Overview of combining regional strain-rate, slip-rate variability and stress transfer during fault interaction for seismic hazard assessment and understanding of continental deformation


Abstract: Active faults experience earthquake rupture due to stress transfer from neighbouring earthquakes only if the fault in question is close to its failure stress. We lack knowledge of which faults are close to their failure stress and thus cannot interpret calculations of Coulomb stress transfer in terms of the probability of impending earthquakes. This presentation suggests that for active normal faults in central Italy whose geometry and slip-rates are well known, it is possible measure slip-rate variability and perhaps the elapsed time since the last earthquake(s), normalised to the fault slip-rates averaged over many earthquakes, using 36Cl cosmogenic exposure dating, because these are proxies for how close a fault is to its failure stress. We will combine this with calculations of stress transfer from historical and palaeoseismic earthquakes to reveal which faults are late in the cycle of loading and stress release, allowing end-users to prepare and increase social/economic resilience to earthquakes.

Key words: Cosmogenic dating, elapsed time, slip-rate variability, Coulomb stress transfer, interseismic loading.

INTRODUCTION

The seismic hazard represented by a fault, averaged over numerous seismic cycles (10^2-10^4 yrs), is controlled primarily by the fault slip-rate because earthquake recurrence intervals, for a given magnitude of damaging earthquake on a specific fault, are shorter for higher slip-rates (Roberts and Michetti 2004, Faure Walker et al. 2010). However, following a damaging earthquake, the seismic hazard represented by a neighbouring fault is altered by Coulomb stress transfer, with subsequent rupture either brought forward in time or delayed, depending on the geometry of the faults in question. It is common practice to attempt to re-calculate the probability of a damaging earthquake on the fault that received the stress by using rupture-time advance/delay to refine the probability implied by the long-term slip rate (e.g. Stein 2003, Pace et al. 2014). However, key elements in such calculations are knowledge of the elapsed time since the last damaging earthquake, and whether recent slip has kept pace with longer term slip-rates, because the stress renewal process, whereby ruptured faults are re-loaded by regional stress, takes time to prepare a fault for subsequent rupture. Unfortunately, data on elapsed times and slip-deficits are generally lacking, especially for faults whose recurrence intervals for damaging earthquakes are hundreds to thousands of years, that is, a time period longer than the historical record (Peruzza et al. 2010). In summary, a fault will only experience earthquake rupture due to stress transfer in the days/years after a neighbouring earthquake if that fault was already loaded to an extent that it was ready to fail, but whether it is ready to fail or not is usually unknown. Thus, despite the commonly held view that it is possible to calculate rupture-time advance/delay and hence short-term changes in probability, we emphasise that this is not the case unless the elapsed time and presence, or not, of late Holocene slip-deficits is known. We are trying to measure elapsed times and slip-rate variability (including late Holocene slip deficits and surpluses) on the major active normal faults in central Italy whose 15 ±3 ka –averaged slip-rates and geometries are known (Figure 1; Roberts and Michetti 2004). We utilise in situ 36Cl cosmogenic exposure dating, following, but modifying to an extent the approach of recent pioneering work (e.g. Benedetti et al. 2002, 2013; Schlagenauf et al. 2010, 2011), to assess rupture-time advance/delay across an entire intra-plate fault system. With a background knowledge that earthquakes may cluster in time due to elastic interactions between neighbouring faults (e.g. Cowie et al. 2012, and this issue), we emphasise the need for knowledge of late Holocene slip-deficits or surpluses as well as a single value for elapsed time (compare with Peruzza et al. 2010 and Pace et al. 2014). We do not know for how long and by how much a fault can be behind or ahead of its multi-seismic-cycle slip-rate due to temporal earthquake clustering. This is important because,
presumably, a long elapsed time since the last earthquake is even more significant in terms of imminent rupture if the fault, and faults sharing the tectonic process across strike, have been behind their multi-seismic-cycle slip-rates for a time period that approaches that for several seismic cycles and/or by an amount of slip that approaches that for several seismic cycles. We will show that it is precisely these kinds of features that our results from $^{36}$Cl dating can reveal (see Gregory et al. and Cowie et al. this issue). This is important because natural variability in earthquake recurrence intervals (temporal earthquake clustering), although known from only a small number of high quality palaeoseismic investigations worldwide, is thought to be common due to results from numerical models of fault growth (Cowie et al. 2012). These models show that it is not just the elapsed time since the last earthquake that is important. Rather, in the models, temporal clustering exhibits spatial variations in cluster characteristics (duration, slip amplitude during the cluster) across variable fault geometries, with greater irregularity in the timing and magnitude of earthquake slip-event sequences where faults overlap in complex geometries to share the regional load (Cowie et al. 2012). This implies that values for elapsed time normalised to the multi-seismic cycle loading rate will vary both through time and spatially across a fault system, as will cluster duration and slip amplitude during that cluster; we lack measurements of these variables.

