Active Faulting During Positive and Negative Inversion: Examples from New Zealand and Italy

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1. Introduction

Reactivation of faults over different deformation phases has been described for many tectonic settings worldwide (Cooper and Williams, 1989). Reversal of fault slip following compressional reactivation of inherited normal faults or extensional reactivation of inherited reverse faults is typically selective, but deformation may affect large crustal domains, resulting in: (1) shortening, uplift and crustal thickening of inherited extensional basins in the case of "positive" inversion; and, (2) extensional collapse, foundering and crustal thinning of orogenic belts in the case of "negative" inversion. Field studies, seismic reflection profiles and analogue experiments suggest that factors contributing to preferential reactivation rather than the creation of new faults include: orientation, dip and crustal penetration of the fault systems; mechanical strength of the fault zones; fluid overpressure, and the amount of imposed finite strain vs. total shortening (or extension) that individual faults can accommodate. The South Island of New Zealand and the Apennines of Italy provide a complete case history of active faulting and seismicity during inversion, and illustrate the difficulties of assessing seismic hazard in areas of positive tectonic inversion (New Zealand) and negative inversion (Italy).

2. Compressional, positive inversion in the South Island, New Zealand

The present tectonic setting of New Zealand results from the interaction between the Australia, Pacific and Antarctic plates, with: (1) collision and accretion of Terranes at the Gondwana margin during the Paleozoic and Mesozoic; (2) non coaxial rifting (Laird and Bradshaw, 2004) in the Late Cretaceous-Paleocene (at ~ 110-80 Ma and 70-55 Ma), with separation of "Zealandia" from Australia and West Antarctica and spreading in the Tasman Sea; (3) Eocene-Oligocene sagging, with propagation, from 45 to 25 Ma, of a new divergent plate margin across the South Island; (4) convergence, since 25 Ma, between the Australia and Pacific plates, with the opposite-polarity Hikurangi and Puysegur trenches connected by the transpressive, right-lateral Alpine Fault, developed along inherited belts of crustal weakness (Sutherland et al., 2000). Miocene to present convergence has resulted in crustal thickening and uplift of the Southern Alps, with development of a "*Compressional Inversion Orogen*" west and east of the Alpine Fault. In NW and SE South Island, uplifted basement blocks and coastlines are controlled by high-angle faults, associated with steep escarpments and coastal highs. Initial fault growth during the Late Cretaceous rifting is documented by syn-rift basins now uplifted in the fault hanging wall, whilst evidence of Miocene to Quaternary reactivation with reverse movement is recorded in syn-compressional basins in their footwall (Fig. 1**A**). The C*ompressional Inversion Orogen* (Ghisetti and Sibson, 2006) is characterised by steep (>60º) and moderate-dipping (30º≤dip≤60º) N-S to NNE-SSW faults, and by E and W vergence imparted by reactivation of systems of conjugate normal faults. Inverted faults display a change in vertical separation from normal (or null) in the basement to reverse in the cover sequence, folded with "harpoon-head" geometry. Largest offsets are documented by reverse throw of the basement, and by crosscutting low-angle thrust faults that decapitate the high-angle reverse fault, or propagate as footwall shortcuts of blind basement faults (Fig. 1**A**). These geometries reflect an increasing amount of shortening. In fact, any further upward growth of an original normal fault above the syn-rift sequence requires propagation of a new, optimally oriented fault in the compressional stress field. Compressional reactivation has imparted cumulative shortening up to 20-40% (Ghisetti and Sibson, 2006). The largest faults contain segments with demonstrated Holocene activity, and strong historical seismicity is related to ongoing compressional inversion. Six earthquakes of 6≤**M**≤ 7.8 occurred since

1868 west of the Alpine Fault. Focal mechanisms for the 1962 Westport (**M**~6), 1968 Inangahua (**M**7.1) and 1991 Hawk's Crag (**M**~6) earthquakes are consistent with near-pure reverse slip on NNE-SSW faults under compressional stress trajectories oriented WNW-ESE (Balfour et al., 2006). This is also consistent with the sinistral strike-slip observed on the N-S trending White Creek Fault during the 1929 **M**7.8 Murchison earthquake. East of the Alpine fault, seismicity related to compressional inversion of coastal faults includes the 1974 **M**~5 Dunedin earthquake and two **M**~6 Oamaru earthquakes of 1876.

