Pergamon

Journal of Structural Geology, Vol. 18, No. 10, pp. 1275 to 1279, 1996
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0191-8141/96 $15.00 + 0.00

PII: S0191-8141(96)00054-5

Extensional processes driven by large-scale duplexing in collisional regimes

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(*Received* 19 *February* 1996; *accepted in revised form* 4 *July* 1996)

Abstract—Syn-orogenic extension and 'normal-sense' pressure-break contacts in collisional regimes have been modeled by considering the behaviour of a stationary roof sequence undergoing layer-parallel stretching above a growing duplex showing an antiformal stack geometry. Model results show good agreement with geologically-derived stretching and pressure break values characterizing the western Tuscany core complex of central Italy, which was chosen as a test area. The results of our study support the hypothesis that 'normal-sense' pressure breaks of the order of a few kbars and syn-collisional extension in excess of 50% can be produced in the roof sequence by deformation within growing subduction–collision complexes. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Structures related to syn-orogenic extension have been recognized in many orogens worldwide. They include tectonic pressure-break contacts that are thought to be the most reliable indicators of orogenic collapse associated with uplift and erosion of rocks deformed and metamorphosed at considerable depth below the surface (Platt 1993 and references therein). According to Wheeler & Butler (1994), pressure-break contacts are of 'normal-' or 'reverse-sense' types, the former showing relatively low-pressure rocks overlying high-pressure ones, and the latter displaying an opposite relationship. Our own results from 'normal-' and 'reverse-sense' pressure-break contacts outcropping in the Calabrian Arc of southern Italy (Cello *et al.* 1996), suggest that their apparent complexity may be resolved by referring to a simple model which takes into account the main geometric and kinematic features of a growing antiformal stack accreted by underplating (Cello & Mazzoli 1996). In this paper, we focus on the nature of the extensional processes and on the amount of stretching that may be recorded within the roof sequence of an antiformal stack, using the western Tuscany (Italy) core complex structure (Carmignani & Kligfield 1990) as an example from the Mediterranean orogens.

Structural outline of western Tuscany

In western Tuscany, greenschist-facies metamorphic rocks tectonically underlying very low-grade to non-metamorphic sedimentary rocks of the *Falda Toscana* (Tuscan nappe) and ophiolite-bearing terrains (Liguride units), are exposed through several tectonic windows in the Alpi Apuane region (Carmignani *et al.* 1993 and references therein) (Fig. 1). The occurrence of 'normal-sense' pressure break contacts between younger anchimetamorphic and older higher grade metamorphic rocks has been interpreted as resulting from the development of a warped major detachment and associated brittle tectonites and mylonitic fabrics showing top-down-to-the-SW and top-down-to-the-NE senses of shear on either sides of a NW–SE trending regional antiformal culmination (Carmignani & Kligfield 1990). This NE–SW oriented extension is the only one recorded in western Tuscany (there is no evidence for extension parallel to the axis of the regional antiform), and section balancing carried out along this trend yields a value of 60% extension in the hanging wall to the major detachment (Bertini *et al.* 1991).

The present-day architecture of western Tuscany results from the emplacement of the oceanic-derived Liguride units onto the westernmost sector of the Afro–

