

# Tools and Datasets of the Prompt Assessment of Global Earthquakes for Response (PAGER) System

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## Abstract

The Prompt Assessment of Global Earthquakes for Response (PAGER) System plays a primary alerting role for global earthquake disasters as part of the U.S. Geological Survey's (USGS) response protocol. PAGER monitors the USGS's near real-time U.S. and global earthquake origins and automatically identifies events that are of societal importance, well in advance of ground-truth or news accounts. Current PAGER notifications and Web pages estimate the population exposed to each seismic intensity level. In addition to being a useful indicator of potential impact, PAGER's intensity/exposure display provides a new standard in the dissemination of rapid earthquake information.

This paper provides an overview of the PAGER system, both of its current capabilities and ongoing research and development. Specifically, we summarise the underpinning models and datasets developed to improve PAGER exposure and impact modules. These include: global site-response models, enhanced earthquake source and impact databases, the Atlas of ShakeMaps and population exposure catalogue, and a global building inventory. The use of these methods and databases are demonstrated using the USGS's response to the 12 May 2008 Wenchuan, China, earthquake. Finally, we comment on the utility of PAGER tools and databases for improved near real-time earthquake alerting in Australia.

**Keywords:** PAGER, ShakeMap, hazard, exposure, impact

## 1. INTRODUCTION

It can take days to determine the scope of an earthquake disaster. Six hours after the 12 May 2008 Wenchuan, China, earthquake, major news agencies were reporting 6 deaths. The number of reported fatalities steadily grew over the next 10 days before approaching nearly 70,000 killed and 20,000 missing (World Health Organization 2008). Relying solely on media reports for earthquake response can delay the humanitarian response, prolong suffering, and potentially increase the death toll (e.g., Macintyre *et al.* 2006). To address this delay the USGS National Earthquake Information Center (NEIC) developed the Prompt Assessment of Global Earthquakes for Response (PAGER) system (Wald *et al.* 2008; Earle *et al.* 2009).

PAGER is an automated system that immediately estimates an earthquake's societal impact for events anywhere worldwide. The system estimates the number of people exposed to potentially damaging or fatal shaking levels and distributes this information to users via wireless devices, email and the Web. PAGER's rapid estimates of an earthquake's impact, and its supporting products, inform decisions by governments, insurance agencies, and relief organizations to release aid funds, prioritise regions for reconnaissance, and mobilise rescue teams.

Near real-time PAGER products rely on several tools and datasets to improve ground-shaking estimation and societal impact models on a global scale. Underpinning PAGER ground-motion estimation is the USGS ShakeMap system (Wald *et al.* 1999). This paper introduces several – but not all – of the key tools and datasets that have been developed to calibrate near real-time loss estimation tools in the PAGER system, including: (1) the global  $V_{S30}$  server; (2) PAGER-CAT composite earthquake catalogue; (3) the Atlas of Global ShakeMaps; (4) EXPO-CAT human exposure catalogue, and; (5) a global building inventory. All of the tools and datasets are being developed to be openly available to the seismological and earthquake engineering communities and are available at: <http://earthquake.usgs.gov/eqcenter/pager/prodandref/>.

## **2. GLOBAL $V_{S30}$ SERVER**

Wald and Allen (2007) describe a methodology for deriving maps of seismic site conditions using topographic slope as a proxy.  $V_{S30}$  measurements (the average shear-velocity down to 30 m) are correlated against topographic slope to develop two sets of coefficients for evaluating a surrogate for  $V_{S30}$  across a spatial extent: one for active tectonic regions, and one for stable continental regions.

Having a first-order assessment of seismic site conditions anywhere in the world provides a valuable tool in the rapid prediction of ground-motion amplification following global earthquakes, the primary motivation for this research. These  $V_{S30}$  maps enable us to better quantify possible ground-shaking and rapidly deliver these predictions (i.e., through ShakeMaps) to emergency managers and responders. Global  $V_{S30}$  grids are available via a web delivery service at: <http://earthquake.usgs.gov/vs30/>.

