been enriched with modeling data.

This DB is considered complete and raw data are available for the worldwide database; however, the interpreted dataset will be under intellectual property (which will be formalized by agreement between TEPCO, IAEA and the PFDHA Workshop group). To discriminate between main and distributed faulting (and in case the initial author does not state this), the Scholz criterion has been applied, i.e. ruptures falling in a width range of 1% of fault length are assigned to principal faulting.

9.2.4 NEW TOOLS TO FEED THE PFDHA DATABASE: LIDAR (J. MCCALPIN)

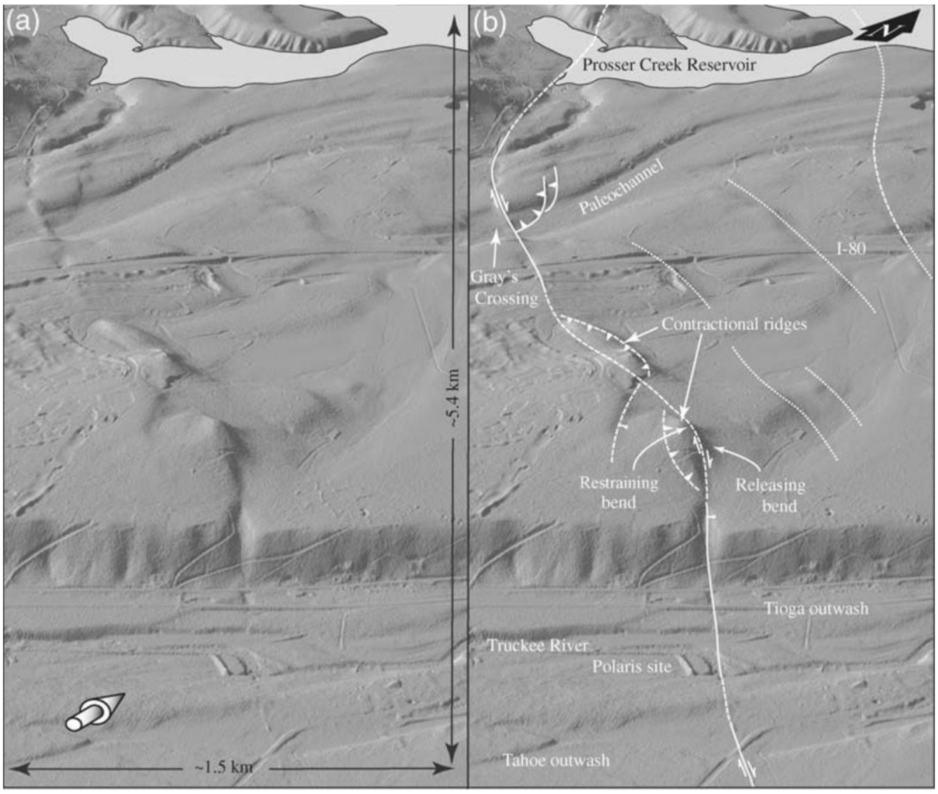
For the new database constitution, we can formulate several preliminary questions:

- Can we use only historic ruptures? Older (pre-1980) field recons primitive.
- Or should we use LiDAR on pre-1980 ruptures?
- Or should we use LiDAR on prehistoric ruptures?

LiDAR technology offers new perspectives in mapping historic and prehistoric ruptures because of its very high resolution. Obviously, vertical component of displacement is easier to infer from LiDAR DEMs, but there is also potential access to horizontal displacement (R. Arrowsmith is developing techniques/algorithms for that). With LiDAR, we have access to fault complexity which could be accounted for in the future DB.

In the USA, the OpenTopography portal is the online source for part of the country (not complete coverage, but most of the fault zones are available in California, for instance). In Sweden and Finland, the coverage is now almost complete and many “new” post-glacial faults in forests were unearthed with this technique (found long and 2-4 m high scarps which were not identified before) (cf Mikko et al., 2015 for Sweden). The LiDAR-based fault mapping with Global Mapper could be performed there and the generation of lot of across-fault profiles (~50,000, one profile every 0,5 m) has been automated by script, giving statistically more robust results.

A suggestion for the future database: if we choose to implement “old” cases (i.e. Hegben Lake or Borah Peak quakes’ ruptures in Basin and Range or Landers and Hector Mine ruptures in California), we could screen them with existing LiDAR to check the completeness and the « reliability » of field data.



Polaris fault, NW of Lake Tahoe (USA). Bare earth DEM from LiDAR in area of dense forest (Hunter et al, 2011, BSSA)

9.2.5 INSAR AND SATELLITE GEODESY TOOLS (R. WALKER)

InSAR allows identifying faults with surface rupture (or near-surface rupture), imaging fault creep, down-dip slip variations and providing a window into fault structure at depth. This technique measures ground displacement at ~10 m spatial resolution and is suitable for earthquakes > M5. In addition, it is useful in mapping the large-scale deformation zone. As for the catalogue, more than 100 earthquakes have been analyzed with InSAR (e.g. Wright, 2013). Resolutions are getting better due to more satellites with better sensors and shorter passes (ex. Sentinel: 12 days repeating views).

