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SHORT NOTE

Kinematics of primary contacts between low- and relatively high-pressure rocks in orogens

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Abstract—Primary contacts among low- and relatively high-pressure rocks in convergent orogens have been mainly interpreted as a result of extensional tectonics, or reimbrication of high-pressure thrust units already resting on low-pressure ones and by consequent inversion of their stacking order. Our work in northern Calabria allows us to ascertain the nature and kinematics of several of these contacts, and to work out a general model that considers primary pressure break contacts as resulting from the growth of a deep passive roof duplex within a subduction–accretion system. Estimates of pressure differences across these contacts may be obtained for a simple passive roof duplex geometry as a function of the aspect ratio of the structure and of the angle of subduction. Our results suggest therefore that there may be a further possibility, in addition to extension or reimbrication, which explains pressure break contacts in orogens.

INTRODUCTION

The nature of tectonic contacts between relatively high- and low-pressure rocks in convergent orogens represents a general problem in many geological settings as, for example, the Franciscan Complex, the Betic Cordillera, the Alps (e.g. Platt 1993, and references therein) and the Calabrian Arc (e.g. Cello *et al.* in press). In this paper, a kinematic model, mainly inspired by field observations on exposed contacts between metamorphosed ophiolitic units in northern Calabria (southern Italy), is discussed. Here, several nappes of oceanic and continental crust derivation show both 'normal-' and 'reverse-sense' pressure break contacts (Wheeler & Butler 1994) (Fig. 1). Contacts of low-pressure (LP) rocks overlying relatively high-pressure (HP) ones occur between ophiolitic units, consisting of greenschist rocks (Malvito unit) tectonically overlying blueschists (Diamante–Terranova unit). Both units include Jurassic–Lower Cretaceous metabasites and metasediments; the Malvito unit is characterized by greenschist (lawsonite) metamorphic conditions, whereas the Diamante–Terranova unit is affected by a moderately HP–LT metamorphism (lawsonite and glaucophane), with $P = 8$ kb and $T = 400$°C, and by a lower greenschist facies (actinolite–pumpellyite) overprinting event (Cello *et al.* 1991, in press). An opposite relation is shown by the superposition of HP rocks of continental crust derivation (Castagna unit) on top of LP rocks (Bagni unit) (Fig. 1). The complexity of these contacts is highlighted by contrasting information derived from shear sense indicators from different localities and by their resulting interpretation either as normal or reverse faults (Faure 1980, Dietrich 1988, Knott 1994, Monaco & Tortorici 1994, 1995). Wheeler and Butler (1994), however, have shown that the exist-