## **3. PAGER-CAT**

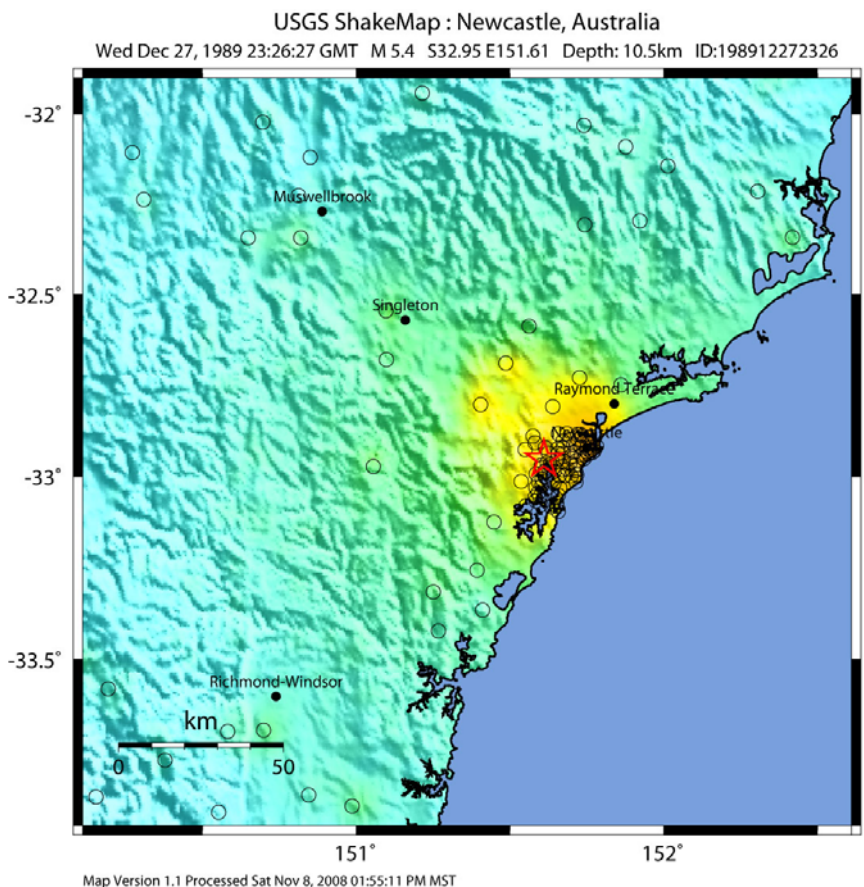
PAGER-CAT forms the basis for the development of both the Atlas of ShakeMaps and EXPO-CAT. It was developed by combining high-quality earthquake source and loss information from eight global earthquake catalogs (Allen *et al.* 2009a). Although unpublished proprietary catalogues exist within the loss modelling community, we found no publicly available catalogue containing both comprehensive earthquake source parameters and fatality information. The high-quality earthquake hypocenters and magnitudes indicated in PAGER-CAT are necessary for the calculation of individual ShakeMaps in the Atlas of Global ShakeMaps (Allen *et al.* 2008; 2009b).

PAGER-CAT also incorporates additional auxiliary data to provide accurate information, not only for hypocentral locations, magnitudes and human casualties, but also detailed focal mechanism information, the country of origin, local time and day of week. Where available, an indication of secondary effects (e.g., tsunami, landslide, fire or liquefaction) and deaths attributed to these effects (Marano *et al.* 2009), the number of buildings damaged or destroyed, and the number of people injured or left homeless

are also provided. Regularly updated versions of PAGER-CAT will be available at: <http://earthquake.usgs.gov/research/data/pager/>.