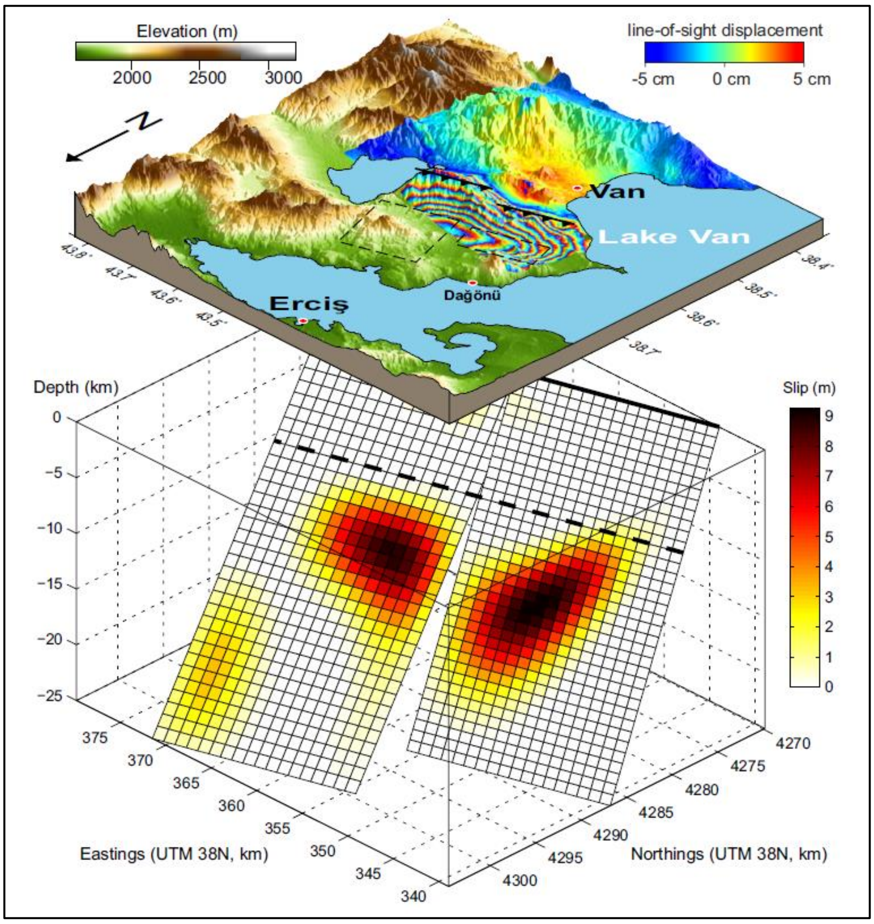
Some limitations are to be kept in mind for direct application to database. Resolution may not be sufficient for mapping details and this technique gives relative displacements in the Line-Of-Sight (limitation in providing quantitative values for DB). There is often a loss of correlation in high deformation zones.

From this, arises the issue on how can we use the InSAR information to implement the DB? Can we use the "regional" deformation field it provides in the DB?

During the talk, many examples of InSAR application to earthquake study were presented:

1. 2014 Napa EQ (California): see the Tim's talk #2
2. 2003 Bam EQ (Iran): Envisat interferogram revealed that the surface rupture did not occurred on the mapped fault;
3. 2015 Ghorka EQ (Nepal): interferogram evidences a surface deformation 25 km-long line 50 km south of Kathmandu, along an unknown fault
4. 1981 Golbaf EQ (Iran): triggered aseismic slip 30 km away from the main fault
5. 2011 Van EQ (Iran): co-seismic and post-seismic slip allows to image fault structure (at depth)

The 2013 Balochistan EQ was analyzed using InSAR data and Pleiades stereo optical imagery (giving 1 m resolution DEMs), giving access to fault complexity (geometry, partitioning, etc). After the 2010 El Cucapah EQ (Mexico), InSAR, LiDAR and optical satellite data provided consistent deformation/faulting fields.



Mw 7.1 Van earthquake, Eastern Turkey. Imaging rupture at depth, postseismic creep and fault structure thanks to InSAR (McKenzie et al., in prep.)

9.2.6 HISTORIC AND PREHISTORIC SURFACE RUPTURE INFORMING PFDHA: NEW ZEALAND CASES (P. VILLAMOR)

From NZ case studies, we formulate several uncertainties in informing surface faulting:

