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Structural inheritance in mountain belts: An Alpine–Apennine perspective

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Abstract

The geological structure of continental lithosphere shows complex variety that is inherited into orogenic belts and influences the localization and amplification of contractional structures during mountain building. In the Alpine–Apennine sector together with other sectors of the Tethyan orogenic system the pre-orogenic crustal template can include arrays of extensional faults. Other faults can form adjacent to the evolving mountain belt and subsequently become incorporated as the thrust belts migrate into their forelands. While in some areas these inherited features may simply reactivate under inversion, more commonly faults show complex, partial reactivation structures. In volumes of distributed strain, faults may serve to nucleate large-scale buckle folds, for example, along basement-cover interfaces. These different patterns of basement reactivation may reflect spatially varying strength–depth profiles in continental lithosphere that are themselves inherited from spatially-distinct geological histories. Even when not themselves reactivating, basement faults can control deformation in the overlying sedimentary cover by offsetting otherwise regionally extensive detachment horizons. The 3D form of thrust systems can be strongly compartmentalized by pre-existing cross-faults, such as the oblique lineaments of the Apennines. On a large-scale, the distribution of pre-existing faults and other weaknesses may affect the propensity for orogenic contraction in basement and therefore directly control larger-scale tectonic processes. In the central Mediterranean the evolution of slab roll-back and the related growth of overlying extensional basins (e.g. Tyrrhenian Sea) may be strongly modulated by the distribution of rift-related weak zones in the adjacent continental crust. The subduction of continental crust will strongly depend on the inherited structure of this crust, specifically the distribution of deep crust of basic composition. This develops relatively higher densities associated with eclogite metamorphism which act in turn to reduce the buoyancy of thickened continental crust that otherwise serves to inhibit further shortening. Investigating all these aspects, from the scale of bulk crustal compositions to the geometry, timing and strength of earlier fault zones preserved in orogenic belts requires the integration of substantial multidisciplinary geological data sets. The extent to which continental orogenic belts represent the amplification of inherited geological heterogeneities as opposed to self-ordered phenomena modulated by the syntectonic environment remains unclear.

Keywords: Inversion tectonics; Structural inheritance; Basement reactivation; Rheology; Alps; Apennines; Maghrebides

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1. Introduction

Structural inheritance is a critical component of the geological evolution of continental lithosphere. Dewey and Bird (1970) recognized that rheological differences between different continental blocks promoted strain partitioning across collision belts. Thus for these workers and others since, following collision between India and Asia it has been deformation of the originally weaker Tibetan side that has accommodated most of the continuing plate convergence. The notion that continental collision zones guide subsequent rifting and vice versa is central to the Wilson cycle concept (Wilson, 1966). Within orogenic belts it has long been recognized that

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important lateral changes in tectonic structure coincide with changes in stratigraphic style, so that broad elements of continental margin architecture are inherited into mountain belts (see Marshak, 2004 for review). Pre-existing fault structures developed during continental rifting may be preferentially reactivated during subsequent contractional tectonics. Thus notions of structural inheritance are fundamental to understanding how deformation localizes in the continental lithosphere. Of course the long and complex history of many volumes of continental lithosphere are characterized by sporadic episodes of tectonic reworking (e.g. Holdsworth et al., 2001), so that in this sense, concepts of structural inheritance and geological legacy are fundamental to descriptions of continental geodynamics.

In this introductory contribution to the *Special Issue on Tectonic Inheritance and Tectonic Inversion in Mountain Belts* we overview some of the key concepts and developments at a variety of length scales. Ideas of fault reactivation, especially with respect to the evolution of sedimentary basins, have been the subject of several previous compilations and reviews on inversion tectonics (e.g. Williams et al., 1989; Coward, 1994; Buchanan and Buchanan, 1995). These studies concentrate primarily on brittle deformation where contractional reactivation of pre-existing normal faults (positive inversion in the sense of Williams et al., 1989) is highly dependent upon the orientations of these early faults with respect to the new, imposed stress field (e.g. Coward, 1994) together with the fluid pressure states on the faults (e.g. Sibson, 1995). However, as Ranalli (2000) pointed out, fault reactivation also depends upon the rheology of the lithosphere within which pre-existing faults are embedded. Thus understanding local reactivation processes is best achieved by framing them within the context of longer length scales and rheological variations in space and time. Hansen and Nielsen (2002) consider that the propensity for particular sedimentary basins to focus contractional deformation when subjected to regional horizontal compression depends on the temperature of the underlying upper mantle. This in turn may reflect heterogeneities in the thermal structure and conductivity of the overlying crust. This notion challenges conventional wisdom that it is the distribution of pre-existing weak zones, especially faults and shear zones, that promotes regional basin inversion (cf. van Wees and Beekman, 2000). Similar effects may apply to larger scale inversion of sedimentary basins and continental margins during orogenesis.

Insights from inverted sedimentary basins indicate that a range of geological attributes may be inherited into mountain belts to influence the progression of contractional deformation. Faults form only one part of this inheritance. The rheological structure of the lithosphere, reflecting composition, thermal structure and fluid distribution (e.g. Ranalli, 2000 and references therein), is also part of the legacy arising from the pre-contractional geological history. Some of the inherited geological attributes, such as fault orientation, may be incorporated into mountain belts with little modification. Others, such as the large-scale thermal structure of the lithosphere, may evolve dynamically during orogenesis (e.g. Toussaint et al., 2004). Large-scale variations in lithosphere composition will also play a geodynamic role.

Our aim here is to examine the role of structural inheritance in mountain belts, drawing inspiration from the Alpine–Apennine system of the central Mediterranean. Although these chains have provided important test-beds for the development and modification of inversion tectonic concepts in orogenic settings, there remains significant controversy as to the applicability of particular tectonic models, not only to specific structures but also to the geodynamics of these orogens. We show how different patterns of strain localization, broadly manifest by the range and importance of different types of deformation structure, may owe their origins to the preceding geological history. Much of this discussion is essentially geometric. However, the role of tectonic inheritance in the large-scale geodynamic evolution of orogens necessarily requires rheological considerations. It is not our intention to present numerical solutions to these issues but rather to address the range of processes and their possible tectonic roles. Hopefully these comments will allow numerical models to be better framed in the future to accommodate the constituent heterogeneities in continental lithosphere. Our discussions address some key themes: the nature of basement involvement in thrust belts; the localization of contractional structures in detached sedimentary cover; geological inheritance and compartmentalization in orogens; and the roles played by different forms of inherited structure in the large-scale evolution of mountain belts. This is not a definitive list of issues relating to structural inheritance in mountain belts. We do not discuss the role, if any, of the structural reactivation of pre-existing thrusts by extensional tectonics (so-called negative inversion, Williams et al., 1989), which forms part of the dynamic reworking of continental crust in the interiors of orogens such as the Alps and Apennines.

2. The Alpine–Apennine setting

The concept of structural inheritance in mountain belts dates back at least as far as Argand (1916) who proposed that the nappes of the Alps amplified from Mesozoic sedimentary basins and their intervening highs. Helwig (1976) proposed that the Alps represented restacked continental crust and Butler (1986) showed that pre-orogenic extension could be incorporated in crustal balanced sections for the convergence history. The legacy of Mesozoic basins within the western Alps was spectacularly described by Lemoine et al. (1986), prompting the application of basin inversion models derived from sedimentary basins to the Alpine orogen (e.g. Gillcrist et al., 1987; Welbon, 1988; Welbon and Butler, 1992). Thus, for the past 20 years, simple thin-skinned thrust system approaches to understanding Alpine tectonics (e.g. Boyer and Elliott, 1982) have been questioned, and severely modified (e.g. Gillcrist et al., 1987; Butler, 1989).

Although it has long been recognized that, like the Alps, the Apennines represent a restacked continental margin (e.g. Bernoulli et al., 1979; reviewed by Bosellini, 2004), the application of inversion models has been a recent activity, restricted to understanding local structural development (e.g. Tavarnelli, 1996). Following Coward et al.'s (1999) re-assessment of structural evolution in the outer part of the northern Apennines, the role of structural inheritance in thrust system evolution has increased in scope. However, these applications remain controversial (contrast Butler et al., 2004, with Scrocca et al., 2005), especially as they imply radically different amounts of orogenic displacement and associated crustal shortening (e.g. Tavarnelli et al., 2004) that impact directly upon geodynamic models for the Central Mediterranean.

The Alps and Apennines offer different exposure levels and stratigraphic constraints on how the continental margins of Tethys deformed under contraction and on the rôle of pre-existing structures in these deformations. In both cases we are concerned with the later-formed structures (Oligo-Miocene in the Alps, Mio-Pliocene in the Apennines), developed on the "foreland" sides of the orogenic systems. For the Alps we follow convention and consider the northern and western side of the orogen to be the foreland. The western and central Alps offer exposures of foreland-derived basement and cover relationships in and around the so-called external basement massifs (Fig. 1). In the Apennines the regional structural polarity places the foreland on the east (for mainland Italy) and south (for Sicily; Fig. 1) in Apulia and Hyblea respectively. There are no outcrops of the pre-Mesozoic basement from these forelands within the Apennine thrust systems. These systems do however provide excellent outcrops from which to deduce the geometry and timing of pre-contractional structures using the Mezosoic and Cenozoic (especially syn-tectonic) strata.