**APPROACH**

We are trying to measure, using in situ $^{36}$Cl cosmogenic dating, the spatial distribution of (a) elapsed time and slip deficits/surpluses, (b) cluster duration, and (c) slip amplitude during the most recent cluster, across a fault system where we expect imminent earthquakes, showing how (a), (b) and (c) relate to fault geometries, fault-specific slip/loading rates, stress transfer and earthquake probabilities. The hypothesis we investigate is that the stress baseline [controlled by (a), (b) and (c) above] for refining multi-seismic cycle earthquake probabilities with data on Coulomb stress transfer will be spatially-rough. By “stress baseline” we mean the stress-levels on each fault in a system: if the stress is the same on each fault, the baseline is smooth; if temporal earthquake clustering and its associated history of stress transfer and interseismic loading have produced different stress-levels on each fault, the baseline is rough. A partial example of this is shown in Figure 1 where we present stress heterogeneity solely from coseismic stress transfer, omitting interseismic loading that Roberts and Michetti (2004) have shown must occur at different rates (see Wedmore et al. this issue). As we cannot measure stress directly from faults at depths of 12-15 km where intra-plate, damaging earthquakes nucleate, we need a proxy measure. The proxy measure we propose is provided by (a) elapsed time and slip deficits/surpluses, (b) duration of the most recent cluster, and (c) slip amplitude during the most recent cluster, and we show that this can be measured with in situ $^{36}$Cl cosmogenic exposure dating at enough sites in central Italy to map this proxy for the spatial-roughness of the stress baseline across an entire fault system (see Gregory et al. this issue). Moreover, we can place this knowledge of stress roughness in the context of 8 key constraints of the fault system that can be achieved in central Italy (see Figure 1, which shows the faults are well-characterised in terms of their structural geology and earthquake history). These 8 constraints are in place (Cowie et al. 2013) and consist of knowledge of: (i) the fault geometry; (ii) the kinematics of faulting at multiple sites; (iii) the field regional loading rate implied by geodesy and geologically-constrained motions; (iv) how the regional stress-loading rate has contributed to multi-seismic cycle slip-rates at multiple locations along each active fault and hence regional, but fault-specific strain-rate fields; (v) how overlapping faults interact to share the regional loading rate; (vi) the historical record of past earthquakes; (vii) the palaeoseismological record of past earthquakes; (viii) fault-specific strain-rates from GPS geodesy at this length-scale of individual active faults. Overall, we are trying to understand the mechanism of deformation to help constrain seismic hazard (see Cowie et al. this issue).

**METHOD**

Specifically, we combine observations of structural geology, geomorphology and Coulomb stress transfer with sampling for $^{36}$Cl on fault planes exhumed during slip. We sample portions of the faults exhumed by past coseismic slip, and dig trenches at the bases of fault scarps to collect sub-surface fault-plane samples. This combination of measurements will constrain the residence-time of the samples beneath the ground surface relative to what this residence-time should be given independent knowledge of the multi-seismic cycle slip-rate, providing constraints on (a), (b) and (c). Multiple study sites will allow us to measure the spatial distribution of (a), (b) and (c). We also sample upper slopes above scarps to help constrain the scarp age and long-term slip-rate. We will test the hypothesis that the baseline controlled by (a), (b) and (c) normalised to the slip-rate field (see Faure Walker et al. this issue and Figure 1) is rough, quantifying the extent of this. We will use these quantifications to refine multi-seismic cycle earthquake probabilities with knowledge of Coulomb stress transfer from historical/palaeoseismic earthquakes. For some examples we will calibrate our $^{36}$Cl measurements of elapsed time and cluster duration/intensity with knowledge of known elapsed times since historical earthquakes, like the 1915 Fucino event. However, for most locations, there are no existing measurements of elapsed time. For faults that have (1) long elapsed times, and/or (2) are behind their long-term slip-rate in the late Holocene, we will calculate if they have had their stresses raised by neighbouring earthquakes – such faults are candidates for imminent rupture if the slip deficit has not been filled by slip in the same time period on faults across strike. This will establish a proxy for a stress baseline from which...
Coulomb stress increases from historical and paleoseismic earthquakes can be viewed. At present, Coulomb stress transfer calculations assume the stress baseline is spatially smooth (e.g. Stein 2003), and our measurements will quantify the effect of this assumption, changing the way the earthquake community views and uses Coulomb stress transfer calculations.

