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The Analysis of Seismic Potential Posed by Blind Faults

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Abstract:

The release of seismic moment represented by slip rates on faults is characterized by increasing stability over progressively long time periods. In cases where the faults are blind and the tip lines do not reach the surface, one can concentrate on the shallow deformation features that form as a result of slip on the underlying fault. The analyses of the geometry and evolution of young, shallow growth structures can help us to decipher the previously unknown paleo-earthquake history of the regional faults, providing the basis for effective seismic hazard analysis.

In order to understand the paleo-earthquake history and structural evolution of blind-thrust faults and their associated folds, a multi-disciplinary methodology can be applied to link blind faulting at seismogenic depths directly to near surface fault-related folding. This multi-disciplinary approach should combine various sources of data such as high-resolution seismic reflection profiles, borehole excavations, geophysical and paleoseismological data in order to analyze the near-surface fault-related folding related to the blind faulting of the hidden faults at seismogenic depths. A complete catalogue integrating reliable estimates of slip rate values, containing data concerning individual blind faults can be helpful to have an extended point of view in seismic hazard assessment.

Keywords : blind fault, buried fault, rupture, earthquake

Introduction:

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Hidden faults often lead to under-estimation of the earthquake hazard. Blind faults in earthquake triggering are the important questions for earthquake hazard assessment. Blind-thrust faults that are capable of generating large earthquakes are generally buried deep in the earth. They are difficult to directly locate until after a major earthquake.

Dealing with blind thrusts is not easy. When blind faulting occurs in flat terrains the associated hazard is generally not perceived due to the lack of associated morphologies. The large earthquakes definitely raised awareness of the risk posed by the numerous blind thrusts buried beneath the surface; but while assessing the region's exposure and vulnerability is relatively straight forward, little is known to date about how tectonic strain is partitioned across the different faults. Here are some examples of events that occurred on unidentified seismogenic sources and were hence largely unexpected. The 25 March 2007, Mw 6.9, Noto-Hanto, Japan (Toda and Awata, 2008), the 4 September 2010, Mw 7.1, Canterbury, New Zealand (Quigley et al., 2010), and the 23 October 2011, Mw 7.1, Van, eastern Turkey (see Selim, 2013).

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Methods:

Blind thrust faults are low angle detachments that unlike most active high-angle faults do not cut the earth's surface (Figure 1). Blind thrust faults have near surface expressions in the form of overlying fold trends that are known to grow or uplift during large earthquakes.





Figure 1: High-angle faulting typically generates surface scarps that can be analyzed to determine fault offsets, slip rates and earthquake ruptures. Blind-thrust faulting causes near surface deformation at points (P) along active fold hinges (A) that are pinned to subsurface fault bends.



Active blind thrust faults pose significant seismic hazards, especially where they form in rapidly subsiding sedimentary basins and are buried continuously throughout their period of activity. There are implications for the assessment of seismic hazards, as one concentrates on the geometry of blind thrusts and the depth at which folding is replaced by broader shear in the forelimbs of fault-propagation folds.



Figure 2: Progressive development of a fault-bend fold after Suppe et al.,1992. 0: A thrust ramp connecting two decollment fault segments in pre-growth strata. 1: Fault slip causes folding of the hanging wall block along the active (A and B) and inactive (A' and B') axial surfaces.

Discussion:

Blind fault's slip rates

Slip rate is a key parameter for understanding the seismogenic potential of active fault systems and assessing the seismic hazard they pose. However, they are difficult to calculate in slow deforming regions. Fault slip rate variability at intermediate timescales contradicts some of the classic conceptual models of long-term fault behavior. The characteristic model of fault behavior (Schwartz and Coppersmith, 1984) predicts fault slip to be steady over the intermediate timescales (10^3-10^5 yr) that span multiple seismic cycles (Shimazaki and Nakata, 1980). Recent field and modeling studies have





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suggested the existence of slip rate variability on intermediate time scales (Cowie et al., 2012; Gold and Cowgill, 2011; Mouslopoulou et al., 2009; Nicol et al., 2009). Although previous studies have proposed that slip rates on faults become constant over time, few opportunities exist to test this in detail (Nicol et al., 2005, 2009; Mouslopoulou et al., 2009).