3. Styles of basement involvement and the reactivation of basement faults

The role of pre-existing normal faults in locating basement thrusts was proposed as a general process in continental tectonics by Jackson (1980), based on studies of earthquake foci beneath the Zagros ranges of Iran. Subsequent studies however suggest that ideal fault reactivation, as envisaged by Jackson (1980) and subsequently recognized in moderately inverted sedimentary basins (e.g. Buchanan and Buchanan, 1995) is not common within mountain belts. The rôle of pre-existing basement faults in controlling the structural style in the external western Alps was reviewed by Gillcrist et al. (1987). In the Apennines of Italy there are rather few outcrops of Apulian-derived basement, and therefore the rôle of inversion of basement faults has remained speculative (e.g. Butler et al., 2004). Thus here we examine the degrees of structural reactivation in

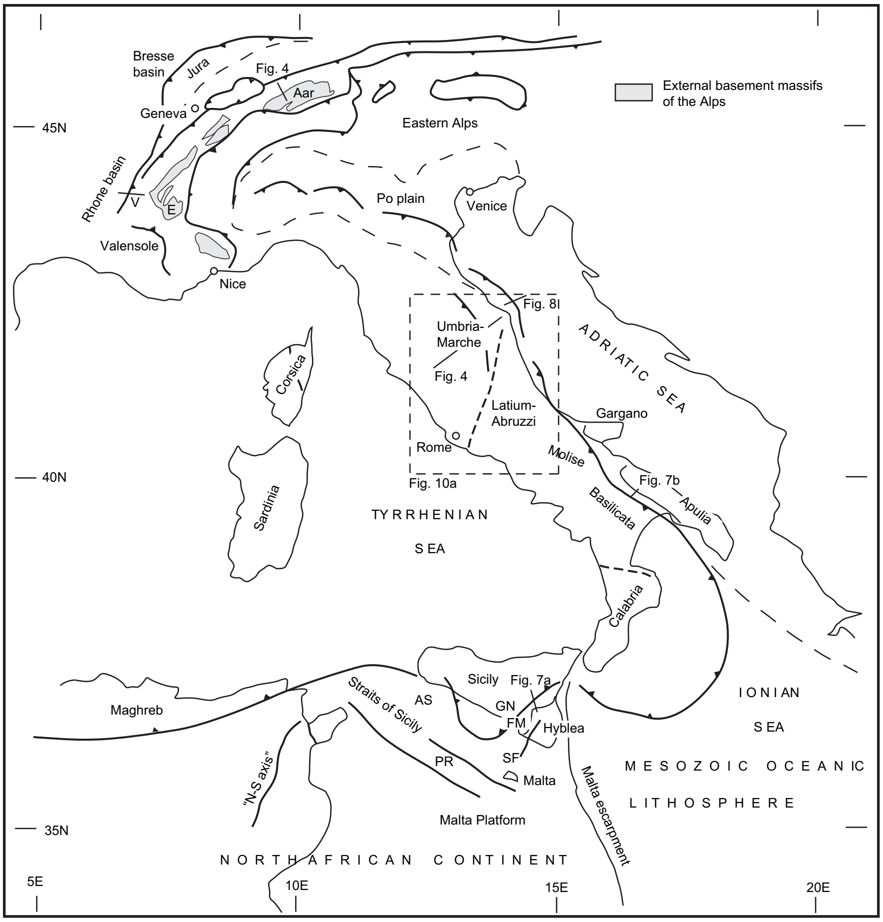

Fig. 1. Simplified geo-tectonic map of the Alpine–Apennine orogenic system showing the location of sites mentioned in this paper. AS, Adventure Shelf; GN, Gela Nappe; FM, Fiume Margi foredeep of Sicily; SF, Scicli Fault; PR, Pantelleria Rift; E, Ecrins (external basement massif); V, Vercors (Subalpine chain).

controlling basement involvement in the Alps and then discuss the application of these examples to the Apennines.

3.1. Variations in Alpine basement reactivation

The finest array of pre-orogenic normal faults preserved at the level of the basement-cover contact in the Alps is found in the Ecrins region (Lemoine et al., 1986; Fig. 1). In general these faults dip counter to the WNW direction of thrusting. However, the most recognizable faults that are the least modified by contraction have dips in excess of 60°. Consequently they are not especially well-oriented for reactivation (e.g. Coward, 1994; Sibson, 1995). Gidon (1981) demonstrated that the basement faults did not simply reactivate as thrusts, but rather served to partition thrust-related contraction into zones of predominantly vertical stretching, especially strongly developed in Jurassic shales and thin-bedded limestones adjacent to early normal faults. This behaviour has since been termed ‘‘buttressing’’ (Gillcrist et al., 1987). Other parts of the basement-cover relationships show complex folding and fault offsets, catalogued by Gillcrist et al. (1987) and de Graciansky et al (1989; Fig. 2). These include isolated wedges of basement (so-called *Iles flottantes*) that represent trimmed footwall corners to early normal faults. For the larger-displacement thrusts it is unclear whether they originated as reactivated normal faults or are entirely new fault surfaces. Slip from these structures transfers within the cover sediments, presumably feeding into the buttressed sedimentary successions in more outlying half graben. The sequence of inversion activity and other thrusting in these regional arrays remains unclear.

de Graciansky et al. (1989) suggest that many of the old Mesozoic basins now caught up in the Ecrins region have been penetratively shortened. The description harks back to the notion that Mesozoic-cored synclines in Alpine basement (so-called pinched-in synclines, e.g. Ramsay, 1967) appear previously sheared and are systematically associated with thrust and nappe structures. The type area for this behaviour is the northern flank of the Aar massif of the central Alps (Fig. 1). Boyer and Elliott (1982) interpreted the pinched-in synclines of Mesozoic as lying in the footwalls to thrust ramps climbing out of basement. However Collet’s (1927) descriptions indicate that these synclines show stratigraphic omissions along their lower limbs (Fig. 3a), whereas thrusting models predict stratigraphic truncation on the upper limb. The stratigraphic relationships are better explained as being strongly compressed half-graben (Butler and Mazzoli, 2006; Fig. 3b). It is likely, then, that pre-contractional offsets of the basement-cover contact provided perturbations that localized the hinges of interfacial buckle folds (Fig. 3).

The discussions of basement-cover styles in the Alps serve to indicate that pre-existing basement faults and their related sedimentary rift basins can play different roles in the structural history during contraction. As ideal fault reactivation is rare it is likely that the old fault zones themselves are not especially weak with respect to the surrounding basement. This may be a feature of the specific lithologies and geological history of Alpine and Apennine basement. For example, the Ecrins basement of the Alps (Fig. 2) contains a wide variety of lithologies from large tracts of granites and migmatites to lower-grade micaschists (von Raumer et al., 1993) that might be inferred to have had significantly differing strengths. As yet there have been no studies to investigate how the different styles of basement reactivation correspond to these variations in basement type. In other situations, for example in anhydrous, otherwise strong crystalline basement, weak faults may serve to localize contractional deformation more strongly (see discussion by Butler and Mazzoli, 2006).

3.2. Models of Apennine thrusting

The paucity of information on the nature and depth of the crystalline basement and of its relationships to the overlying

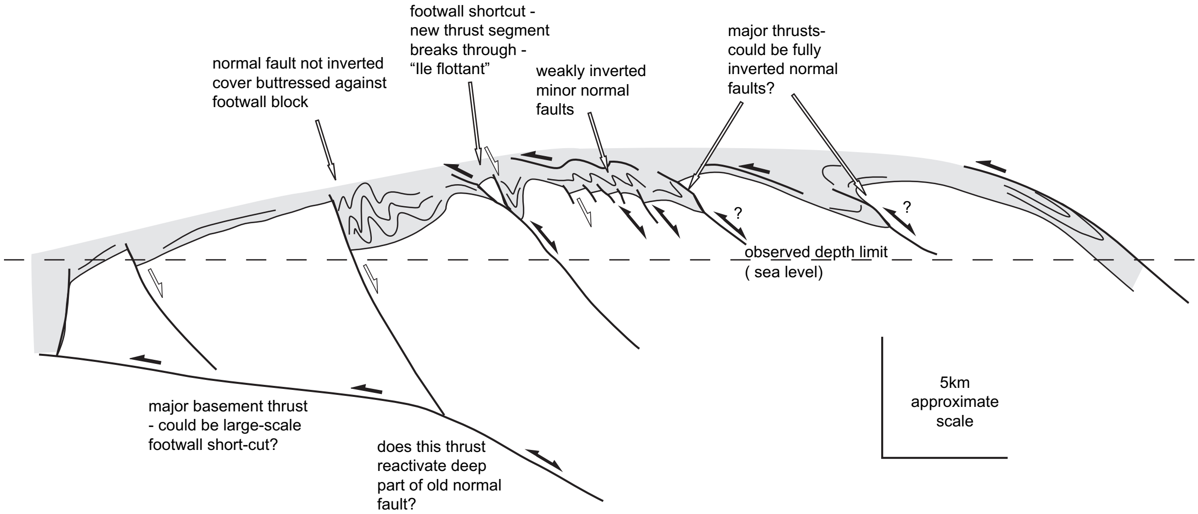

Fig. 2. Compilation of structural styles exhibited by the basement-cover Ecrins massif, in the based on the scale and distribution of thrusts and pre-existing normal faults that outcrop in the Ecrins area of the French Alps (location E on Fig. 1). Basement is unornamented, Mesozoic cover (chiefly shale and thin-bedded limestones) are shaded. Modified after the work of Gillcrist et al. (1987).