Figure 1: Overview of the structural geology (throw, throw-rate and kinematics) and earthquake-induced coseismic stress changes for active normal faults central Italy. Throws correlate with throw-rates, suggesting the latter are representative of longer time periods. Sites have been selected for $^{39}$Cl in situ cosmogenic dating principally due to considerations of the geomorphology and structural geology (see McCaffrey et al. and Watson et al. this issue) so that we can be sure exhumation of fault planes form the ground is solely due to coseismic slip. Sites have also been selected to allow tests of along strike and across strike fault interaction. We assume scarps date from 18 ka in this figure, but consider a wider range (15 ±3 ka and larger in our modeling of $^{39}$Cl accumulation).
RESULTS

The slip-rates on faults averaged over 15 ±3 ka from geomorphic offsets constrain strain-rates that, when summed across strike over multiple faults, correlate with topography that has developed over 2.3 Ma (Cowie et al. 2013). This suggest slip-rates over 15 ±3 ka (Figure 1) are a good measure of the multi-seismic-cycle deformation rates. We can use these as a baseline from which we can assess slip-rates measured over shorter timescales from \(^{36}\)Cl cosmogenic dating. Our results from \(^{36}\)Cl cosmogenic dating show that few of the faults we have measured exhibit constant slip-rates over a <15 ±3 kyr timescale, instead exhibiting pulses of activity that we interpret as temporal earthquake clusters (see Cowie et al. this issue for the implications of this). Periods of activity last several thousand years, separated by periods of inactivity of similar duration. We have several examples where when one fault exhibits a period of activity, whilst another, across strike, has a period of inactivity. This suggests that faults share the work involved in maintaining regional, across-strike strain-rates on a <15 ± 3ka timescale. We emphasise this additional complication to the concept of elapsed time, because it is clear that slip-deficits on individual faults may only be significant when viewed in terms of the overall budget of slip summed across strike. This is because partitioning of deformation between faults across strike suggests they are interacting. Our Coulomb stress transfer work is designed to test whether simple elastic interaction can explain the partitioning of deformation. We show that cumulative interseismic loading and cumulative coseismic stress changes from all the earthquakes since 1349 A.D. can be summed to produce a regional stress map for comparison with \(^{36}\)Cl cosmogenic results (see Wedmore et al., this issue). One interpretation, following combined analysis of Coulomb stress transfer and slip deficits/surpluses from \(^{36}\)Cl, suggests the ruptured portion of 1915 Mw 6.9 Avezzano earthquake fault had a significant slip-deficit compared to slip expected from its 15 ±3 kyr slip-rate. To this extent, and with hindsight, the 1915 earthquake should have been expected. Overall, this work impacts on how we view \(T_{\text{mean}}, T_{\text{lag}}\) and \(\alpha\) in probabilistic seismic hazard assessments that include faults as seismic sources (\(T_{\text{mean}}\) = mean earthquake recurrence interval; \(T_{\text{lag}}\) = elapsed time since the last earthquake; \(\alpha\) = the variation in earthquake recurrence intervals compared to the mean interval; see Peruzza et al. 2010). \(T_{\text{mean}}\) can only be defined if measured over multiple seismic cycles. \(T_{\text{lag}}\) and \(\alpha\) are important, but must be considered taking into account the existence (or not) of slip deficits/surpluses summed across strike that last for several seismic cycles due to elastic interaction between faults.

CONCLUSIONS

We suggest that a combination of knowing how slip-rates are shared across strike using \(^{36}\)Cl cosmogenic dating and Coulomb stress transfer studies is an under-utilised approach to studying seismic hazard. We have much to learn about both techniques, but suggest that initial results are consistent with the idea that faults located along and across strike from each other share the job of maintaining regional strain-rates because they interact, with implications for how we perceive seismic hazard.

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References