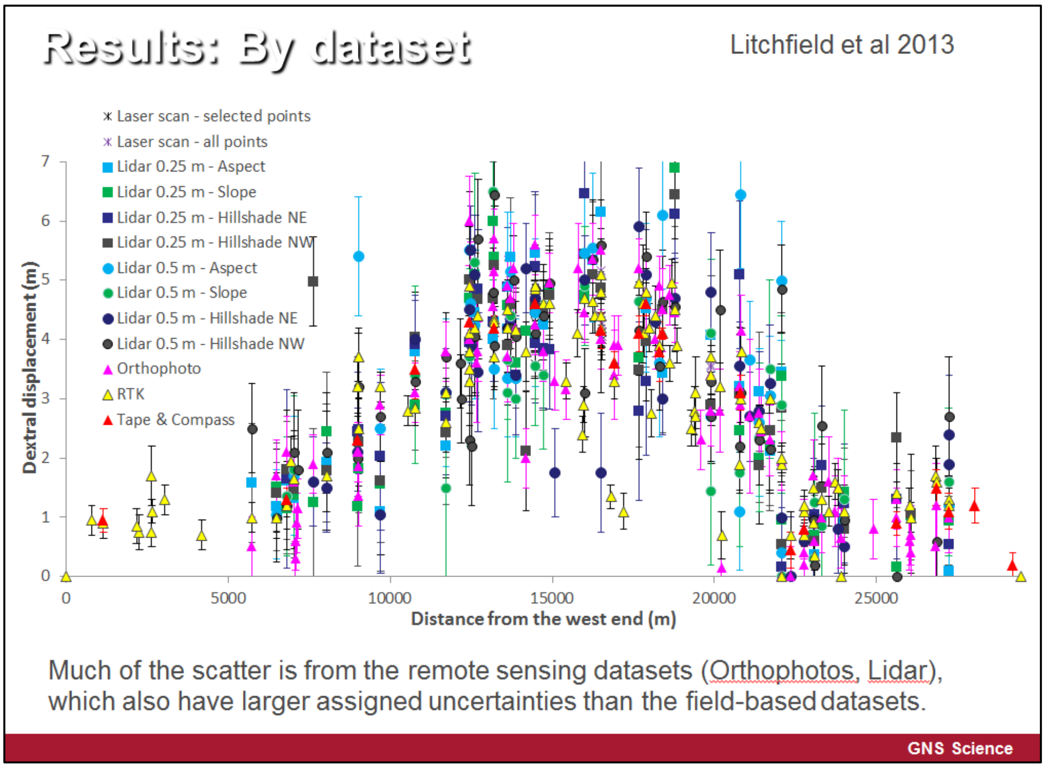
- Fault maturity: young and non-mature Greendale EQ led to complex faulting; is immaturity a parameter to implement? If yes, how evaluate and characterize the fault immaturity?
- Soft sediments may influence surface faulting pattern (ex. Greendale and Taupo EQ). For sure, this parameter is relevant.
- How to handle with unusual slip gradients

The surface rupture history in NZ contains 14 events. The most significant are:

- 1848 M7.5 Marlborough EQ on the Awatare fault (AD 5 m);
- 1929 M7.1 Murchison EQ on White Creek fault, with reverse kinematics: length at depth is 80 km, but SRL only 8 km with high displacement 4 m: inversion tectonics may have influence fault pattern compressional settings need to add uncertainties
- 1855 M8.1 Wairarapa EQ led to 15m of surface displacement
- 1968 Inangahua EQ caused by a complex structure and led to complex surface rupture (flexural-slip)
- 1987 Edgecumbe EQ: 18 km rupture at depth but soft sediments induced complex surface faulting, with several ruptures. This is tricky to discriminate between primary/secondary but paleoseismology could inform about fault interactions
- 2010 M7.1 Darfield EQ: Surface rupture has been covered by LiDAR. Deformation is distributed around main trace, typically in band ranging from 30 to 300m in width. Van Dissen calculate the band width accomodating

50% of deformation amount. A lot of feature to map: what is the relevant one to get in DB? How to handle with the width of deformation? LiDAR data give more uncertainty than field mapping.

From this case study, Litchfield et al. 2013 tried to understand the sources of uncertainties in displacement measurements: they considered the dataset source (aspect, slope, hillshade NE, different LiDAR resolutions etc.) and the operator source (one, several, many geologists).



Variation of slip measurements, according to the method (M7.1 Darfield earthquake)

Final thoughts: can we include prehistoric data? Could we revisit pre-1980 faults with LiDAR?

9.2.7 SURFACE RUPTURES IN SOUTH AMERICA - SOME CASE STUDIES AND CHALLENGES (C. COSTA)

There are very few surface ruptures in South America, less than 10 documented from Venezuela to Tierra del Fuego. However, several capitals are under threat of crustal EQ (Quito, Caracas, La Paz, Bogota, Santiago de Chile). The continent holds a high variability of morphoclimatic and morphotectonic contexts, although strike slip kinematics prevails in Andes.