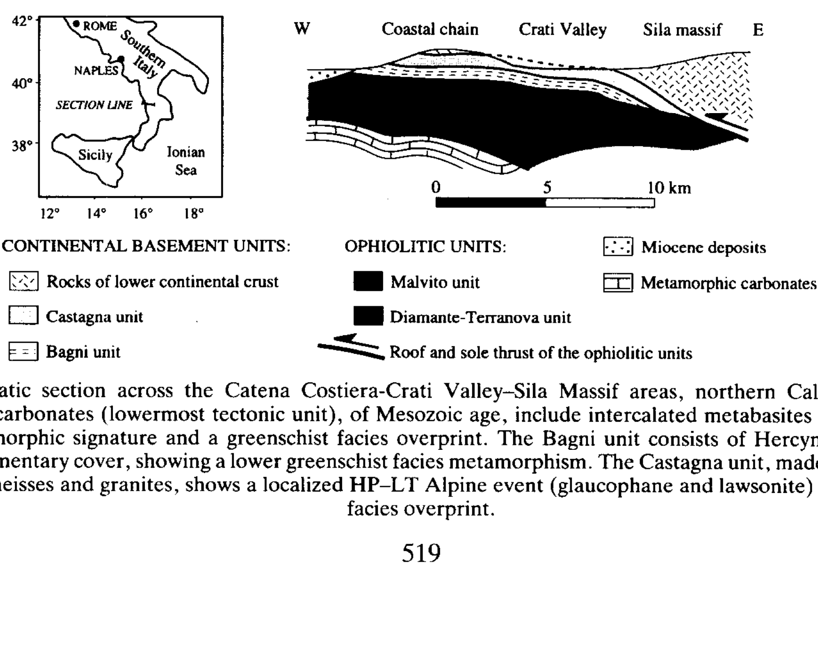

Fig. 1. Schematic section across the Catena Costiera-Crati Valley–Sila Massif areas, northern Calabrian Arc. The metamorphic carbonates (lowermost tectonic unit), of Mesozoic age, include intercalated metabasites locally showing a HP–LT metamorphic signature and a greenschist facies overprint. The Bagni unit consists of Hercynian phyllites and Mesozoic sedimentary cover, showing a lower greenschist facies metamorphism. The Castagna unit, made up of Hercynian micaschists, gneisses and granites, shows a localized HP–LT Alpine event (glaucophane and lawsonite) and a greenschist facies overprint.

ence of 'normal-sense' pressure breaks (i.e. LP rocks directly overlying HP ones) between hanging wall and footwall rocks across tectonic contacts is not sufficient, by itself, for ascertaining the nature of the contacts. These, in fact, may be either accounted for by syn- or late-orogenic extensional faulting, or by reimbrication processes affecting HP thrust units already resting on LP ones and by consequent local inversion of their stacking order. Based on our work in Calabria (Cello *et al.* 1981, 1990, 1991, 1995, in press), we envisage a further possibility for the genesis of pressure breaks across tectonic contacts between low- and relatively high-pressure rocks in convergent orogens.

KINEMATIC MODEL

For the sake of simplicity, we approach the problem by discussing a kinematic model which is focused on the deformation history and resulting contacts between two superposed ophiolitic units, showing specific geometric relationships and different conditions of metamorphism achieved during the evolution of a subduction–collision system (Fig. 2).

The first stage in the evolution of the system (Fig. 2) shows a roughly 60°-dipping oceanic slab subducting below a rifted continental margin (Fig. 2a). The growth of the accretionary prism is inferred to be accompanied, at deepest levels, by an extensive superposition of oceanic crust, detached from the lithospheric mantle, which originates two distinct ophiolitic units (units 1 and 2 in Fig. 2b). As continent–continent collision takes place and mountain-building processes proceed, the development of a deep duplex may occur through the imbrication of oceanic slices above a main crust–mantle decollement in the subducting slab (Fig. 2c). The deep structure consists of a passive roof sequence (Banks & Warburton 1986) made up of ophiolitic unit 1, whereas the duplex sequence includes several horses accreted from ophiolitic unit 2. *P–T* values in the deepest sectors of the subduction complex are typical of high pressure–low temperature metamorphic conditions, whereas at shallower depths (above the buried duplex) the ophiolitic units are likely to undergo greenschist facies metamorphism. During the latest events in the evolution of the system, exhumation may occur due to erosional processes and extensional collapse of the mountain belt (Platt 1993, and references therein) following the growth of the deep structure.

The final configuration in Fig. 2 may be schematically depicted as in Fig. 3(a), where the passive roof duplex is assumed to have a semicircular shape. The growth of the duplex is envisaged to occur by progressive increase of the amplitude (A) of the structure, which maintains a constant radius of curvature (r), up to a maximum value of the aspect ratio which is defined by $A/r = 1$ (Figs. 3b–d). As the passive roof sequence is assumed to remain relatively stationary above the growing duplex (Banks & Warburton 1986), its folding may be accompanied by internal stretching and/or by slip on the limbs as shown