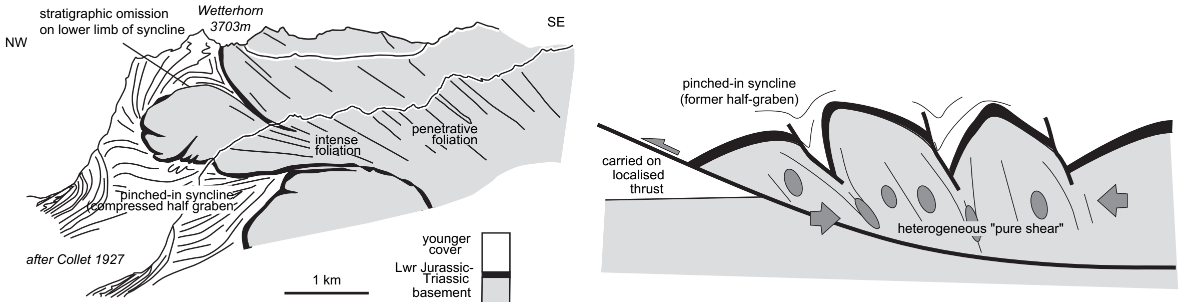

Fig. 3. A structural model for the ‘‘pinched-in synclines’’ on the northern flank of the Aar massif of the central Alps (modified after Butler and Mazzoli, 2006). (a) shows the observed structural geometry (modified after Collet, 1927). (b) illustrates a schematic restored geometry of the basement-cover contact through the pinch-in synclines, with pre-folding half-graben localizing the syncline axes. Note that the surrounding basement is penetratively deformed during the contraction and that the basement-cover interface serves as the rheological boundary that induces buckling.

sedimentary cover has long generated debate on the structural evolution of Apennine thrust systems. Gaining good control on the geometry and depth to the top of basement has been challenging. Yet even if basement has a regionally simple geometry as defined by low-resolution geophysical data (e.g. potential field data or widely spaced 2D seismics) it need not require that contractional deformation be restricted to within the sedimentary cover alone, a common assumption for many earlier studies of the Apennines. Reactivation of pre-existing normal faults such that the contractional slip broadly matches the finite extensional slip will restore the basement contact to a near zero-offset state (the null point of Williams et al., 1989) although the contractional deformation will have been effectively transferred from basement to cover.

Surface geology may be interpreted in different ways, as illustrated by the outer part of the Umbria-Marche thrust belt (e.g. see Butler et al., 2004). Classical thin-skinned interpretations (e.g. Fig. 4a) predict that the ca. 3 km thick Mesozoic-Cenozoic sedimentary cover was decoupled along Upper Triassic evaporites from a shallow crystalline basement and affected by simple east-verging detachment folds (Baldacci et al., 1967). Subsequent aeromagnetic determinations of the depth to crystalline basement (Arisi Rota and Fichera, 1985) and selected 2D seismic profiles then led to a proliferation of thin-skinned tectonic models (Bally et al., 1986; Lavecchia et al., 1987; Calamita and Deiana, 1988; Hill and Hayward, 1988; Barchi, 1991; Roeder and Scandone, 1992). The implications are high shortening rates and large thrust displacements (Fig. 4b) that have been carried out into Apennine geodynamic models (Scrocca et al., 2005 and references therein).

An increase in availability of information on the deep geometry of the Apennines in the 1990s has challenged the thin-skinned models. The results of a regional seismic survey (CROP 03 project: Barchi et al., 1998), aimed at unravelling the deep structure of the belt, suggest that many thrust-related anticlines are cored by conspicuous slices of basement rocks (Fig. 4c). This is also supported by a recent re-interpretation of aeromagnetic data (Speranza and Chiappini, 2002). Consequently, progressively more thick-skinned models have been developed where fold structures in the cover are basement-cored, bounded by inverted normal faults (Tavarnelli et al., 2004; Fig. 4d). In contrast to the older, thin-skinned interpretations, thick-skinned models with implicit basement reactivation generally involve a few tens of km displacement for equivalent profiles, at more reasonable rates of <1 cm/yr (Barchi et al., 1998; Coward et al., 1999; Butler et al., 2004; Tavarnelli et al., 2004). As subsurface imaging has improved, at least for the northern Apennines (Tozer et al., 2006), basement reactivation is becoming more evident. This progression of structural models follows that shown by other orogenic belts such as the Alps. They are however, yet to be applied to the larger-scale geodynamic models for Apennine tectonics (cf. Scrocca et al., 2005, and references therein).

Although modern interpretations of Apennine structure are converging on thick-skinned models, the detailed geometry of basement involvement has yet to be resolved. Basement reactivation may involve ideal inversion of pre-existing normal faults, as shown on Fig. 4d, or where some combination of the styles shown by Alpine basement (Figs. 2 and 3) are more appropriate. Thus the degree to which contractional deformation has localized onto faults or been distributed through tracts of generally weak crystalline basement remains unresolved. It is an issue to which we return later in this contribution.

4. Structural inheritance within cover sequences

Basement reactivation need not be the only way in which inherited structures play a role in thrust belt evolution. Even where cover and basement deform disharmonically, with regional detachment horizons, pre-existing structures can still be found in the sedimentary cover. Welbon (1988) showed that the chief role played by normal faults is to offset the mechanical stratigraphy in sedimentary successions (Fig. 5). Commonly these offsets serve to locate preferentially the hinges of buckle folds that amplify into major anticlines (e.g. Butler, 1992). Thin-bedded and low-competence units, where downthrown against thick, competent units, tend to deform with distributed short-wavelength folds, upright cleavage and distributed strain (Welbon and Butler, 1992). This is a form of buttressing, as described above for syn-rift deposits crumpled against basement fault blocks by contractional

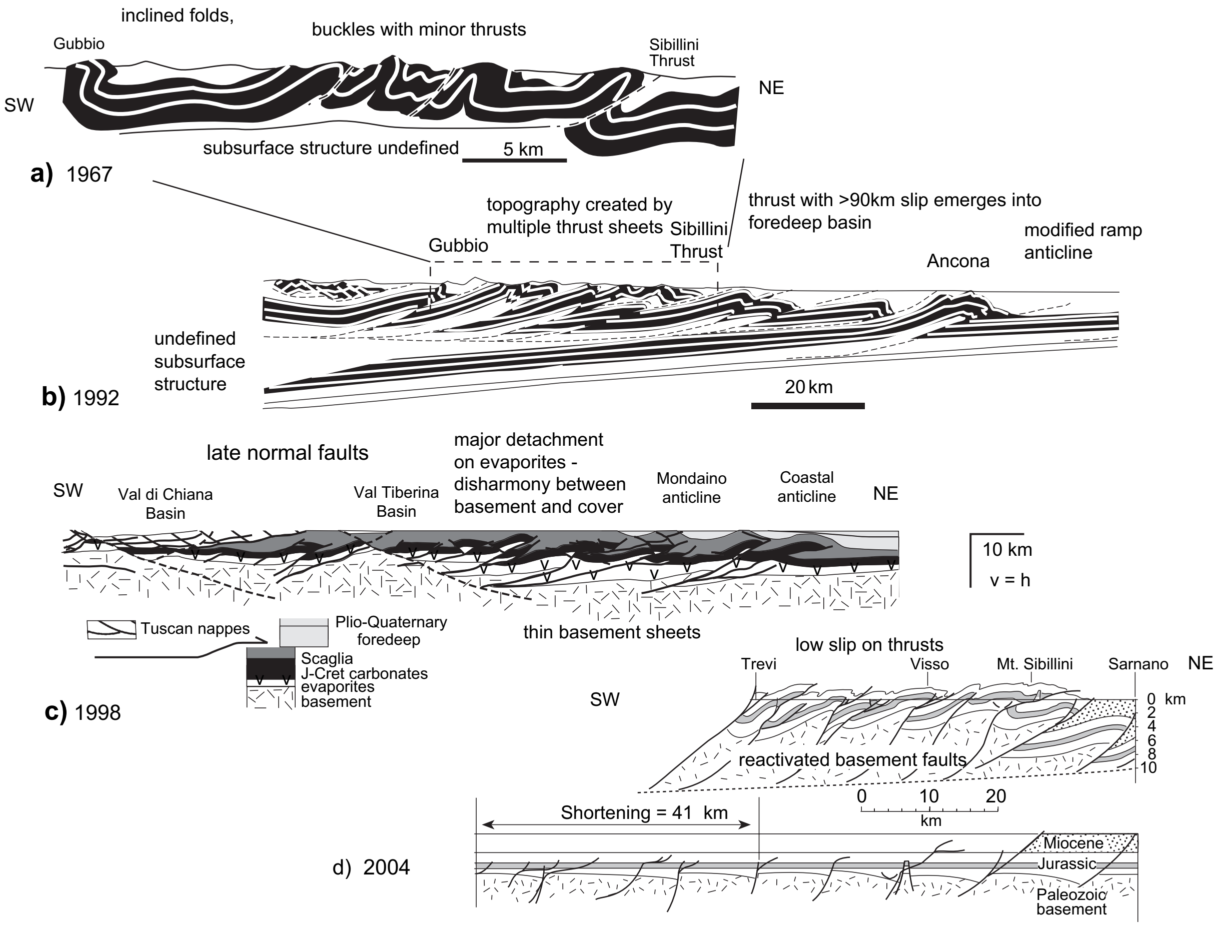

Fig. 4. Styles of thrust system interpreted for the Umbrian-Marche thrust system through the Gubbio area (approximately located on Fig. 1). (a) Baldacci et al.'s (1967) cross-section, based largely on surface geology; (b) Roeder and Scandone's (1992) thin-skinned interpretation. Note that the basement is not involved in the thrust systems and that the cover sediments are essentially layer cake. Fold structures are simply a geometric consequence of the thrust trajectory. (c) Barchi et al.'s (1998) interpretation of basement-involved thrusting for the Umbria-Marche area. Note that basement and cover deformation is disharmonic, decoupled along evaporites at the base of the cover. The thrust belt is disrupted by late-orogenic normal faults. (d) Ramp-dominated (thick-skinned) structural interpretation with basement involvement directly under the folds of sedimentary cover that outcrop (Tavarnelli et al., 2004). Note that the styles of basement structure are necessarily schematic as these have yet to be imaged by seismic data beneath the Apennines nor are their outcrop analogues to be found within the orogen.

deformation of Mesozoic half-graben in the French Alps (Gidon, 1981). In other situations the effect of normal faulting is to offset detachment horizons that serve as major thrust flats. These offsets may in turn localize thrust ramps (Welbon and Butler, 1992). For example, the front of the southern Jura fold belt of the western Alps (Fig. 1) coincides with the margin of the Oligocene Bresse basin where the detachment horizon for folding (Triassic evaporites) has been downthrown (Butler, 1989). In the Vercors (Fig. 6) the late Miocene thrust front coincides with the stratigraphic variations in the Mesozoic sediments and with minor basins of Oligocene age. These features suggest the presence of pre-contractional normal faults that again have offset the regional detachment of Triassic evaporites. The thrust front is interpreted as having localized on these pre-existing fault structures.