Historic surface ruptures in South America include:

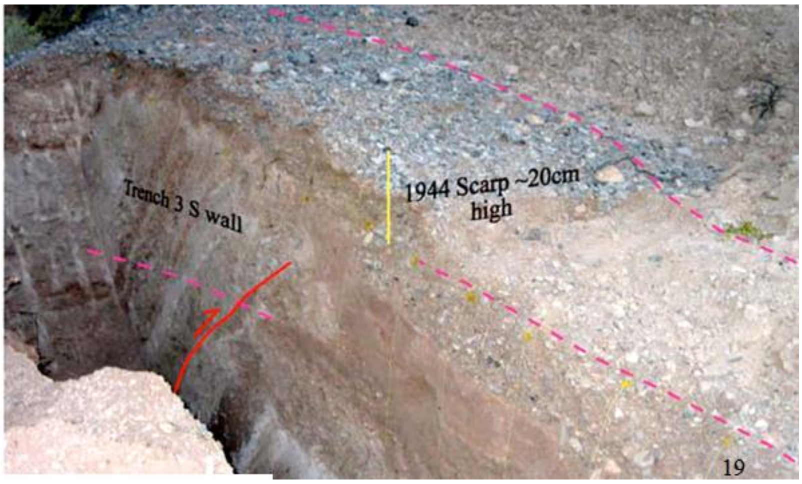
- 1946 M7.2 Ancash normal EQ (Quiches fault); coseismic slip 3.5 m; SRL 8 km
- 1969 M Huytapallana EQ with 1.6 m slip (reverse sinistral)
- 1929 and 1997 Pilar fault EQ (strike slip)
- 1950 and 1986 Cuzco EQ
- 1949 M7.8 Tierra del Fuego EQ, with 100 km of SRL

Deformation is also accommodated in the Sub-Andean and Foreland zone of Argentina). In the San Juan area, several large events occurred:

- 1977 M7.5 reverse EQ, with only SRL 5 km; MD 1 m, not consistent with deformation at large scale
- 1944 M7 reverse EQ, with SRL 8 km and less than 1 m of secondary surface displacement.

- 1952 M6.8 reverse EQ, with complex system of duplexes, flat thrusts. Surface deformation as flexural slip or moment bending is probable in this tectonic context. Faulting is accommodated at surface by warping because of loose surface material.

LA LAJA FAULT – reverse-
1944 SAN JUAN EARTHQUAKE
ARGENTINA
Mw 7.0
RUPTURE LENGTH: 8 KM
COSEISMIC SLIP: 60 CM



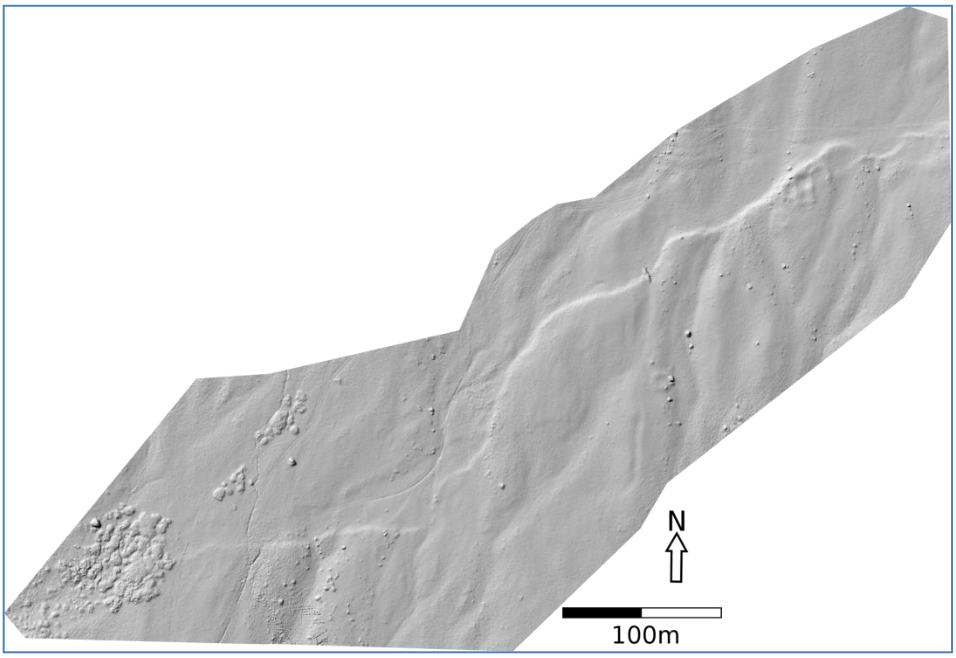
Secondary surface rupture caused by the 1944 San Juan earthquake (Argentina). D. Ragona (2007), unpublished thesis.

From the South-American cases, it appears that rheology of surface material is a relevant parameter for DB, as well as water table position. Also hanging wall effect.
Thoughts: Structural style; hanging wall effect; shallow geometry of fault are relevant parameters to include. Strong earthquake without extensive primary faulting are common in the compressive contexts (Argentina). In addition, the most obvious faults at surface are not necessarily the most important active ones, because of basinwards propagation of fault movement.