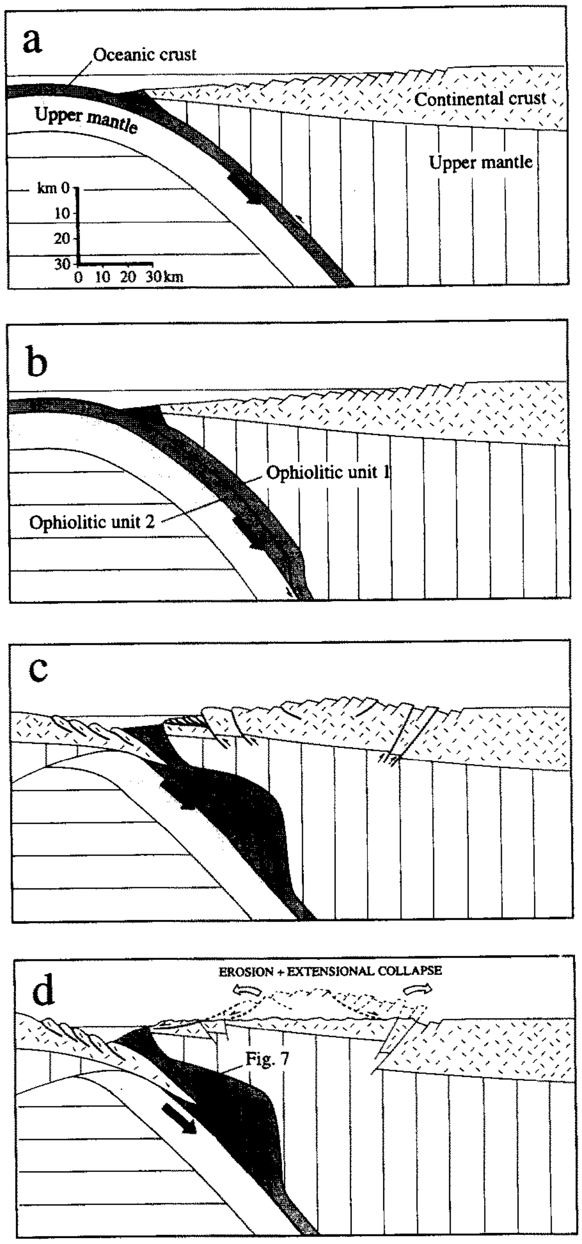

Fig. 2. Cartoon showing the evolution of a subduction–collision system and the growth and exhumation of a buried passive roof duplex (see text for discussion).

in Fig. 3(a). By assuming that the roof sequence will maintain its original thickness, the slip on the limbs may also be quantified, in the general case, by placing a median pin line within the roof sequence (Fig. 4). The net slip (S) on one limb of the antiform is then given by the difference between the length of the semi-arc ($l_{sa} = r\beta$, where β is the angle between the two radii defining the semi-arc) and the length of the semi-chord (x):

$$S = l_{sa} - x = r \arctan[(2rA - A^2)^{1/2}/(r - A)] - (2rA - A^2)^{1/2}. \quad (1)$$

Mass balance arguments suggest that, for a given constant thickness of the roof sequence, the value S gives an estimate of the amount of material (m) which needs to be 'dragged in' laterally into the antiformal limbs in order to maintain compatibility and physical continuity within the sequence. Therefore, considering the same