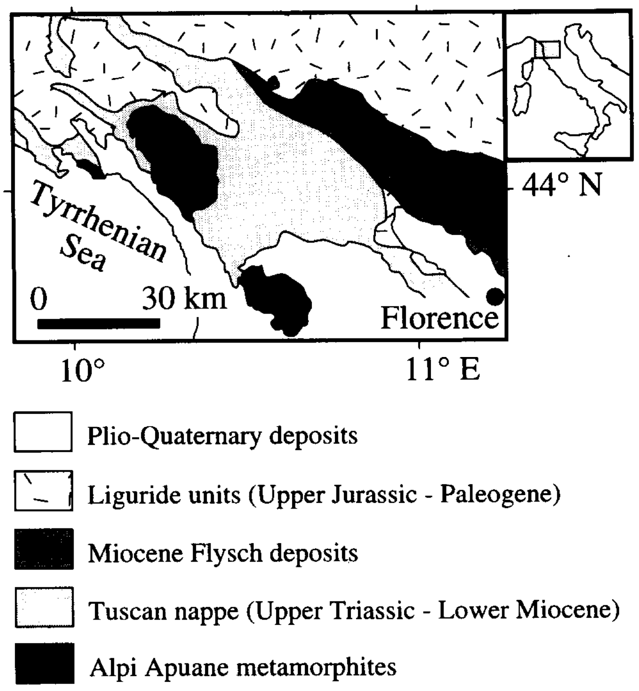

Fig. 1. Geological sketch map showing the main tectonic units of the northern Italian Apennines (modified after Carmignani *et al.* 1993).

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Adriatic continental margin and from shortening, imbrication and local extension of different sectors of the latter.

During the Late Oligocene, part of the continental margin succession (Fig. 2a) was emplaced, together with the tectonically overlying Liguride units, over the Alpi Apuane zone, achieving the complete superposition of the sedimentary rocks of the Tuscan nappe onto the latter (Carmignani & Kligfield 1990 and references therein). Continued shortening led to duplexing and (beginning in the Early Miocene) to the development of an antiformal stack made of the metamorphic (Alpi Apuane) units, with the Tuscan nappe and Liguride units constituting its roof and with an unexposed floor thrust (Fig. 2b). Contemporaneously with the build-up of this antiformal stack, extension of the roof sequence occurred by means of (mainly listric) normal faults detaching either along its base or along the thrust contact between the Tuscan nappe and the overlying Liguride units (Carmignani & Kligfield 1990) (Fig. 2c). The coeval development of extension within the roof sequence and shortening within the underlying duplex is clearly indicated by K–Ar and ^{40}Ar/^{39}Ar dating of metamorphic events associated with both contractional and extensional structures in the Alpi Apuane, which yields ages in the range of 27–10 Ma (Kligfield *et al.* 1986). Additional evidence for extension within the roof sequence being contemporaneous with the growth of the underlying duplex is given by fluid inclusion data (Hodgkins & Stewart 1994). These show that the last movement along the major detachment fault at the base of the roof sequence is coeval with the later stages of metamorphism associated with the development of the duplex structure (> 10 Ma). Low-angle extensional faulting of the Tuscan nappe also produced the *serie ridotta* (reduced succession) of southern Tuscany, characterized by large amounts of missing stratigraphic sections. As a consequence of this process, the Alpi Apuane rocks, having experienced greenschists-facies metamorphism with peak temperatures of 350–400°C (Di Pisa *et al.* 1985), were brought into contact with overlying very low-grade (anchizonal; Cerrina-Feroni *et al.* 1983 and references therein) rocks of the Tuscan nappe.

From late Tortonian times onwards, western Italy has been affected by extensional processes which are thought to be linked to the opening of the Tyrrhenian Sea (Fig. 1). These processes are clearly distinguished from those of Early–Middle Miocene age discussed above for western Tuscany and have not been included in the model presented in this paper.