9.2.8 EARTHQUAKE RUPTURES AND ACTIVE FAULTS OF ASIA (EXAMPLES FROM CENTRAL CHINA, THE TIEN SHAN, AND IRAN) (A. ELLIOTT)

Modern techniques enable detailed characterization of prehistoric EQs and better quantification of uncertainties. However, there are inherent ambiguities on magnitude assessment, and surface rupture length for this kind of events: then, how to incorporate them in the future DB? Also, for prehistoric events, there are issues of correlation along & orthogonal to strike, number of events represented and, unfortunately a lack of preservation of distributed faulting.
Stereo-images can be used to generate low-cost DEMs (and can be compared to LiDAR). These images can be taken from drone, balloon or kite flights, with camera and then processed with photogrammetry.
For uncertainties assessment, two interesting initiative have to be mentioned. First, Terrestrial LiDAR (t-LiDAR) models can be used to re-do field measurements in a 3D model/environment (Gold et al. 2013): repeating the same measurement (10 times) by the same operator leads to significant variability of results. In California, a field test was performed, with a group of geologists of different experience levels, measuring the same features (Scharer et al. 2013, SRL) and a large variability also came out: the paper emitted recommendations, in order to unify offset measurement methods.
These points were developed through several examples in Asia:

- Yinchuan Graben where a well-documented rupture occurred in 1739;
- Kirghiz-Kazakh region: Saty and Lepsy faults, which maybe sources of historical earthquakes;
- Altyn Tagh fault where prehistoric earthquake led to a 65 km surface rupture with systematic 5-6 m individual offsets



Example of high-resolution DEM generated with balloon flight (northern Tien Shan area, Kirghistan)

Discussion

1. How to distinguish between different events for pre-historic EQs and how to include this paleo information in the DB?
2. Is archive of source data (e.g. literature) needed?
3. There is no standardized way to measure the displacement, which induces large uncertainties

9.2.9 BUILDING A WORLDWIDE SURFACE RUPTURE DATABASE FOR PROBABILISTIC ANALYSIS (L. GUERRIERI)

We can take benefit from the EEE catalogue experience, on how to organise the database, for instance. The EEE DB is organized into three levels: the site level where the EEE is assessed and the locality level where ESI intensity is evaluated through the sites information. There is also the EQ level, with relevant information: Surface Rupture Length, Maximum Displacement, Surface Faulting type, etc. For Paleoseismic and Historic Data (like 1915 Fucino EQ in Italy), the EEE DB integrate trench and witnesses data.

The Surface Displacement DB should consider the following:

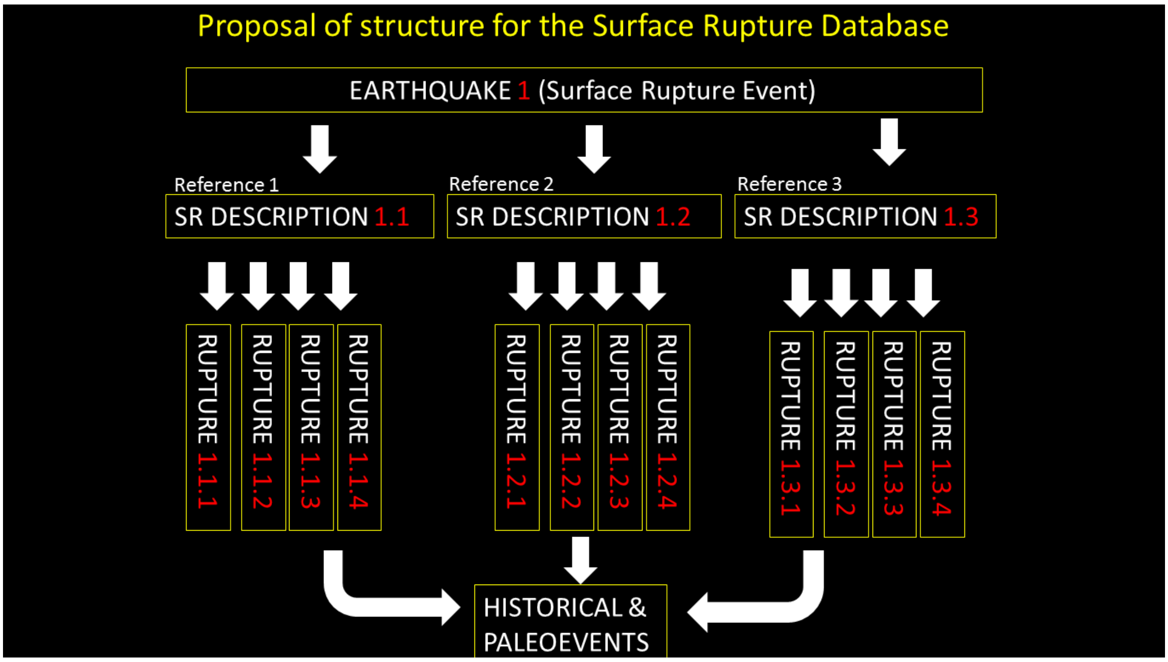
- A minimum accuracy of georeferenced elements should be required (minimum mapping scale)
- A minimum degree of completeness and of quality of data should be also required
- The DB should include moderate events
- The DB needs to integrate controversial descriptions
- How to include paleoevents?