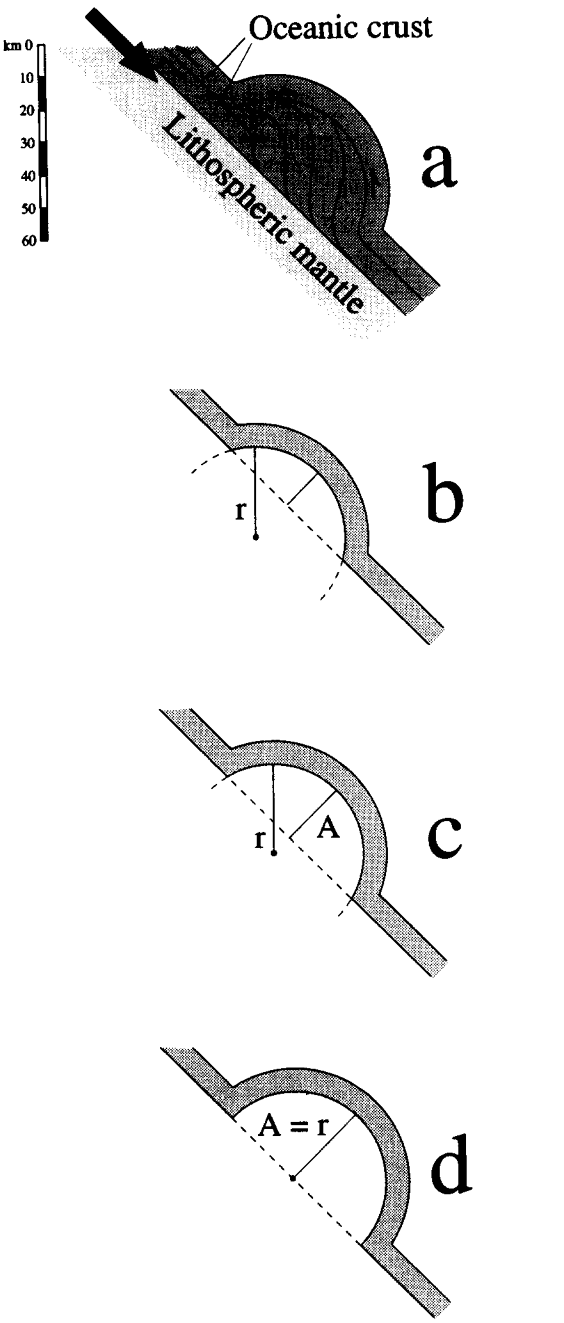

Fig. 3. Simple geometric model of the passive roof duplex shown in Fig. 2. In (a), the local kinematics (thin arrows) along the antiformal limbs of the duplex are shown in contrast to plate motion (thick arrow); while (b) and (c) show progressive increase of the amplitude (A) of the structure for a given radius of curvature (r). In (d), the maximum value of the aspect ratio $A/r = 1$ defines the largest admittable dimensions of the modelled duplex.

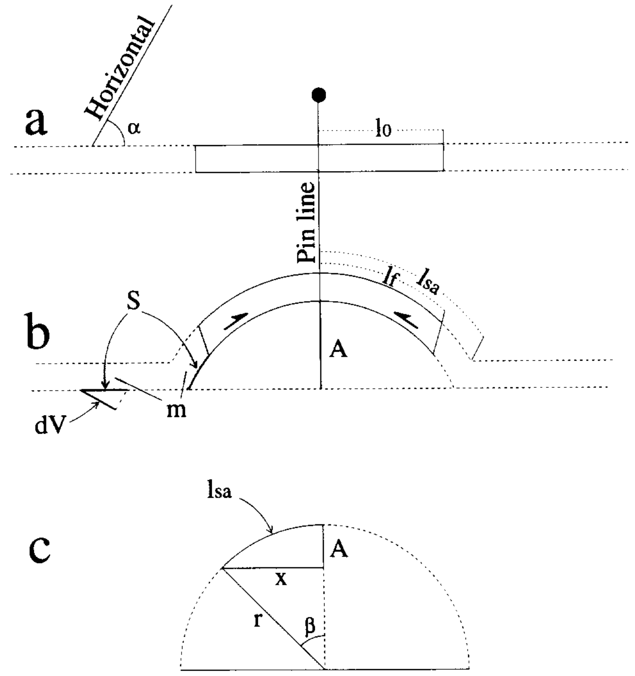

Fig. 4. Geometric relationships between slip (S), its vertical component (dV) and the angle of subduction (α). In (a), l_0 is the original length of a given section of the roof sequence. In (b), l_f is the length of the folded section (as the roof sequence is assumed not to deform internally, $l_f = l_0$); l_{sa}: length of the antiformal limb for a given amplitude (A); m: amount of material 'dragged in' from aside. In (c) r is the radius of curvature; β: angle between the two radii defining l_{sa}; x: length of the semi-chord.

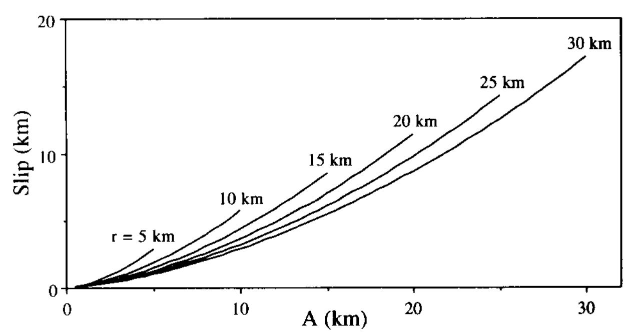

Fig. 5. Diagram showing slip (S) vs amplitude (A) for different values of the radius of curvature (r).

amount of slip (S) along a 'flat' sector in Fig. 4(b), one may also compute the vertical component of the displacement (dV) as a simple function of the angle of subduction (α):

$$dV = S \sin \alpha. \quad (2)$$

Using equation (1), the relationship between the net slip (S) and the amplitude (A) of the duplex was calculated for different values of the radius of curvature (r) and graphically displayed in the diagram of Fig. 5. As can be observed, for a fully developed ($A/r = 1$) large regional duplex with geologically reasonable dimensions (with an r value around 20–30 km), the net slip (S) is in the order of 15 km. Similar A and r values, when introduced into equation (2), lead to variable estimates of the vertical component of the displacement as a function of the angle of subduction (α) (Fig. 6). It is worth noting that with α values in the range of 45°–60°, dV varies between about 10 and 12 km.