#### 4. THE ATLAS OF GLOBAL SHAKEMAPS

Maps of peak ground acceleration and velocity (PGA and PGV, respectively), and intensity have been calculated for some 5,650 recent historical (1973-2007) global earthquakes (Allen *et al.* 2008; 2009b). The goal in developing the ShakeMap Atlas was to only include earthquakes, which resulted in significant population exposures to strong ground-shaking. The Atlas was produced using established ShakeMap methodology (Wald *et al.* 1999) and constraints from macroseismic intensity data, instrumental ground motions, regional topographically-based site amplifications (Wald and Allen 2007), and published earthquake source dimensions. The online Atlas and supporting databases can be found at: <http://earthquake.usgs.gov/eqcenter/shakemap/atlas/>. An example of an Atlas ShakeMap for the 1989 Newcastle earthquake is given in Figure 1. This map can be accessed at the following url: <http://earthquake.usgs.gov/eqcenter/shakemap/atlas/shake/198912272326/>.



**Figure 1.** An example of a ShakeMap from the Atlas of Global ShakeMaps (Allen *et al.* 2008; 2009b) for the 27 December 1989 Newcastle, Australia earthquake. Hollow circles represent macroseismic intensity observations from the Australian Iseismal Atlas, which are used to calibrate observed ground-shaking for historical earthquakes.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

## 5. EXPO-CAT POPULATION EXPOSURE DATABASE

EXPO-CAT provides first-order estimates of the number of people exposed to significant global earthquakes since 1973 using current PAGER methodology (Allen *et al.* 2009b). It combines earthquakes in the Atlas of ShakeMaps (Allen *et al.* 2008) with a gridded global population database to estimate population exposure at discrete levels of macroseismic intensity. Present-day population exposure is estimated using the Oak Ridge Laboratory's Landscan global population database (Dobson *et al.* 2000). We subsequently hindcast these numbers to the date of the earthquake using United Nations (UN) population growth rate information (United Nations 2006). Combining this population exposure dataset with historical earthquake loss data, such as PAGER-CAT, provides a useful resource for calibrating loss methodologies against a systematically-derived set of ShakeMap hazard outputs. This dataset is also the primary source for the automated comments that accompany PAGER's signature product, the "onePAGER" (Fig. 2), which states the estimated population exposure and reported impact from historical earthquakes in the source region of the alerted earthquake. The EXPO-CAT database is available at: <http://earthquake.usgs.gov/research/data/pager/expocat/>.

## 6. GLOBAL BUILDING INVENTORY

A global database of building inventories has been developed (Jaiswal and Wald 2008) for pre-earthquake risk analysis, and for use in near real-time post-earthquake loss estimation (e.g., Porter *et al.* 2008a; Jaiswal *et al.* 2009; Wald *et al.* 2009a; 2009b). At the country level, the inventory database contains estimates of building types categorised by material, lateral force-resisting system, use, and occupancy characteristics. The database draws on and harmonizes numerous sources: (1) UN statistics (UN, 2001), (2) UN Habitat (pers. comm., 2007), (3) national housing censuses, (4) the World Housing Encyclopaedia (Porter *et al.* 2008b) and (5) other literature.

## 7. PAGER RESPONSE TO THE 2008 WENCHUAN, CHINA, EARTHQUAKE

The first PAGER exposure estimates for the 12 May 2008 magnitude  $M_W$  7.9 Wenchuan, China, earthquake were automatically generated and distributed 31 minutes after its occurrence (Fig. 3A). Version 1 predicted 1.2 million people were exposed to intensity VIII or greater shaking. Even a first-order exposure estimate this high, in a region with vulnerable infrastructure, is a clear indication of a major humanitarian disaster. For all earthquakes, the initial ShakeMap intensity includes effects of site response (Wald and Allen 2007), but contains no information about the fault rupture length or orientation. Thus, ShakeMap predicts the strongest intensities near the epicenter. This "point-source" approximation produces bulls-eye contours seen in Figure 3A.

Figure 3B shows the third PAGER alert generated for the Wenchuan earthquake. Produced about 2 hours after the earthquake, it was the first version to incorporate an estimate of the rupture length and orientation. We inferred that the rupture propagated from the hypocentre to the northeast based on aftershock locations, fault length versus magnitude relations (e.g., Wells and Coppersmith 1994), and regional topographic lineaments. The use of an extended linear fault for estimating shaking produces shaking contours of concentric ovals. The estimated population exposure to the highest intensities did not significantly change from PAGER's first estimate, but this version provided a better estimate of the geographical extent of the highest shaking levels.