The suggested structure is as follows:

1) Earthquake level
2) Surface Rupture description: account for different interpretations
3) Individual Fault Portion descriptions: primary/secondary/triggered; strike, length, max D, etc; also account for different interpretations
4) Individual level: type rupture, geometry, accuracy map ¤ link to the previous (Ind Fault Portion

<u>Standard criteria for summarize the Surface Rupture Parameters</u>

- SRL: maximum value taking into account the fully reliable and complete datasets or weighting the different SF descriptions (logic tree)?
- Can we estimate Max D value for historical and paleoseismic events? Maximum measured or larger?
- How to rank the reliability of assessment in case of different SR descriptions?



Proposition of database structure, accounting for various descriptions of the same earthquake surface rupture (SR)

9.2.10 SURFACE RUPTURE CASES IN ITALY (F. CINTI)

In Italy, there are 3 EQ with good surface rupture documentation:

- M6.9 Irpinia EQ (1980): primary surface rupture 38 km long; Blumetti looked at secondary triggered. We can include it in the DB but we have to "flag "
- 1997 M6 good mapping of SR; plus InSAR for regional data; database with point information; actually double event with two faults separated by a structural discontinuity; Problem with discriminating primary to secondary
- 2009 L'Aquila; Paganica fault ruptured; InSAR is available. Many teams with a common agreement on a section of Paganica for primary faulting; max length is not consensual but we can use the strong motion/GPS inversion to take decision

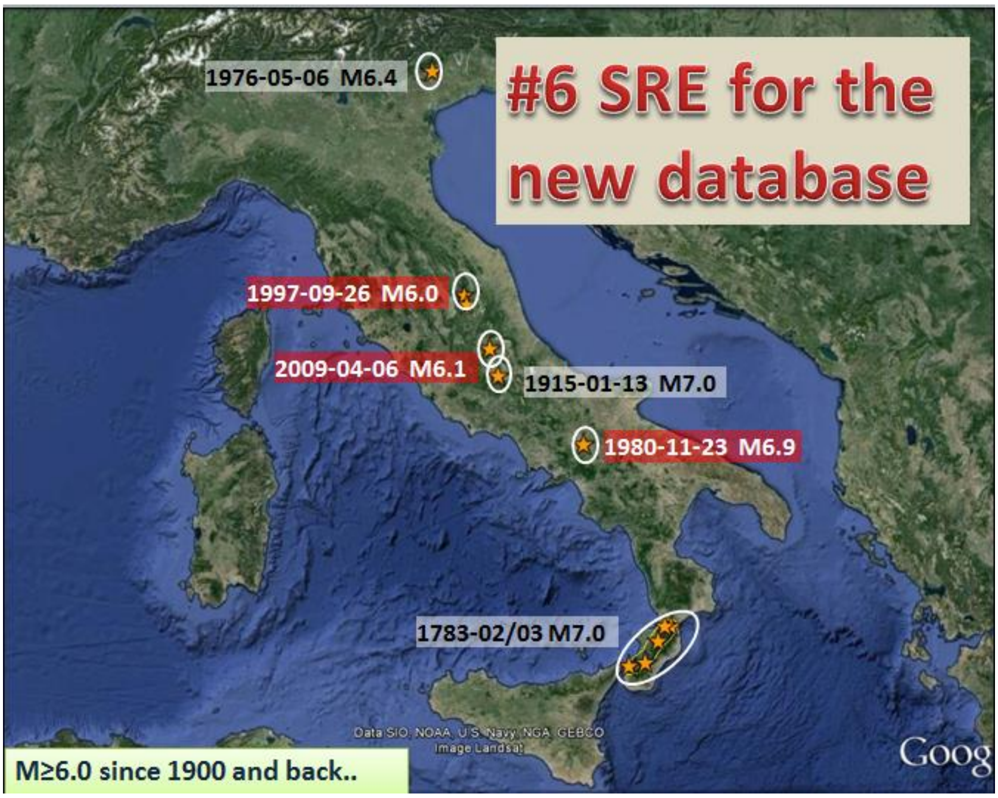
In addition, three more events could be added, one in Calabria (1783), one in Abruzzo (1915), one in Friuli (1976), with reverse mechanism.

How to integrate the Paleo/old historic data?

For the future database, we could use stable criteria for surface rupture:

- SRL min and max
- D min and max

Another big issue is the manpower, because there is much to do (compilation, implementation, and analysis).