4.1. Syn-orogenic faults in the foredeep

Many normal faults incorporated into thrust belts are not formed during the passive margin stage of the system. The substrates to many foreland basins contain normal faults that accommodate part of the flexural subsidence, in a deviation from ideal elastic behaviour (e.g. Miall, 1995). The margins of the Apennine (Bradanic) foredeep at Matera (Fig. 7b; Tropeano et al., 2002) and of the Gela nappe of Sicily (Fig. 7a) both contain normal faults that control the deposition of foredeep deposits (discussed by Tavarnelli et al., 2004). The orogenic foreland of the Apennines is extensively dissected by both strike-slip and normal fault systems (e.g. Ben Avraham and Grasso, 1991; Reuther et al., 1993). Similarly, the foreland of the western Alps was structured by faults associated with the composite Rhone–Bresse–Rhine graben system that were active from at least Oligocene times (e.g. Sissingh, 1998). At least some of these structures presumably reflect failure due to the long wavelength deformation of the continental lithosphere caused by orogenic loading. Thus they are manifestations of large-scale rheological structure, which produces local effects. These in turn influence the subsequent evolution of contractional structure at the thrust front.

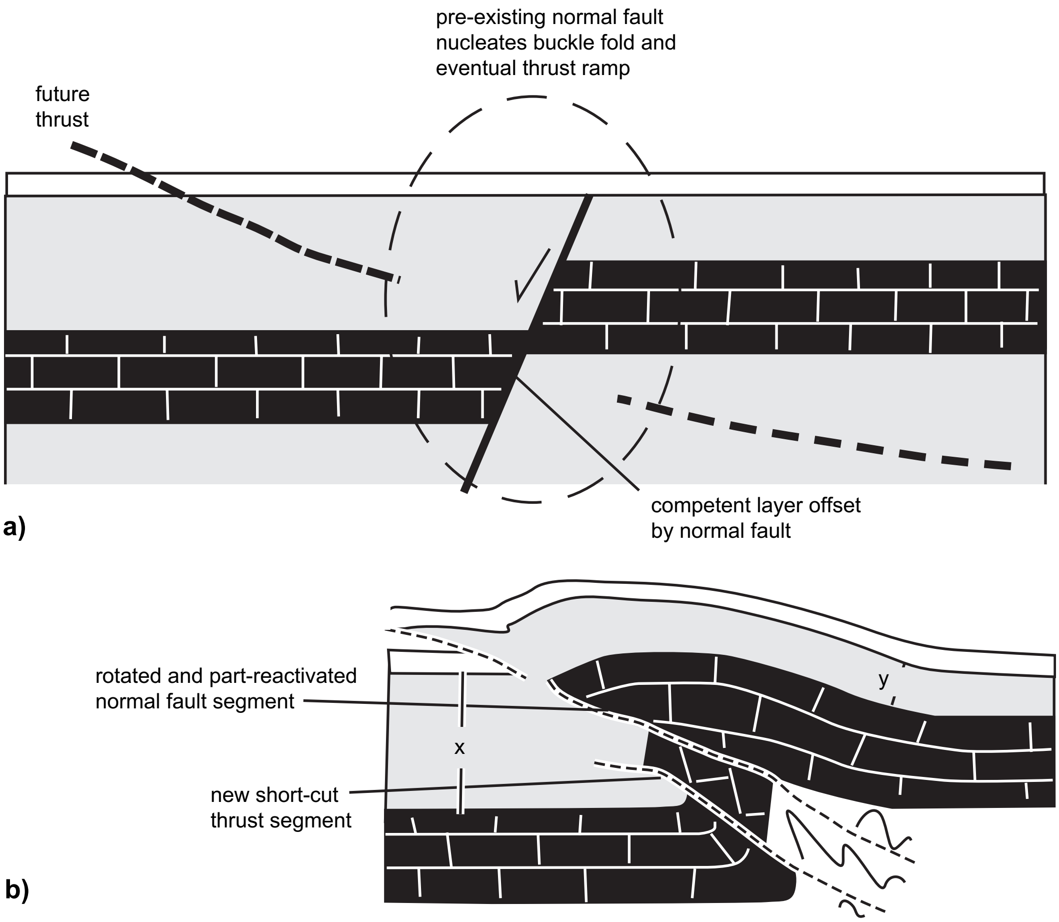

Fig. 5. A thrust ramp interacting with a pre-existing fault that has offset a competent layer (brick ornament). This offset (a) serves to nucleate a zone of buckle folding and associated distributed deformation. Continued deformation and fold amplification (b) can rotate the old normal fault into an orientation suitable for activation as a thrust. Other thrust segments commonly form in the surrounding rock volume. Collectively these fault strands create a composite thrust zone. After significant shortening it may be difficult to resolve the original normal fault offsets. However, they may be inferred from the different stratigraphic thickness of pre-thrusting units (e.g. thicknesses *x* and *y*). These geometries are inferred from a series of Alpine fold-thrust structures. Modified after Welbon and Butler (1992).

The effect of emergent faulting in the orogenic foreland is to create a series of structures that influence the architecture of thrust structures detached within the foredeep. In Sicily (Fig. 1) the distribution of syn-tectonic sediments within the foredeep is inferred to be controlled by syndepositional normal faults (Fig. 7a; Butler et al., 1992). The modern foredeep basin (Fiume Margi basin) is currently separated from the adjacent foreland (Hyblean plateau) by young normal faults that down-throw towards the orogen. These structures in the modern and ancient foredeep have influenced thrust belt structures, especially the structural geometry and evolution of the Gela Nappe (Lickorish et al., 1999). Their effect is to create lateral variations in the thickness of foredeep sediments that are incorporated into the evolving orogen, thereby changing the thickness of the evolving orogenic wedge (e.g. Adam and Reuther, 1995; Grasso et al., 1995).

Similar normal faults to those that control the Fiume Margi basin on Sicily are found throughout the foredeep of the Apennines (e.g. Fig. 7b). In some places these structures are inverted (Fig. 8), creating broad anticlines typical of inversion structures in anorogenic sedimentary basins. In these situations, the continuity of contractional folds and the inferred strike-length of their associated thrusts could be pre-conditioned by the strike-lengths of the foredeep basin extensional faults. These in turn are likely to relate to the rheology of the continental lithosphere at the time of normal faulting.

Foredeep-related normal faults may be identified within the main Apennine thrust belt. Scisciani et al. (2002) showed that the La Queglia anticline is bounded on both limbs by normal faults (Fig. 9b, located on Fig. 10). These control the preservation and facies within the Messinian evaporite sequence, although the fold itself is a Pliocene-age structure. The normal faults themselves have not reactivated, but the Messinian basin seems to have located the original thrust ramp. A similar situation has been recognized along part of the Sibillini Thrust (Monte Prato area, Fig. 9a; located on Fig. 10) in the Umbria-Marche thrust belt. Here early normal faults are inferred to control the preservation of the turbidites of the late Miocene foredeep basin (Laga Formation; Alberti et al., 1996; Fig. 9b). In both examples slices of pre-orogenic carbonates are detached as *Iles flottantes* (Fig. 9) as occurs on some basement structures in the Alps (Fig. 2). For both of these outcrop examples the normal faults do not themselves reactivate under contraction but serve to localize the thrust ramps.