## M 6.3, CENTRAL ITALY

Origin Time: Mon 2009-04-06 01:32:39 UTC

Location: 42.33°N 13.33°E Depth: 8 km

## PAGER

Version 8

Created: 44 days, 14 hrs after earthquake

### Estimated Population Exposed to Earthquake Shaking

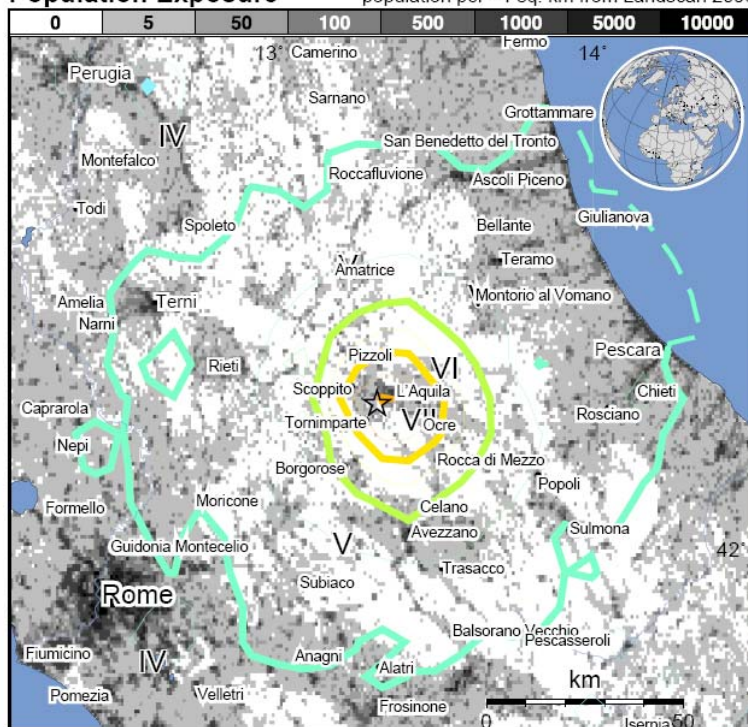
ESTIMATED POPULATION EXPOSURE (k = x1000)	--*	2k*	4,724k*	1,559k	42k	55k	33k	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

\*Estimated exposure only includes population within the map area.

#### Population Exposure

population per ~1 sq. km from Landsat 2006

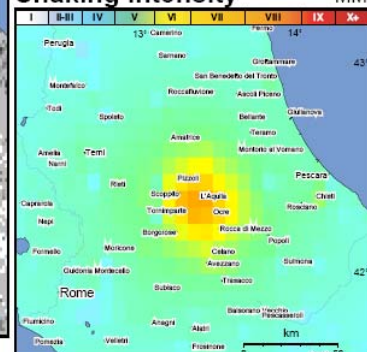
#### Selected City Exposure



MMI City	Population
<b>VIII L'Aquila</b>	<b>68k</b>
<b>VII Tornimparte</b>	<b>2k</b>
<b>VII Ocre</b>	<b>1k</b>
<b>VII Scoppito</b>	<b>2k</b>
<b>VII Pizzoli</b>	<b>3k</b>
<b>VII Poggio Pienze</b>	<b>1k</b>
<b>V Terni</b>	<b>105k</b>
<b>V Pescara</b>	<b>116k</b>
<b>IV Rome</b>	<b>2,563k</b>
<b>IV Guidonia</b>	<b>75k</b>
<b>IV Perugia</b>	<b>149k</b>

bold cities appear on map (k = x1000)

#### Shaking Intensity



Overall, the population in this region resides in structures that are a mix of vulnerable and earthquake resistant construction. A magnitude 6.0 earthquake occurred near the Umbria-Marche, Italy, region 88 km northwest of this earthquake on September 26, 1997 (UTC), with estimated population exposures of 10,000 at intensity VIII and 112,000 at intensity VII, resulting in an estimated 11 fatalities. A magnitude 6.9 earthquake occurred near the Irpinia, Italy, region 242 km southeast of the location of this earthquake on November 23, 1980 (UTC), with estimated population exposures of 37,000 at intensity IX or greater and 252,000 at intensity VIII, resulting in an estimated 2,483 fatalities. Recent earthquakes in this area have caused landslides that may have contributed to losses.