Large earthquakes in Italy, with surface ruptures

9.2.11 NORMAL FAULTING EVENTS IN PFDHA DATABASES (J. MCCALPIN)

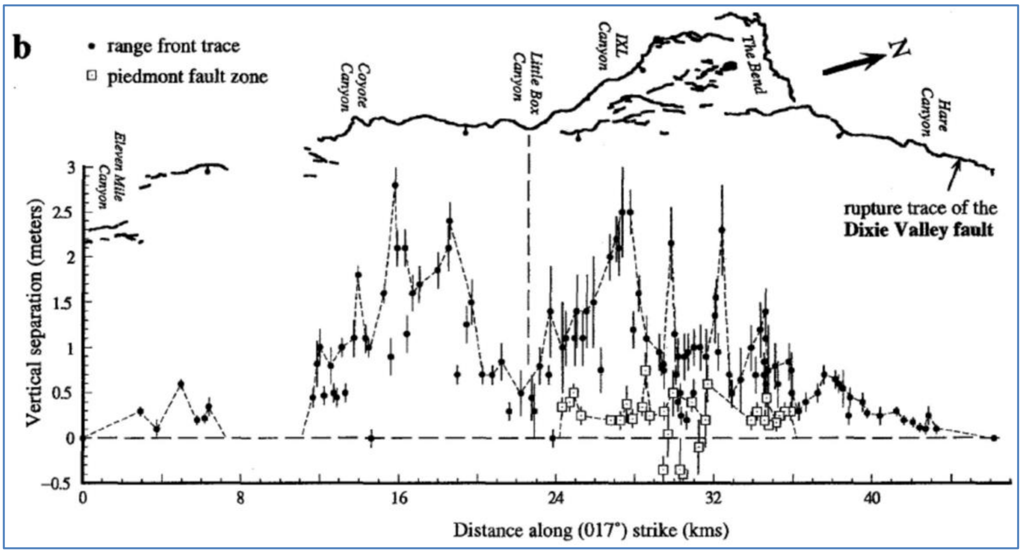
The completely empirical approach of PFDHA method was developed in 1996, with “old” data, in the framework of the Yucca Mountain nuclear waste depository (Youngs et al., 2003). The database at the base of the Youngs et al methodology includes the following surface ruptures, among a set of 24 ruptures in the Basin and Range: 1915 Pleasant valley, 1954 Dixie, 1954 Fairview Peak, 1959 Hebgen Lake, 1983 Borah Peak. The detail of the ruptures is given in the Pezzopane & Dawson (1996) report, which also contains a statistics on conditional probability of primary faulting. This includes a majority of M>6 events, with low maximum displacement (Dmax). The associated regressions have been frozen in 1995 and the whole database needs to be updated.

Borah Peak (1983) was the first surface rupture that was specifically investigated after the beginning of paleoseismology. This rupture was extensively studied by many field geologists and is, probably, one of the most complete of the database. Published maps indicate that Dmax = 270 cm and that the rupture crosses the segment boundary and loses slip amplitude.

Approaches to distributed faulting assessment:

- Empirical approach, developed by Youngs et al 2003 and Petersen et al 2011: distributed faulting regressions of Youngs is controlled on the hanging wall by only 1 point value; and footwall regression goes up to 20 km, whereas Petersen et al 2011 regressions stop at 3 km (further, points are assigned to triggered slip and not included in processing);
- Geodetic approach, by McCalpin: a part of the interseismic bend around the fault is “stored” during the earthquake and this is the driving force for distributing faulting;
- Rock mechanics: calculate displacement at distance (used for waste deposits and in Japan).

For the Dixie earthquake, distributed surface faulting is controlled by the Structural complexity.



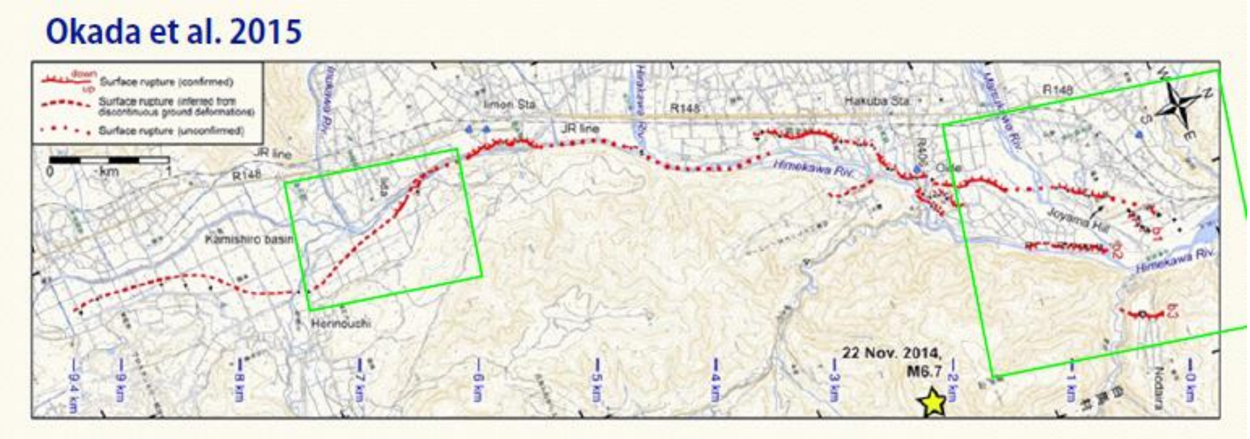
Ruptures of 1954 Dixie Valley, Nevada from Caskey et al 1996 BSSA. Note most distributed faults occur in fault bend ("piedmont faults"), a stationary feature that will persist. Elsewhere distributed faults are rare.