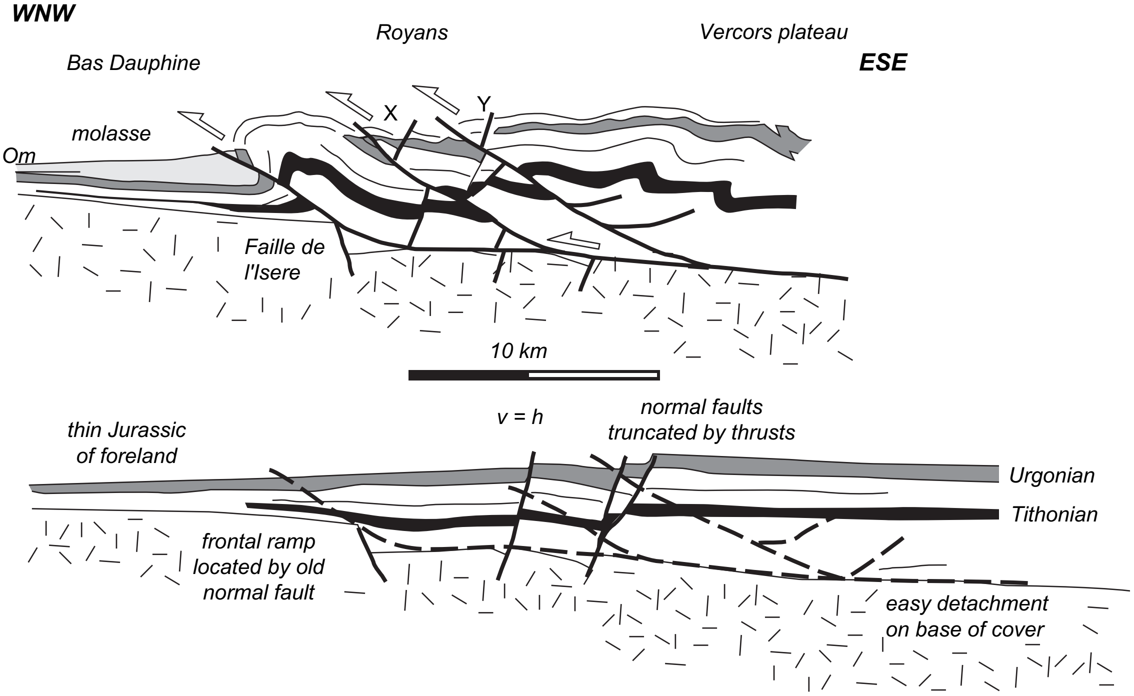

Fig. 6. Vercors cross-section, modified after Butler (1989). The frontal thrust ramp is nucleated on a pre-existing normal fault, inferred from stratigraphic variations in the pre-thrusting strata. Large-scale variations in the separation between competent thick carbonate beds (Aalenian, Tithonian, Urgonian horizons) embedded in shales and thin-bedded limestones (unornamented) generates different propensities for buckling. Elsewhere, normal faults (Oligo-Miocene, labelled X and Y) are truncated by later thrusts, although in detail the thrust-normal fault interactions show similarities with those shown on Fig. 5.

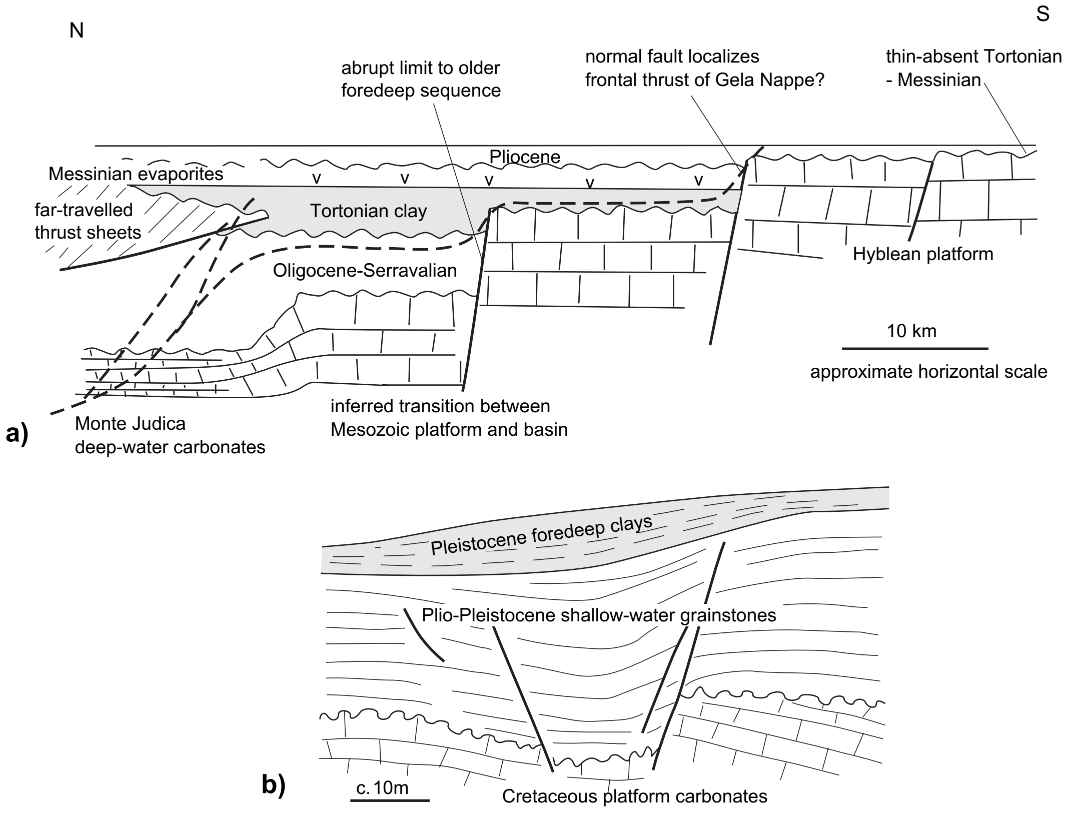

Fig. 7. Examples from the modern margin of the Apennine foredeep illustrating how the Apennine foreland basin was controlled by active normal faults. (a) The Fiume Margi foredeep and its relationship to the Hyblean foreland block, determined from restorations of the frontal Gela Nappe (modified after Butler et al., 1992). (b) the Bradanic foredeep margin at Matera (modified after Tropeano et al., 2002). See Fig. 1 for locations.

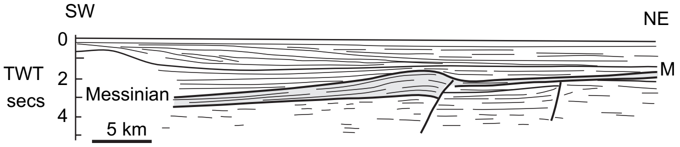

Fig. 8. Inversion of late Miocene faults under contraction in the Adriatic sea (located on Fig. 1, modified after Butler et al., 2004).

5. Role of cross-faults—compartmentalizing orogens

The large-scale segmentation of orogenic belts into salients and recesses has recently been reviewed by Marshak (2004). This style of compartmentalization is found throughout the Afro-European zone of convergence of the central Mediterranean (e.g. Reuther et al., 1993) and is well illustrated in the Apennines. Different thrust compartments are bounded by major lineaments. The most continuous of these is the ''Ancona–Anzio'' Line (e.g. Castellarin et al., 1982; Fig. 10a) which separates the Umbria-Marche thrust systems of the northern Apennines from the Latium-Abruzzi plateau of the central Apennines. A further lineament, the Ortona–Roccamonfina Line, separates Latium-Abruzzi from the Molise sector of the Apennine belt. Both of these tectonic lineaments serve to offset the distribution of earthquakes (Faccioli et al., 1996) along the Apennine chain (Fig. 10a) indicating that their surface manifestation overlies an important change in basement structure beneath the modern mountain belt. The lines are also associated with anomalously high heat flow and, along their southwestern ends, are the loci for volcanic activity. Most of the seismicity along the Ancona–Anzio Line relates to normal faulting, the modern expression of post-orogenic extension in the Apennine hinterland. This tectonic regime has developed through the Neogene and is manifest by the rifting of the northern Tyrrhenian Sea basin (e.g. Lavecchia, 1988). The modern expression of the Ancona–Anzio Line also marks an important change in the style of contractional structures that formed in the late Miocene and Pliocene. Thrust structures in the hanging-wall to the Sibillini Thrust, the major structure of the Umbria-Marche system, branch onto or are cut by the Ancona–Anzio Line. The Sibillini Thrust itself climbs section and shows a reduction in displacement approaching the line (Tavarnelli et al., 2004; Mazzoli et al., 2005). Similarly, thrust structures in the central Apennines climb section towards the line. Thus the modern structure, which currently acts as a transfer fault to ''post-orogenic'' extensional tectonics, was a major compartmental fault during the orogenic contraction. The same pattern is shown by the Ortona–Roccamonfina Line (Fig. 10a) where ramp-dominated thrusts of the Latium-Abruzzi area branch onto the detachment sheet of Molise (Butler et al., 2004). Both of these lineaments record earlier history, best explored using the Ancona–Anzio structure. This coincides with a major change in the stratigraphy of the Mesozoic and lower Cenozoic strata (Fig. 10b). To the south, in Latium-Abruzzi, the strata represent a carbonate platform. In the Umbria-Marche, to the north of the line, the time-equivalent strata are deep-water carbonates. Thus the Ancona–Anzio Line formed an important basin-bounding structure on this part of the stretched continental crust of the Apulian block during the Mesozoic.