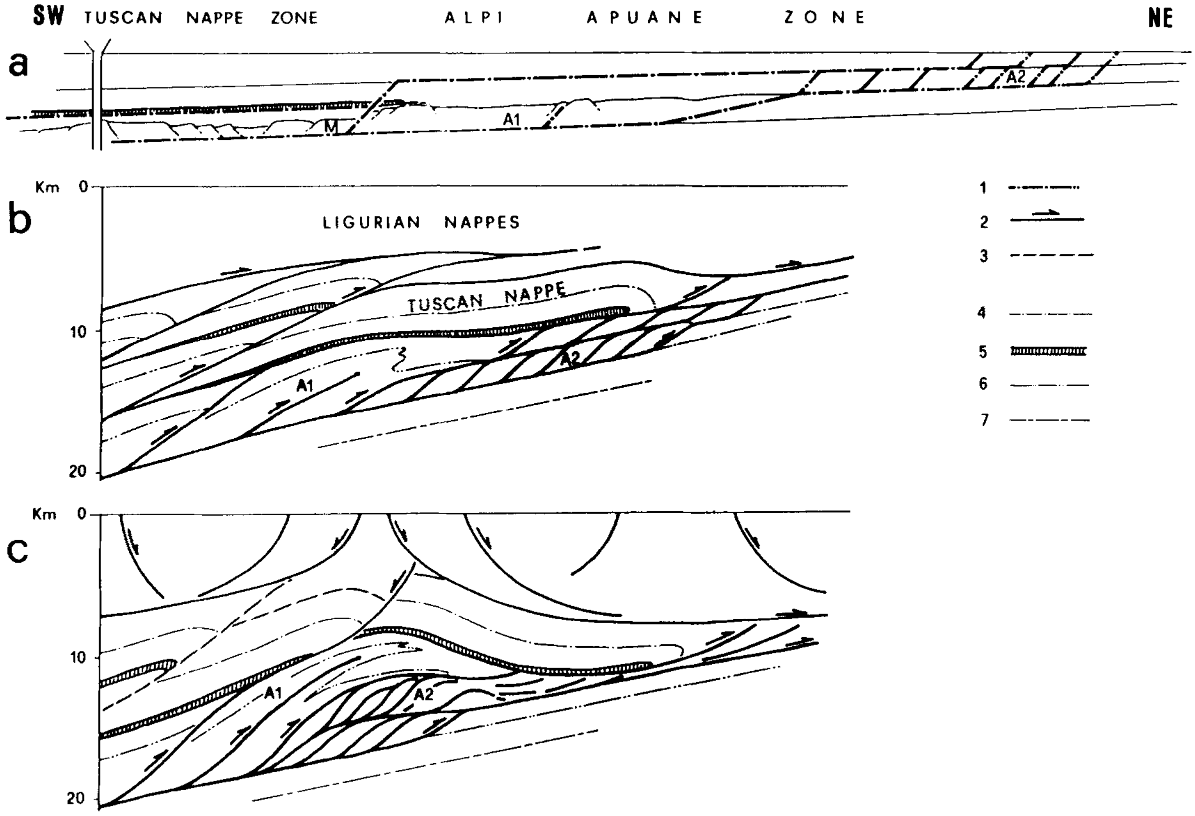

Fig. 2. Cartoon showing interpreted Oligo–Miocene evolution of the western Tuscany structure (from Carmignani & Kligfield 1990). (a) Pre-collisional geometry showing restored state traces of main thrust faults and original location of the Tuscan nappe and Alpi Apuane zones within the continental margin. (b) Development of the Alpi Apuane duplex structure below the Tuscan nappe overthrust. (c) Development of an antiformal stack geometry by underplating. Note simultaneous thrusting and normal faulting in the deep-seated duplex and in the roof sequence, respectively. Legend: 1 = thrust fault traces; 2 = active thrusts and normal faults; 3 = inactive thrusts; 4 = base of Flysch deposits; 5 = Triassic evaporites; 6 = top of Paleozoic phyllites; 7 = top of crystalline basement. A1 and A2 are NW and SE portions of the metamorphic complex, respectively. All diagrams at same scale with no vertical exaggeration.

KINEMATIC MODEL

In our companion paper on the kinematics of primary contacts between low- and relatively high-pressure rocks in a subduction–collision system (Cello & Mazzoli 1996), we considered the possibility that both 'normal-' and 'reverse-sense' pressure breaks may be produced by slip of a passive roof sequence on the limbs of a growing deep-seated antiformal stack. The growth of the structure was modelled by assuming that the thickness of the roof sequence remained constant throughout deformation (Fig. 3a). In this paper, we introduce the possibility that the roof sequence also deforms internally by layer-parallel extension, and present a 2D model in which plane strain conditions are assumed. This appears to represent a reasonable assumption for our test-area, since it has been shown that extension of the roof sequence overlying the Alpi Apuane antiform was essentially unidirectional (Bertini *et al.* 1991). It must be stressed, however, that in the general case of 3D strain conditions some material of the roof sequence may move sideways out-of-section (Butler 1982), thus resulting in more complex geometrical relationships with respect to those obtained from our simple model. This also means that extension values derived by assuming plane strain conditions must be considered as the maximum admissible ones.