**Figure 2.** An example of a “onePAGER” report for the 6 April 2009 L'Aquila, Italy, earthquake. The onePAGER report contains a concise summary of the estimated number of people exposed to varying levels of shaking intensity, the major population centres affected, and a description of exposure and impact from historical earthquakes in the region.

Figure 3C shows the sixth PAGER alert. Created about 14 hours after the event, this version contained the last significant change in PAGER's population exposure estimates. For this version, the estimated rupture width, in addition to its length was included and its length was extended further to the northeast primarily based on seismic waveform modelling and validated from aftershock activity (Fig. 3E). This more robust

representation of the earthquake's rupture increased PAGER's exposure estimate to about 5.2 million people exposed to intensity VIII or greater (about 4.3 times our original estimate).

## **8. CONCLUSION**

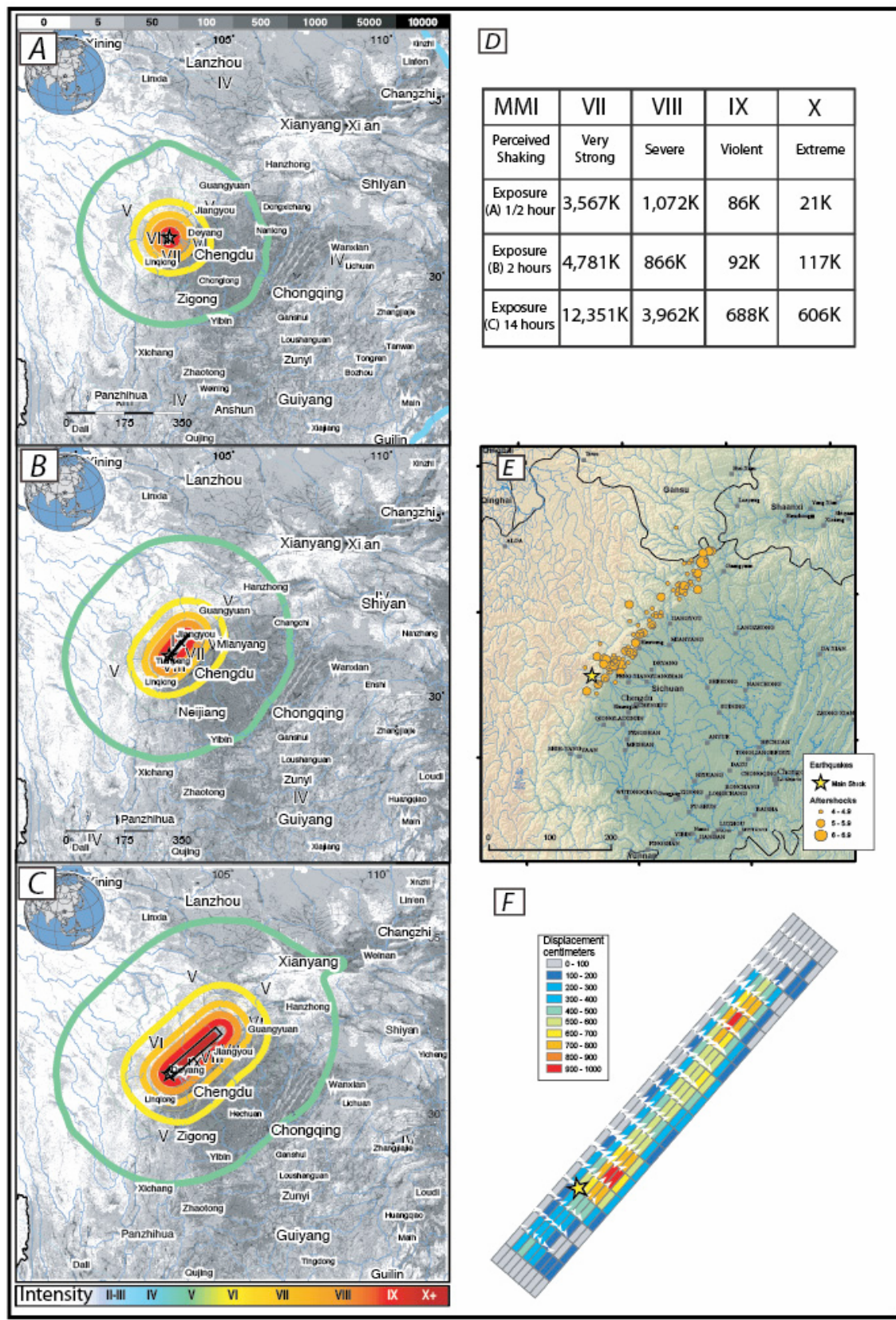
Herein we have introduced several of the key tools and datasets, which have been developed specifically to calibrate near real-time earthquake impact assessments in the USGS's PAGER system. In addition to having knowledge of impact from historical earthquakes, it is also necessary to be able to compute reliable ground-shaking globally (e.g., Allen and Wald 2009). PAGER currently reports the population exposed to different levels of shaking intensity, which is a useful indicator of an earthquake's potential impact. However, estimates of the number of people killed, injured, and displaced would provide more actionable information for emergency response. To provide this information, a significant effort is underway to develop earthquake loss models and collect the required datasets on a global scale.