Slip over non-planar thrust faults requires folding of the overlying strata to conserve rock volume during deformation. Such folds grow above blind thrusts by motion of the hanging wall block through active axial surfaces that are pinned at depth to fault bends (Figure 2). Dipping fold limbs (kink-bands) widen with increasing fault slip. In many cases, kink-band width is equal with the total amount of slip on the underlying thrust fault, possibly summed through repeated earthquakes (Figure 2).

The application of a fault-propagation fold model is supported by the observations that folding has occurred above a blind thrust tip, and the forelimb growth strata displays progressive limb tilting and forelimb thickness variations, eliminating both fault-bend fold and fault-propagation fold models, respectively, as possible kinematic solutions.

Blind thrusts can trigger slip on secondary faults in the shallow crust, producing aftershocks over a broad area. Based on computation on static stress change, Lin and Stein (2004) and Toda (2008) suggested that the blind thrust does not need to be long to trigger the rupture of adjacent faults with a comparable size. Maesano et al. (2015) calculated Plio-Pleistocene slip rates on the blind thrusts of the outer Northern Apennines fronts. They developed a framework which included the preparation of a homogeneous regional dataset of geological and geophysical subsurface information, constructing 3D geological models around selected individual structures to decompact the clastic units and restore the slip on the fault planes.

Growth sediments are folded and translated above thrust ramps (Figure 3). The amount that the fault has moved since the rocks were deposited is recorded by the width of the panel of dipping rock for each horizon. Therefore, sediments deposited early in the slip history of the underlying fault develop wider kink-bands than do sediments deposited later. If the ages of any two horizons can be accessed, the average long-term slip rate can be calculated. The difference in kink-band widths of two horizons divided by the difference in their ages equals the long-term fault slip rate on the underlying blind-thrust ramp (Figure 3).

Growth strata (Suppe et al., 1992) are good potential recorders of slip rate variability at intermediate time scales because growth strata span long periods of time and are commonly continuous. Magneto-stratigraphically dated syn-orogenic growth strata are useful for determining slip rates on intermediate timescales but these records rarely provide a resolution better than a ~500kyr and often the resolution is closer to 1Myr (Charreau et al., 2008).





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Figure 3: Growth strata after Shaw (1993) are folded about axial surfaces (A) and translated about thrust ramps. The distance strata move up the ramp (recorded by the dipping limb-width L) equals the amount of fault slip since their deposition.

Due to the inherent difficulty in identifying the hidden or blind seismogenic sources to characterize their seismic behavior, the hazard they pose is also difficult to assess using traditional geologic tools. There are various modern methods to gather information at depth which are briefly summarized in following sections.

Paleoseismologic Trenching:

Paleoseismic trenching is the preferred method for understanding the most recent earthquakes on a fault segment; however, even the longest paleoseismic records are not of sufficient length to observe the full range of slip rate variability (Weldon et al., 2004). Dip-parallel displacement profiles can be constructed from fault-trench data and provide information about the timing and single-event displacement of earthquakes that ruptured the ground surface (see McClymont et al., 2009).

Paleoseismologic trenching is done to provide a record of paleo-seismic events that are recorded within the trench walls. The basic objective of fault trenching is to identify particular paleo-event indicator structures recorded within the trench walls. These event indicators include upward fault terminations, growth stratigraphy, fissure fills and laterally continuous layers that overlay faulted layers.





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These features help identify specific event horizons and they can constrain the age of that paleo-events (see McAuliffe et al., 2013).

Geophysical Data

Geophysical methods may be able to provide an image of subsurface structural settings within the fault zone areas from a position on the near surface (Flechsig et al., 2008; McClymont et al., 2008) down to a few kilometers depth (Becken et al., 2008; Schütze et al., 2010). The information on the distribution of seismic velocity and electrical resistivity can be applied to map shallow structures with adequate spatial resolution according to electrode/geophone spacing and alignment. Therefore, seismic sections can be used to identify the structural geological boundaries of the shallow subsurface (see Giustiniani et al., 2010).