For a geometry like that shown in Fig. 3, layer-parallel extension of the roof sequence may occur by processes including normal faulting and/or ductile extension, with major normal faults detaching along its base (i.e. along the roof thrust to the underlying duplex; Fig. 3b) as it has been inferred to occur in Tuscany (refer to Fig. 2c). In the kinematic model of Fig. 3(c–e), the roof sequence is shown to undergo extension by ductile thinning of the material overlying the antiformal stack, which is assumed to have a semicircular shape. The ductile process shown in Figs. 3(c–e) is equivalent to one involving normal faulting, in that the resulting amount of stretching along the base of the roof sequence is the same in the two cases. Following Cello & Mazzoli (1996), 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. 3c–e). As the passive roof sequence is assumed to remain relatively stationary above the growing duplex (Banks & Warburton 1986), the maximum amount of stretching resulting from the growth of an antiformal stack may also be quantified, in the general case, by placing two pin lines within the roof sequence at both ends of the structure, as shown in Fig. 4. The amount of extension (e) is then given by:

$$\begin{aligned} e &= (l_1 - l_0)l_0^{-1} = \\ &= \{r\,\mathrm{Arctan}\,[(2rA - A^2)^{1/2}(r - A)^{-1}] \\ &\quad - (2rA - A^2)^{1/2}\}(2rA - A^2)^{-1/2}. \qquad (1) \end{aligned}$$

In Fig. 5, equation (1) has been used to obtain a curve displaying the extension of the roof sequence as a function of the amplification of the underlying antiformal stack (expressed as the ratio between the amplitude (A) and the radius of curvature (r) of the duplex structure). As can be observed, for a fully developed ($A/r = 1$) antiformal stack in the model, amounts of exten-