All of the tools and datasets discussed herein are openly available to the wider seismological and earthquake engineering communities. Many of these resources will be updated regularly to include information on recent earthquakes, or with new methodologies and data that improves our understanding of historical earthquake impacts.

PAGER has been developed to provide near real-time impact estimates on a global scale. The main benefit of PAGER will be seen in the developing world, giving emergency responders and international aid agencies a rapid, first-order assessment of potential damage and casualties following large earthquakes. In addition to benefits in the developing world, there are also clear benefits to the developed world, where the expected losses are often measured more in economic terms rather than human.

As seen for significant recent global earthquakes (e.g., 2008 Wenchuan, China and 2009 L'Aquila, Italy), reliable measures of the societal impact can take hours to days to filter through to emergency responders who rely on ground-truth reports, potentially delaying the response and prolonging the suffering to those affected. For these events, PAGER outputs have provided valuable and rapid first-order assessments of the potential impact.

In Australia, rapid estimates of earthquake ground-shaking (e.g., from ShakeMap) could be employed to identify a disaster footprint, which could be correlated with information from Geoscience Australia's National Exposure Information System (NEXIS; Nadimpalli *et al.* 2007) to obtain an estimate of the approximate number of structures exposed to potentially damaging levels of ground shaking. NEXIS provides inventory at a resolution much higher than PAGER is likely to achieve (at census district level as opposed to national level). Consequently, near real-time earthquake impact assessments could potentially be delivered at suburb level (or smaller) for all population centres across Australia. Casualty models being developed through ongoing PAGER research (e.g., Porter *et al.* 2008a; Jaiswal *et al.* 2009; Wald *et al.* 2009b) could eventually be applied to exposure information from NEXIS to provide a more reliable indicator of deaths and injuries following significant Australian earthquakes.



**Figure 3.** Evolution of PAGER results for the 12 May 2008, Wenchuan, China, earthquake. Colour-coded macroseismic intensity contours are superimposed over grayscale population per approximately  $1 \text{ km}^2$

for PAGER alerts released (A) 31 minutes, (B) 2 hours, and (C) 14 hours after the event, respectively. (D) Estimated population exposure for the three alerts. (E) Aftershocks recorded in the days following the earthquake. (F) Finite-fault model used to estimate fault dimensions. (After Earle et al. 2009)

Finally, McPherson and Hall (2007) have described the development of a national scale seismic site classification map. However, due to the proprietary nature of this product, it cannot be openly distributed at present. Though it is unlikely to achieve the rigor of the McPherson and Hall (2007) site class map, the global  $V_{S30}$  server offers a first-order estimate of seismic site classification across Australia, which may have utility for earthquake hazard studies.

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