3. Extensional, negative inversion in the central-southern Apennines, Italy

The Apennines results from long-term interaction between the African (Adriatic-Apulia) and European plates (Cavazza et al., 2004) with: (1) Late Permian to Jurassic- Early Cretaceous rifting of the Tethyan margin; (2) Late Cretaceous-Cenozoic subduction of the African plate; (3) orogenic contraction, from the upper Eocene to the late Pliocene. Since the late Miocene, eastward migration of the orogenic front was accompanied by extensional collapse of the thrust belt hinterland, with foundering of the Tyrrhenian basin, and superposition of normal faults onto the thrust belt. In the central-southern Apennines (Fig. 1**B**), progressive, eastward migration of both the extensional and the compressional fronts occurred at rates of 4 cm/yr, with coaxial orientation of the axes of maximum horizontal extension and compression. Negative inversion was probably triggered by strong components of uplift following shortening and thickening of the imbricate thrust wedge. Activity of the largest faults is recorded by the development of Quaternary terrestrial basins in the hangingwalls of the faults and by paleoseismic studies (Vittori et al., 1991). The high-angle normal faults crosscut the earlier thrust faults and associated folds (Fig. 1**B**), but their propagation trajectories and segmentation are dictated by the inherited fabric. The time lag of extensional onset relative to the previous contractional structures controls the development of longitudinal belts possessing distinct degrees of stretching, styles of seismicity, and Quaternary magmatism (Ghisetti and Vezzani, 2002). Today, the mountain divide separates a western, strongly extended belt with mature, deeply penetrating normal faults that favour crustal permeability and ascent of juvenile and magmatic fluids, from an eastern sector where extension is young (<3 Ma), and fluids are trapped into overpressured compartments controlled by the older contractional structures (Fig. 1**B**). The belt of strongest seismicity follows the divide, with 5≤**M**≤7 normal faulting earthquakes confined to depths ≤15 km, and inferred to occur with recurrence intervals ≥ 1 ka. Modelling of recent events (e.g. 1997, Colfiorito normal slip rupture sequence) suggests that overpressured CO_2 fluids in the lower crust trigger extensional reactivation of unfavourably oriented thrust faults, followed by aftershock sequences driven by fluid discharge in the fracture network generated by the mainshock (Miller et al., 2004). Thus, the eastward breakthrough of the extensional front enhances transcrustal permeability, with the largest earthquakes triggered by conditions of overpressuring that promote fault reactivation and propagation of new, favourably oriented, crosscutting normal faults.

4. Conclusions

New Zealand and Italy have contrasting tectonic setting in terms of stress regime, as well as kinematics and rates of plate interaction that control active deformation. However, in both countries evaluation of seismic hazard is made difficult by the activity of inherited faults with: (1) structural complexity resulting from multi-stage reactivation in different tectonic regimes; (2) concealment of basement faults by young sedimentary cover; (3) competition between the reactivation of unfavourably oriented inherited faults and the growth of new structures optimally oriented within the prevailing stress regime; and, (4) low time-averaged slip rates (≤1 mm/yr) and long recurrence interval for reactivation of individual faults. Finite displacement across the structures may be low or contrary to that expected in the prevailing stress field, thereby giving a misleading impression of inactivity.