In the central Mediterranean the formation of the major fault zones or the reactivation of older faults normal to the African–European collisional front of the Maghreb is governed by lateral variations in crustal structure inherited from Tethyan rifting in the Mesozoic. Tull and Holm (2005) discussed how different rift geometries developed along the proto-Laurentian continental margin controlled the large-scale geometry, especially along axis curvature of fold and thrusts in the southern Appalachians. The notion that rifted areas can act as deformation corridors along which crustal shortening is guided during orogenesis was promoted by Gillcrist et al. (1987) in their breakthrough study of inversion in the western Alps. This process is informally termed ''tram-lining'', whereby contractional tectonics may be guided by the rails of earlier structures. In this regard the structure of the outer part of the Sicilian thrust belt and eastern Maghreb may have been ''tram-lined'' by pre-existing lineaments in the

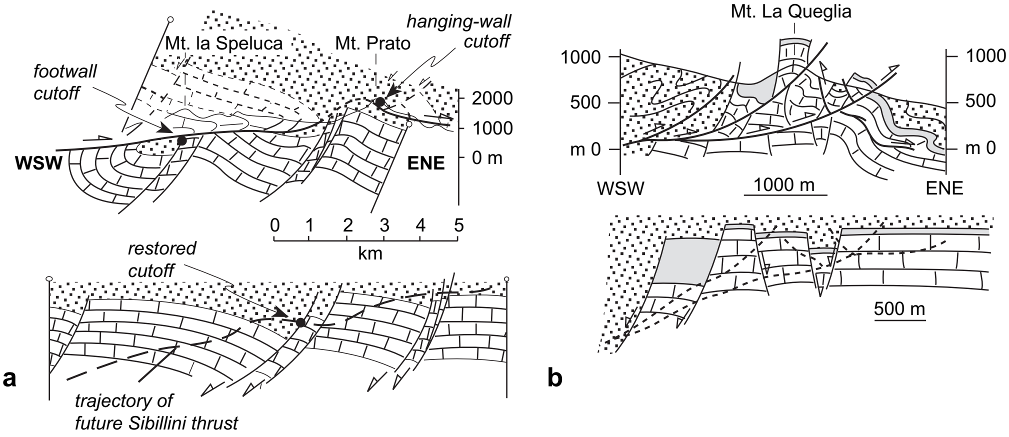

Fig. 9. Examples of extensional faults that formed during foredeep development ahead of the Apennine deformation that have subsequently been incorporated into the thrust belt. The examples are shown as paired observed state and restored state sections. (a) The Monte Prato segment of the Sibillini thrust, modified after Alberti et al. (1996). (b) La Queglia structure, modified after Scisciani et al. (2002). See Fig. 10 for locations.

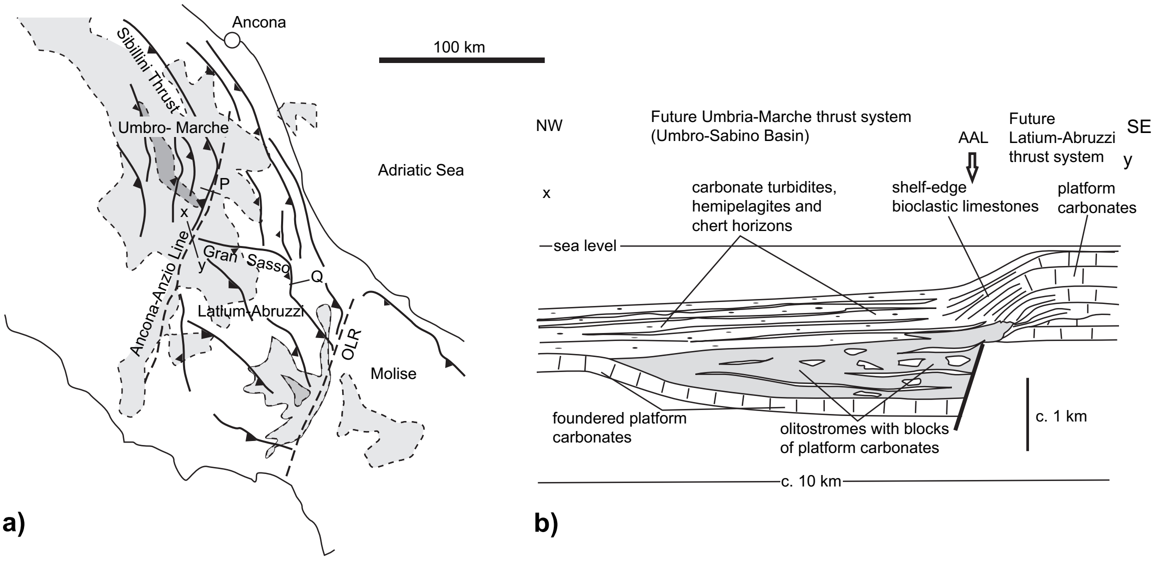

Fig. 10. The role of cross-fault lineaments in controlling thrust architecture the Apennines. (a) Simplified map of the central Apennines showing trends of major thrusts (teeth on hanging-walls). The shade overlay shows the distribution of instrumentally recorded seismicity for the region (chiefly normal fault focal mechanisms). ORL, Ortona–Roccamonfina Line. The location of the cross-sections through La Queglia (Q) and Mt Prato (P) for Fig. 9 are indicated. (b) Castellarin et al.'s (1982) stratigraphic model for the relationship between Latium-Abruzzi and the Umbria-Marche area across the Ancona-Anzio Line (AAL), based on measured stratigraphic sections along the transect *x*–*y* (located on a).

North African continental crust. Preserved examples of lineaments include the weakly inverted, so-called North–South Axis of Tunisia (Bouaziz et al., 2002), the Scicli Fault on the Hyblean plateau of SE Sicily and the Malta escarpment continental margin (Grasso, 1993).

6. Apennine inversion styles—reviewed

Improved geophysical imaging, the incorporation of realistic stratigraphic templates and developing three dimensional approaches to analyse thrust systems have gradually illuminated the role of structural inheritance in the tectonic evolution of the Apennines (reviewed by Tavarnelli et al., 2004; Butler et al., 2004). Fig. 11 summarizes the range of reactivation styles within the central Mediterranean thrust systems, as recorded by the sedimentary cover.

The outer parts of these systems preserve a range of structures that predate the regional onset of thrusting together with fault systems that developed as the thrust belts operated. These include normal faults formed on the outer margins of foredeep basins but also fault systems that do not relate directly to the local thrust system and its associated lithosphere deformations such as flexure. As the thrust belts prograded into their forelands these pre-existing structures influenced styles of contraction in different ways. Some reactivated creating inversion structures equivalent to those found in weakly compressed sedimentary basins away from convergent plate boundaries. However, simple fault reactivation is rare. More commonly the pre-thrusting faults served to localize ramps, either simply through offsetting regionally extensive horizons of preferential detachment, or by nucleating buckle folds. In these situations locally complex composite structural relationships can be created that juxtapose rock units that are not predicted by simple thrust-ramp models. These can include isolated slices of old fault blocks. Commonly the key information for deducing the geometry of these structures lies in using the stratigraphy

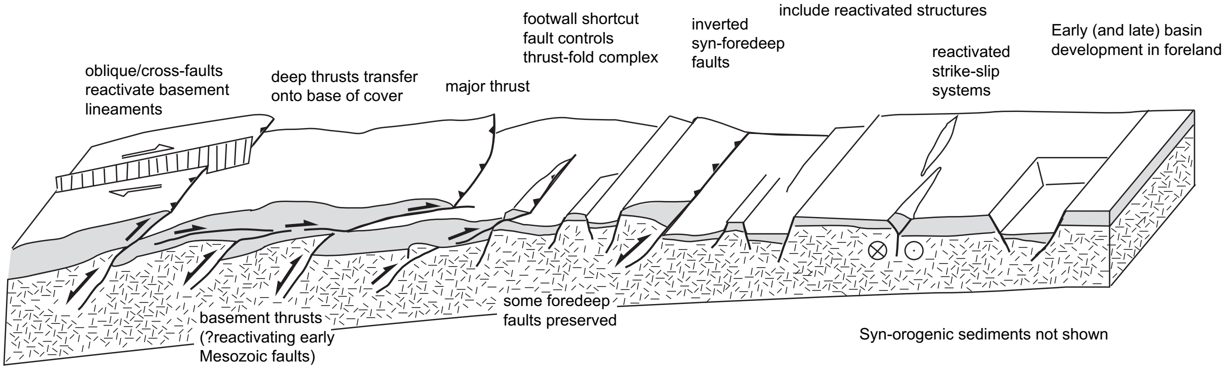

Fig. 11. Styles of structural inheritance in mountain belts, based on the Apennines (modified after Tavarnelli et al., 2004). See text for discussion.

of the surrounding rock units. These approaches may be harder to apply to basement faults.

A key feature of Central Mediterranean and many other thrust systems that distinguishes them from basin inversion structures is the importance of regional detachment surfaces. In the case of the external Alps and Apennines the most important horizons are believed to be extensive evaporitic formations located close to the basement-cover contact. The effect is to decouple basement and cover deformation. However, as Butler and Mazzoli (2006) point out, this form of detachment need not imply the absence of basement involvement, but merely that contractional structures are disharmonic. Thus, in the Umbria-Marche area, the continental crust is thickened beneath the thrust belt but the basement structures do not directly trace onto specific thrusts at outcrop. More research is needed to establish the incremental evolution of such systems. In this regard it may be pertinent to examine how thrust arrays grow and accommodate displacements across regional cross faults, particularly where these are inherited. In the Apennines these types of structure control the large-scale architecture of the chain, echoing the studies on salients and re-entrants described elsewhere by Marshak (2004).

7. Structural inheritance and large-scale evolution of mountain belts

7.1. Does basement reactivation limit orogenesis?

Large-scale contractional deformation in the Alpine–Apennine system is broadly quiescent at present, with the exception of active subduction of Ionian oceanic lithosphere beneath the SE Tyrrhenian Sea. The edge of the deformation zones largely coincides with the margins of rifted continental crust defined by Tethyan and subsequent rifting. In the Western Alps significant thrusting ended by about the start of the Pliocene, with folding in the Jura and linked crustal thrusting beneath the external basement massifs. This coincides with Alpine deformation propagating out to the edge of the rifted crust of the old Tethyan continental margin, essentially represented by the crystalline basement massifs (Lemoine et al., 1986). Note that thrusting in the sedimentary cover relays out ahead of the old rift margins because of the evaporitic detachment horizon beneath the Jura. In the SW Alps deformation continued into the Pliocene to involve the rift basins of the Valensole (Fig. 1). Along the Apennine front deformation has largely ceased with the incorporation of weakly rifted Apulian crust into the orogen. Similarly for Sicily, deformation has largely terminated with thrust systems running up against the weakly rifted foreland of Hyblea and the Adventure Shelf (Lickorish et al., 1999; Fig. 1). A reorientation of the local stress filed has also been documented where the thrust system cuts through the Mesozoic substratum reactivating, or being located by earlier normal faults.