DISCUSSION

Applying the results of our simple model to the geological situation depicted in the cartoon of Fig. 2(c) & (d), we observe that the tectonic contact between the passive roof sequence (ophiolitic unit 1) and the underlying horses of ophiolitic unit 2 is the site where slip occurs toward the crest of the antiformal structure, 'dragging in' material from both above and below the duplex. As a result, material from below will move

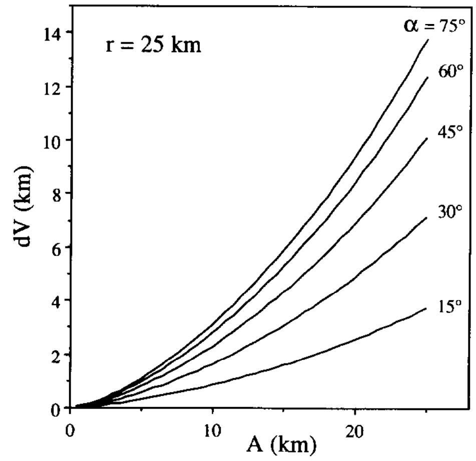

Fig. 6. Diagram showing vertical component (dV) of the displacement vs amplitude (A) for different values of the angle of subduction (α) and for a given radius of curvature (r = 25 km).

toward the surface along the steep limb of the structure, thus producing tectonic contacts across which higher pressure rocks rest above lower pressure rocks. Local kinematic indicators from this deep part of the structure would show overthrusting of HP onto LP rocks and therefore 'reverse-sense' pressure breaks. Along the shallower flat-lying limb, material is instead 'dragged in' from above, thus coming into contact with relatively higher pressure rocks of ophiolitic unit 2. Within this context, a 'normal-sense' pressure break across the contact will be associated with local kinematic indicators recording a 'normal' sense of shear given by the downward movement of the hanging wall relative to the Earth's surface (Fig. 7). The overall geometry accomplished by this mechanism consists therefore of a set of structures characterized by different contacts among rocks showing variable metamorphic imprint. In particular, the situation 'zoomed in' in Fig. 7 highlights how structurally-higher horses within the duplex sequence (ophiolitic unit 2) record progressively-increasing pressure conditions and are arranged in such a way as to show 'reverse-sense' pressure breaks, whereas across the low-angle contact to the roof sequence, progressively-larger 'normal-sense' pressure differences are to be expected moving down-dip. Although this main contact between LP and HP rocks shows quite similar features to those that would result from tectonic

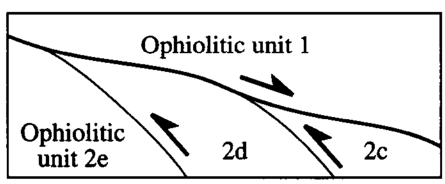

Fig. 7. 'Zoomed in' cartoon from Fig. 2, showing different-order structures within the subduction complex. The main flat-lying tectonic contact to the roof sequence records a 'normal-sense' pressure break with the underlying duplex sequence and apparent extensional kinematics. Progressively larger 'normal-sense' pressure breaks are to be found along the latter contact moving down-dip from horses 2e to 2c, whereas 'reverse-sense' pressure breaks characterize the thrust contacts between the horses.

elision due to normal faulting, it must be stressed that, in this case, no material is actually removed from within the tectonic pile.

According to our calculations (Figs. 5 and 6), the vertical displacement associated with the growth of a duplex with A = 25 km is in the order of 12 km, for α = 60°, corresponding to a pressure increase of more than 4 kbars. This pressure increase, however, will not be recorded as a metamorphic high-pressure event in the rocks of ophiolitic unit 1 which are 'dragged in' along the flat-lying limb, because a comparable amount of lithostatic load is meanwhile relieved due to the removal of material by uplift and erosion, and by crustal thinning associated with the extensional collapse of the orogen. On the other hand, as exhumation may cause re-equilibrium at lower pressure metamorphic conditions (in rocks belonging to ophiolitic unit 2), 'normal-sense' pressure break contacts can be locally recorded only if relict minerals of HP–LT are preserved within footwall rocks, as occurs indeed in the northern sector of the Calabrian Arc.

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