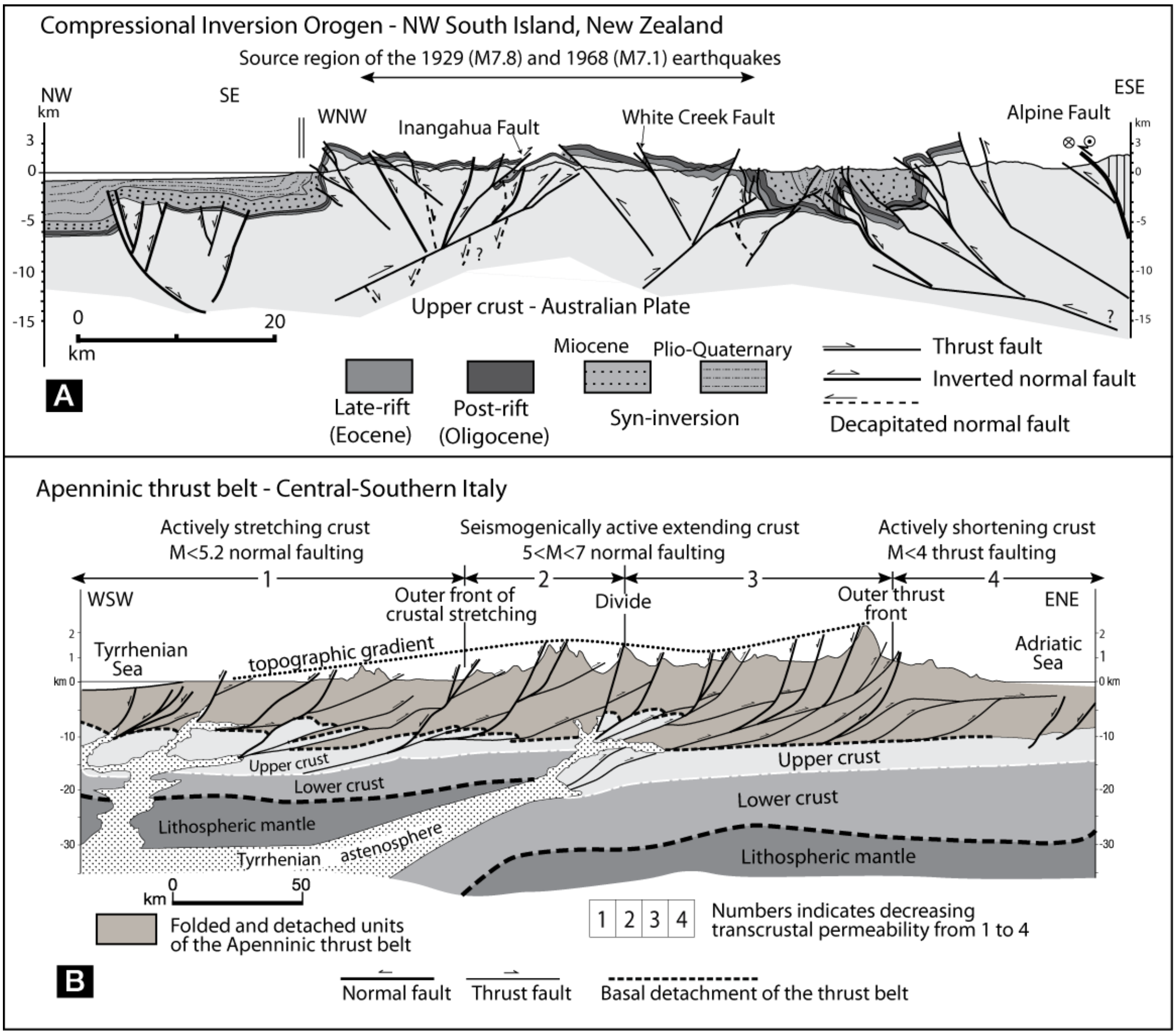

Figure 1. Regional transects across the northwestern South Island of New Zealand (**A**) and the central-southern Apenninic thrust belt of Italy (**B**). Note the different scale and vertical exaggeration for the two transects. See Ghisetti and Sibson (2006) for location of transect **A** and Ghisetti and Vezzani, (2002) for location of transect **B**.

In the South Island of New Zealand, distributed seismicity away from the main plate boundary is generated by a large number of inherited, basement penetrating faults, susceptible to reactivation in the contemporary compressive stress field, with the possibility of large, tsunamigenic reverse earthquakes along the coasts where most human infrastructure is concentrated. Moreover, blind active faults that have not moved in the short time period of New Zealand historical record (<200 years) may remain undetected in the subsurface. In the Apennines of Italy, historical normal fault earthquakes occur in a wide belt of distributed deformation, with shallow, large shocks and long aftershock sequences that affect the highly vulnerable infrastructure of densely populated regions. Though the catalogue of historical seismicity covers ~ 2 ka, the definition and mapping of individual seismogenic faults is far from complete because of the complex segmentation, unknown fault geometry at the depth of earthquake nucleation, and lack of markers documenting cycles of Holocene rupture. In fact, instrumental data of recent earthquakes have shown that the geometry of earthquake faults covers a wide (and often unpredicted) spectrum of orientation, dips, and location, resulting from the complex seismogenic interconnectivity of pre-existing fault networks and newly generated faults.

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