It is interesting to speculate whether the availability of weak continental crust, containing rift faults, exerts the prime control on orogenesis in the central Mediterranean (Fig. 12). Most current studies emphasize the role of slab processes, chiefly roll-back and slab detachment, as providing both the motor and brake to the Alpine–Apennine system (e.g. Wortel and Spakman, 2000). However, for these mechanisms to drive horizontal motions at the surface the adjacent plates must

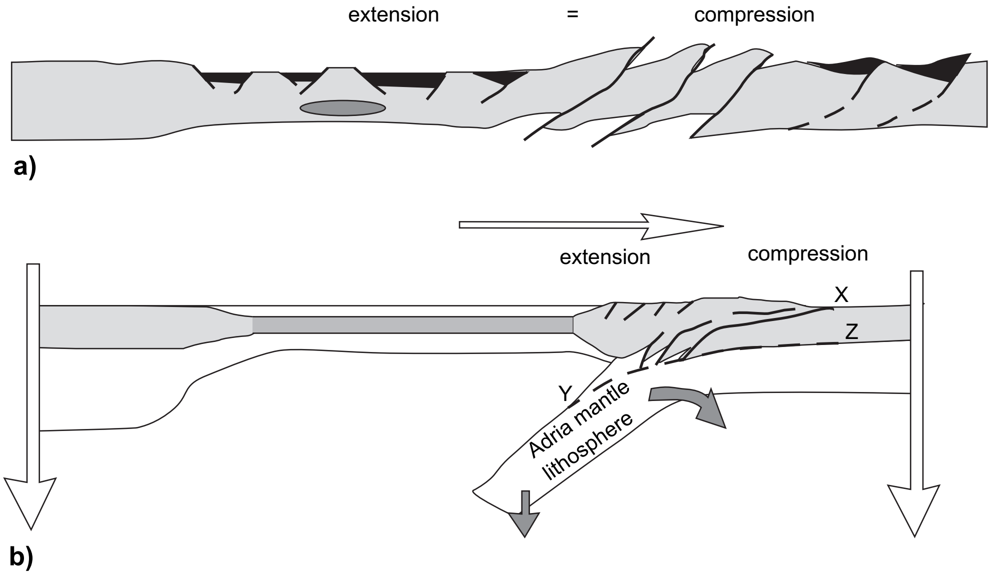

Fig. 12. (a) Schematic illustration of the kinematic links between crustal extension and crustal contraction in the Northern Apennines, as proposed by Elter et al. (1975), and modified here to show the basement-involved (inversion) structural style deduced here (also Butler et al., 2004). In this model the crustal shortening is limited by absence of pre-existing normal faults. (b) explores the larger-scale consequences of this tectonic limit. Inability of the compression zone to step out beyond the thrust front (*x*) could require further shortening within the existing orogenic prism. If this is not achieved then further roll back of the underlying lithospheric mantle can only be accomplished by decoupling at, or near the subcontinental Moho (*y*–*z*). This deformation needs not couple to drive significance horizontal displacements in the crust, but will generate significant vertical motions, presumably manifest by the modern Apennine topography and continued, broadly distributed seismicity.

stretch and contract. Thus mountain building may be limited not simply by the slab but also by the ability of the adjacent lithosphere to accommodate these required strains. Rheological models for continental lithosphere generally show it to be stronger under contraction than extension for a given thermal structure. Thus, the assertion here is that for the Apennine–Tyrrhenian system, it is the ability of the lithosphere to accommodate relative convergence through crustal shortening that has limited large-scale tectonics. For areas of strong crust, with few pre-existing faults, the paired extension-contraction system could lock. Roll-back and foundering of subcontinental lithospheric mantle could continue, provided that this mantle slab detached from its overlying continental crust. In effect this requires tearing at, or close to the Moho. In this regard the roll-back process then is controlled and modulated by the relative strength of continental crust under contraction and the resistance to tearing and decoupling along the Moho. Thus, numerical forward models of orogenic systems (e.g. Pauselli et al., 2004) would need to incorporate initial spatial variations in lithosphere strength and associated propensities for basement reactivation in order to appropriately predict the observed final state geometry.

7.2. Evolving rheology and the changing role of structural inheritance in mountain belts

One approach to understanding the large-scale distribution of deformation during mountain building is to consider strength–depth profiles for continental lithosphere (e.g. Kusznir and Park, 1986; Afonso and Ranalli, 2004). In these approaches, the key control is taken to be the thermal structure of lithosphere, for which Moho temperature may be taken as a proxy. Assuming the same distribution of heat production between different continental profiles, the key control on thermal structure is likely to be manifest by variations in the thickness of lithospheric mantle. Thus cratonic areas with their assumed lower heat flow and thick lithospheric mantle are believed to be stronger than recently rifted continental lithosphere where the mantle component is correspondingly thinner. The implication is that the strength of the continents is largely carried by the upper mantle and that the crust itself plays only a limited role in determining the large-scale distribution of deformation during orogenesis. However, the relationship between strength and buoyancy of the crust is important in placing upper limits on the amount of strain that can be accumulated at a given site, as reflected in the Argand number concept of England and McKenzie (1982).

The notion that the strength of continental lithosphere is largely held in the upper mantle has recently been questioned by Jackson and co-workers (Maggi et al., 2000; Jackson, 2002; McKenzie et al., 2005). Using new determinations of Moho depth, earthquake focal depths, flexural rigidity and thermal structure of the mantle from xenolith suites, they argue that the lower continental crust is generally stronger than the adjacent upper mantle, despite high Moho temperatures. They conclude that the lower continental crust is strong, composed essentially of dry granulite while the upper mantle is slightly hydrated and weak. For this type of lithosphere pre-existing fault zones, within which the ideal strength has been reduced, are likely to play a leading role in any large-scale deformation. The softening processes and the importance of long-lived weak fault zones are reviewed by Holdsworth (2004) amongst others. For our purposes, these concepts imply that inversion of pre-existing weaknesses such as faults are plausibly the critical feature of orogenesis acting upon continental lithosphere where the crust is the load-bearing level. This is the ‘‘inherited weaknesses’’ model of deformation designated by Handy and Stünitz (2002) and summarized on Fig. 13a.

In the Alpine basement however, it appears that simple fault reactivation is rare. Pre-existing faults may have served to create initial perturbations upon which large-scale interfacial buckles nucleated. The surrounding basement rocks are deformed. Thus the continental crust of the former European continental margin of Tethys did not deform in the way predicted by the above discussion. Presumably then Alpine basement was weaker than ‘‘conventional’’ continental crust, perhaps because of earlier metamorphic retrogression and hydration (Butler and Mazzoli, 2006, and references therein). Similar basement types are found throughout the Tethyan province, suggesting that these more complex forms of structural inheritance (Fig. 13b) are likely to be developed elsewhere, including at depth beneath the Apennines. The challenge for future studies is to quantify strength–depth relationships for weaker forms of crystalline basement.

The act of orogeny modifies not only the geometry but also the thermal structure of continental lithosphere (e.g. Toussaint et al., 2004) that in turn influences the patterns of strain localization during orogenesis. Thus the strength profiles for continents are likely to evolve into mountain belts, and with them the influence of pre-existing faults in governing deformation (Fig. 13). These notions have recently gained further support from seismological studies in the central Himalayas by Schulte-Pelkum et al. (2005). Ahead of the orogen, seismicity is essentially restricted to the India crust (see also Maggi et al., 2000), perhaps reflecting reactivation of pre-existing faults (Fig. 13a). However, beneath the Himalayas the earthquakes break into two levels, one in the upper crust, one in the upper mantle. Presumably the lower crust deforms in an entirely distributed fashion where pre-existing faults and other heterogeneities are insufficiently strong to generate stress-risers necessary for earthquakes. Seismic velocity data suggest that the change in rheology in the lower crust of the Indian continent coincides with eclogite metamorphism.