9.2.12 SURFACE RUPTURES AND DEFORMATION ASSOCIATED WITH 3 RECENT EARTHQUAKES OF 2004, 2007, AND 2014 IN CENTRAL JAPAN (K. OKUMURA)

The 2014 M6.2 Nagano earthquake occurred at the very end of the Itoigawa Shizuoka Tectonic Line, a major crustal fault in Honshu island of Japan. Hypocenter is shallow (5 km) and rupture propagated to 10-14 km at depth (aftershocks).The earthquake led to a Surface Rupture Length of 9 km, more or less consistent with the scaling laws' prediction. The DMax was relatively important, around 1 m for the associated magnitude. InSAR data are available, as well as GPS measurements on the hanging wall. Few afterslip was observed. Surface rupture occurred mostly on a previously mapped fault and an outstanding point is that this fault segment was trenched in 2001 and a flat reverse fault was excavated (Okumura). Another interesting point is that earthquake with surface rupture is a reverse case, a fault mechanism for which there is not much data.

The 2004 M6.6 Chuetsu earthquake occurred on a very active fold. Some secondary/triggered rupture (15 cm) occurred, probably due to flexural slip. However, a trench shows that 2004 slip occurred on a previously active fault where a large previous event occurred (with 1.5 meter of offset): then a connection of 2004 rupture with deep fault is possible.

The 2007 M6.6 earthquake was caused by a reverse offshore master fault, dipping to NW. The earthquake was followed by shallow afterslip close to the Kashiwazaki-Kariwa NPP. No damages happened on the nuclear facilities (except some equipment disorders), whereas motion was much higher than design. Consequently to the earthquake, tilt was observed in the NPP, as well as fractures inside the fences of NPP. A nice zone of uplift, 5 km east of NPP, has been observed along the axis of anticline. A very shallow secondary deformation affected the up tip of anticline, as well as triggered slip along the fold and broad deformation.



Surface rupture observed after the 2014 M6.2 earthquake in Nagano region

9.2.13 OVERVIEW OF THE AUGUST 24, 2014 SOUTH NAPA EARTHQUAKE AND NEW DATA COLLECTION METHODS (T. DAWSON)

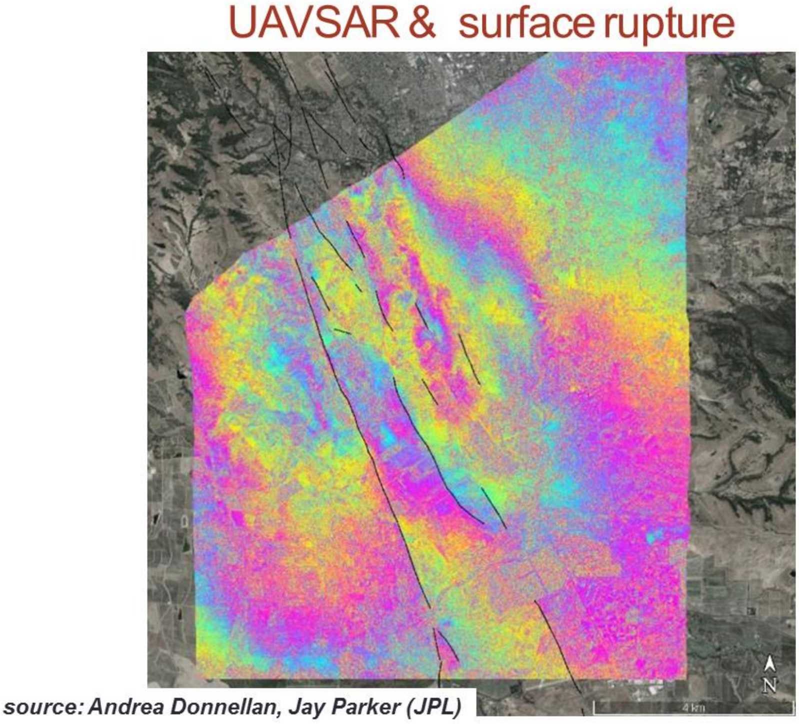
The West Napa Fault (WNF) is a minor fault zone of the San Andreas Fault System. The UCERF3 models gives a 2% of occurrence probability for a M>6.7 in the next 30yr.

The 2014 surface rupture occurred on Quaternary fault strands which were not considered as active during the Holocene. However, the West Napa Fault shows a nice morphological signature in the South Airport area. This specific strand belongs to Alquist-Priolo Zoning of active faults, a California regulation guideline: when the fault is recognized as active, studies are to be performed before any project built above it.

The 2014 surface rupture is 14 km long. InSAR helped in mapping on secondary strands, which facilitated the field check and measurement. Cosmo Skymed but also UAVSAR data (able to resolve 5 cm displacement) have been used. The maximum displacement was measured in the north-central zone of the rupture (about 46 cm). A large amount of afterslip occurred, especially to the south (80% of total slip in places). According to UAVSAR data, slip (or afterslip?) goes more to the south than previously mapped.

Concluding thoughts

This example is one of the best documented, with numerous offset cultural features, a large scientific community living close to. The rupture was complex, at least 5 strands. Also this earthquake questions a lot about our ability to recognize active faults.



Primary (black line to the left) and distributed ruptures (other black lines) associated with the M6 earthquake in Napa Valley (2014). The deformed zone is around 3 km wide.