Joint interpretation of geophysical results and determined distributions of radon and carbon dioxide concentration can be practical for the identification of permeable fractured zones hidden underneath sedimentary covers (Schütze et al., 2012). Joint data interpretation leads to more reliable models being derived of the investigated structures. They also carried out refraction seismic measurements to delineate the possible fault zone by identifying deformed refractor horizons which would indicate the presence of a fault structure.

VLF Method:

VLF radio transmitters operating in 15–30 kHz frequency band width provide an electromagnetic source for geophysical investigations. VLF method has been used successfully to investigate faults all over the world. VLF parameters such as the apparent resistivity, phase (VLF-R response) real and imaginary parts of tipper (VLF-EM response) can be achieved using a reliable radio station. For tracing of 2-D structures, it is possible to make VLF measurements in the E-polarization or in the H-polarization modes where primary E field of a VLF transmitter is perpendicular or parallel to the geological strike, respectively with standard equipments. Gürer et al. (2009) presented the results obtained during the VLF surveys across fault rupture of Fethiye–Burdur Fault Zone (Turkey) to characterize features of shallow faults and explore the possible location of the subsurface faulting where the surface rupture is covered with the basins of sediments. They suggested that the VLF method can be used to locate subsurface faults.

High-Resolution Seismic Reflection Data:

Seismic imaging is a tool commonly used by academics and industry workers alike to image and characterize the subsurface geology. The resolution of the seismic reflectors should be considered in the analysis. Sometimes the resolution of the subsurface seismic reflection data does not allow to estimate the direct correlation of each dated horizon throughout the subsurface. Therefore, it is possible

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to use the general geometry provided by the seismic reflectors to create model horizons for which we have surface structural and geo-chronologic control.

Basin sediments are practical in the imaging of blind-thrust faults with a high degree of accuracy. Industry seismic reflection data is used to constrain the subsurface geometry of the growth Shallow folds which are imaged by seismic reflection profiles. Seismic reflection images of folds that deform recently deposited near-surface sediments lead to potentially dangerous seismic faults lying at depth.

The geological data with seismic reflection and well data can be analyzed to construct structural models of the anticlines and forelimb growth strata as well as hidden faults. Seismic reflection surveys in Osaka Bay revealed a previously unknown active blind thrust fault (Kitada et al., 2001, Grothe et al., 2014). Acquisition of the high-resolution seismic reflection data, which image growth strata in detail offers the opportunity to define how a large compressive fault-related fold grew with time. Grothe et al. (2014) used the growth of the fold as a proxy for assessing how the underlying blind thrust propagated upward with increasing displacement.

Gorum et al. (2013) carried out a study on inventory compilation and statistical analyses of landslides triggered by the 2010 Haiti Mw 7.0 earthquake. They revealed that spatial distribution patterns of the co-seismic landslides were mainly controlled by complex rupture mechanism and topography. They suggested that blind-rupture earthquakes trigger fewer landslides than surface-rupture earthquakes on thrust reverse faults. Xu (2014) indicated that this cannot be always true. According to his studies, a buried-rupture earthquake can trigger a larger quantity of landslides that are distributed in a larger area, whereas surface-rupture earthquakes can trigger larger but a fewer landslides distributed in a smaller area.

Zhang et al. (2016) studied the blind thrust rupture of the 2015 Mw 6.4 Pishan earthquake in the northwestern Tibetan plateau by joint inversion of InSAR and seismic data. Their inferred coseismic slip model shows two slip asperities. They resolved a slip deficit region between the slip asperities, which may indicate friction heterogeneity on the fault plane. According to their studies, the Pishan earthquake ruptured a segment of a deeplyseated detachment fault, buried 5 ± 2 km beneath the surface.

Results:

Recent worldwide examples of earthquakes that were caused by blind, difficult-to-identify or previously unmapped faults indicate that this issue is critical even in countries where active faulting studies are advanced, though mostly focused on surface cutting structures. The analysis of modern stress





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data derived from earthquake focal mechanisms, borehole breakouts and stress orientations measured in young sediments can be useful to estimate the trend of the buried faults.

It is suggested to compile a database which integrates reliable estimates of slip rate values. The dataset should span the time interval from Pliocene to the Present, containing data concerning individual blind faults. This catalogue can list active faults able to generate Mw 5.5 and larger earthquakes. The slip rates contained in the database can be compared with other geological slip rates deduced from geodetic observations.

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