Some generalities may be drawn from the above discussion (Fig. 13). In the cooler, outer parts of mountain belts the ambient continental lithosphere is likely to be strong with a thick seismogenic crust. Pre-existing narrow weak zones within the crust, especially faults, are likely to act to localize contractional structures, provided that they are appropriately oriented. Thus inversion and the reactivation of pre-existing faults are most likely to occur ahead and in the outer parts of mountain belts, at least for those continental lithospheres where the strength is largely supported by the crust. This behaviour

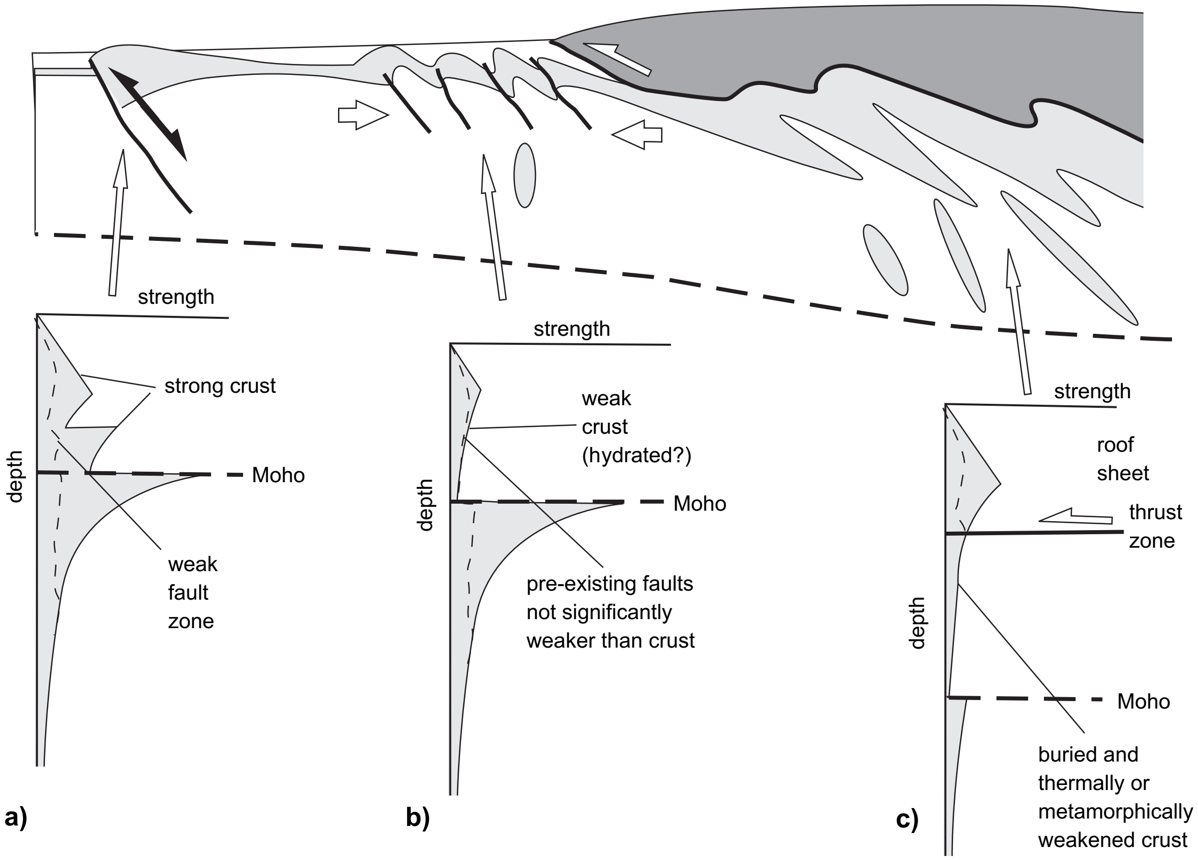

Fig. 13. Schematic illustration of the different propensities for structural reactivation in an idealized thrust-type orogenic belt. The outlying areas (rheological profile a) are prone to inversion tectonics where contractional deformation is strongly localized onto pre-existing faults (e.g. Adriatic foreland, Fig. 8). This assumes that the surrounding crust is strong (in the sense of Jackson, 2002) and pre-existing fault zones are weak (e.g. Holdsworth, 2004). Other parts of the continental lithosphere (b) may be characterized by weaker crust, perhaps marked by retrogressed basement, so that pre-existing faults are not significantly weaker than their surroundings. In these situations the faults are less prone to reactivation but may nucleate folds or other strains by having offset rheological layering (e.g. Aar massif structures, Fig. 2). Deeper into the mountain belt the foreland crust may become buried beneath large thrust sheets (or subducted). In these areas the crust may weaken, as implied by earthquake distributions and measurements of seismic anisotropy beneath the Himalayas (Schulte-Pelkum et al., 2005). In these settings pre-existing faults are unlikely to simply reactivate. The role of structural inheritance in these internal zones of orogenic belts remains unresolved.

may be shown by the inversion structures in the Adriatic foreland of the Apennines (Fig. 8).

Where the crust is weak, because of abundant hydrated phases, or by elevated heat flow, the rheological contrast between pre-existing faults and the ambient crust may be less marked (Fig. 13). While these segments of lithosphere may act as large-scale instabilities, focussing contractional deformation, individual faults may be less prone to reactivation. This form of distributed basement reactivation may be typified by structures in the external Alpine basement massifs (Figs. 2 and 3).

Deeper into mountain belts (Fig. 13), ductile instabilities are presumably more important in governing deformation when the deep crust has been weakened, due to thermal, magmatic or metamorphic processes (e.g. Toussaint et al., 2004). These are likely to play a key, if transient role within and beneath the internal parts of mountain belts. In these settings simple fault reactivation is likely to play only a subordinate role. However, understanding their impact on the development of ductile instabilities, as proposed for example in the heart of the Grampian mountain belt of Scotland (e.g. Robertson and Smith, 1999) may be a fruitful line of enquiry for further research. In these settings it seems unlikely that simple reactivation of thrust faults has been a critical control on the patterns of normal faults generated towards the end of orogenesis (negative inversion of Williams et al., 1989). Simple distributed stretching of the metamorphic root appears to be the chief expression of post-orogenic extension, although thrusts and other heterogeneities may refract the trajectory of normal faults in the upper crust.

7.3. Inherited compositional heterogeneity in mountain belts

Crustal composition inherited from earlier parts of continental history can play a critical role in orogenic evolution (e.g. Ranalli, 2000). In this regard we view the presence of basic magmatic underplate in the lower crust to be especially important. Eclogite metamorphism is a common feature of early burial of continental crust during collision, a process that increases the density of the crust thereby offsetting some of the buoyancy that resists further crustal thickening and promoting post-orogenic extension (discussed by Ryan and Dewey, 1997). Granitic crust will achieve a modest density increase (to ca. 3120 kg m^{-3}) but will still be more buoyant than average upper mantle rocks (3300 kg m^{-3}). Eclogitic metabasalt can achieve densities in excess of 3400 kg m^{-3} that may founder into the mantle (e.g. Austrheim, 1991) or promote further crustal subduction (Butler, 1986). Ryan and Dewey (1997) argue that eclogitic orogenic roots are particularly weak, guiding subsequent extensional tectonics, effectively providing a mechanism for that phase of the Wilson cycle.

However, as Austrheim et al. (1998) point out, the geological evolution of lower crust depends not only on the distribution of mafic and granitic rocks but also on the availability of fluid. As Leech (2001) noted, fluid availability can exert a first order control on orogenic processes. Thus some old mountain ranges such as the Urals have resisted post orogenic extensional tectonics while retaining roots of thick, normal density, continental crust. In these settings the lower crust may have originally been represented by dry granulites that remained metastable during orogenesis, metamorphism limited by the paucity of fluid. It is interesting that as post-orogenic extension is commonly accompanied by mafic intrusions into the lower crust, that may in turn promote crustal subduction in a subsequent episode of continental tectonics, given adequate fluid supply.

8. Discussion

Numerous studies, some of which have been presented here, have shown that the localization of deformation within the continental lithosphere is strongly dependent on inherited structures. Fault reactivation and tectonic inversion are manifestations of only one form inheritance. Existing conceptualizations of tectonic inversion in brittle regimes have emphasized the importance of the orientations of fault arrays with respect to the orientation of the stress field operative during crustal shortening, together with the condition of pore-fluid pressure in the fault zones (e.g. Sibson, 1995). These approaches can be modified to consider the role of ductile instabilities at depth within the lithosphere (e.g. Willingshofer et al., 2005). However, these parameters must be related to the strength of the lithosphere into which the faults are embedded. Presumably it is the contrast in strength between an appropriately oriented fault zone and the lithosphere within which it is embedded that will influence its propensity for reactivation (e.g. Ranalli, 2000). Models of lithosphere rheology, expressed as strength–depth profiles, are necessarily generalized. Understanding the complexities of basement reactivation of natural systems, such as the external Alpine basement massifs (Fig. 2) requires rheological models to have greater resolution. The question arises as to what length scales local faults and arrays effect the large-scale deformation of the lithosphere. Understanding the geometry and kinematics of basement reactivation on the km scale may however aid in the choice of appropriate rheological approximations when upscaling to the lithosphere.

In the Apennine system, the role of basement reactivation has, we believe, been historically underestimated, probably because the current outcrop levels are dominated by deformed sedimentary cover that is decoupled from the underlying basement along evaporites. In active settings such as the Iranian Zagros, seismicity can demonstrate basement involvement in the absence of direct outcrop evidence (Talebian and Jackson, 2004). For these and especially inactive systems like the Apennines, the demonstration of structural inheritance generally demands stratigraphic data that can be used to reconstruct pre-orogenic basin geometries independent of the definition of the contractional structures that have deformed them. This is necessarily a multidisciplinary endeavour. However, while the three dimensional structure of the Apennine thrust system coincides strongly with pre-existing basin geometries, and recent structural interpretations of thrusts and folds indicate basement involvement, the mode of basement reactivation in the subsurface remains unresolved. Using Alpine basement structures as analogues predicts that ideal fault reactivation is rare. It may be that more distributed strain patterns are more realistic.

On the large scale, it remains unclear the extent to which the structure of mountain belts is largely the result of amplification of pre-existing perturbations (see also Butler and Mazzoli, 2006). Early faults are just one form of initial perturbation. Compositional and thermal heterogeneities are also potentially important. While some recent numerical forward models have incorporated lateral variations in thermal structure both inherited and dynamically evolving, more complex geometric and compositional heterogeneities are under-investigated. The mechanical consequences of inherited structures and their interaction through a range of length-scales would seem to be a fruitful ambition for future numerical modelling.

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