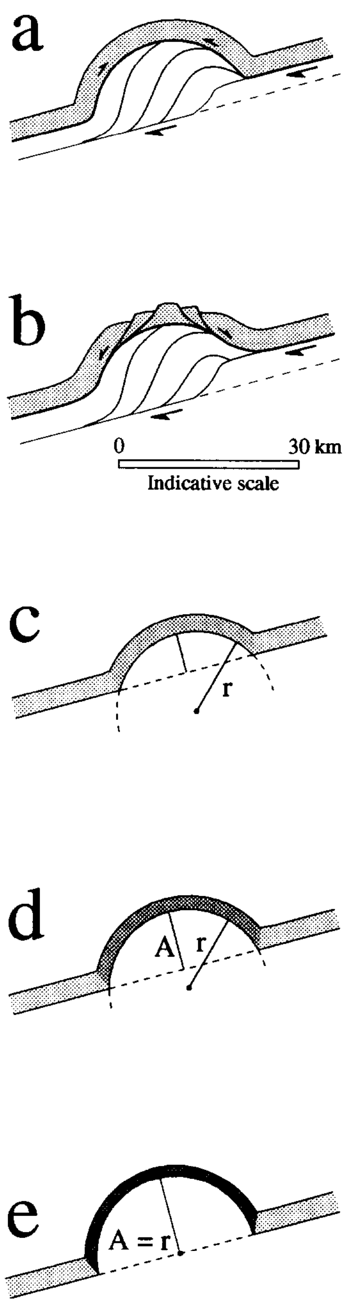

Fig. 3. Simple geometric models of possible behaviour of a stationary passive roof sequence above a growing antiformal stack. (a) No internal deformation of the roof sequence is allowed; local kinematics (thin arrows) characterizing the antiformal limbs of the duplex are shown in contrast to major kinematics (large arrows) of the collisional system. This situation corresponds to that modelled by Cello & Mazzoli (1996). (b) Internal deformation of the roof sequence occurs by layer-parallel stretching, with normal faults detaching along the base of the roof sequence. (c) and (d) Progressive stretching of the roof sequence is shown as continuous (ductile) thinning and extension as a function of the amplitude (A) of the structure for a given radius of curvature (r). (e) The maximum value of the aspect ratio $A/r = 1$ defines the largest admissible dimensions of the modelled duplex and the associated maximum extension of the roof sequence. Increasing density of stipple in diagrams (c)–(e) represents increased ductile thinning of the roof sequence.

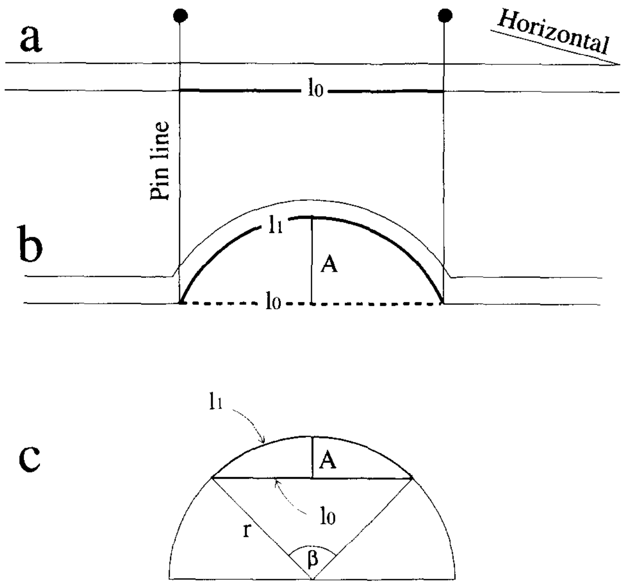

Fig. 4. Diagram showing model parameters. (a) l_0 is the original length of a given section of the roof sequence. (b) l_1 is the length of the folded section for a given amplitude (A). (c) r is the radius of curvature and β is the angle between the two radii defining l_1.

sion in excess of 50% can be obtained. The associated pressure breaks across the base of the roof sequence can be evaluated by considering the amount of material (m) removed from within the roof sequence as a function of the original thickness (t) of the latter:

$$m = t[1 - (1 + e)^{-1}]. \tag{2}$$

The graph in Fig. 6, derived from equation (2), indicates that several km of missing stratigraphic section can characterize the roof sequence, depending on its original thickness (t) and on the amplification of the underlying antiformal stack (A/r ratio). It follows, therefore, that 'normal-sense' pressure breaks of the order of a few kbars can be produced by this process.

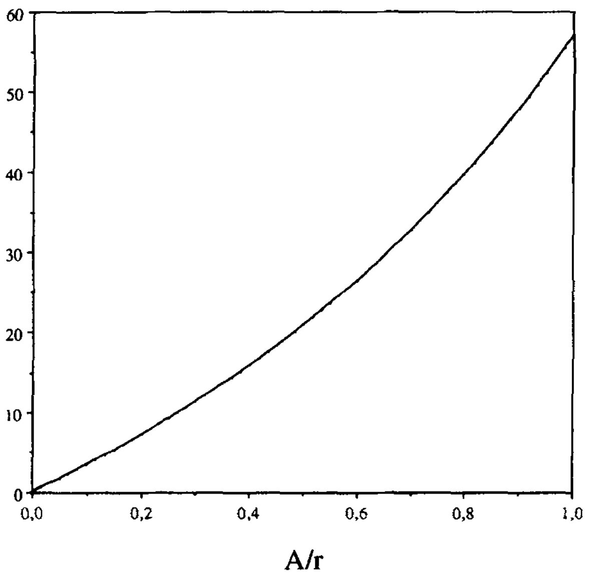

Fig. 5. Diagram showing extension (%) of the roof sequence vs amplification ratio (A/r) of the antiformal stack.

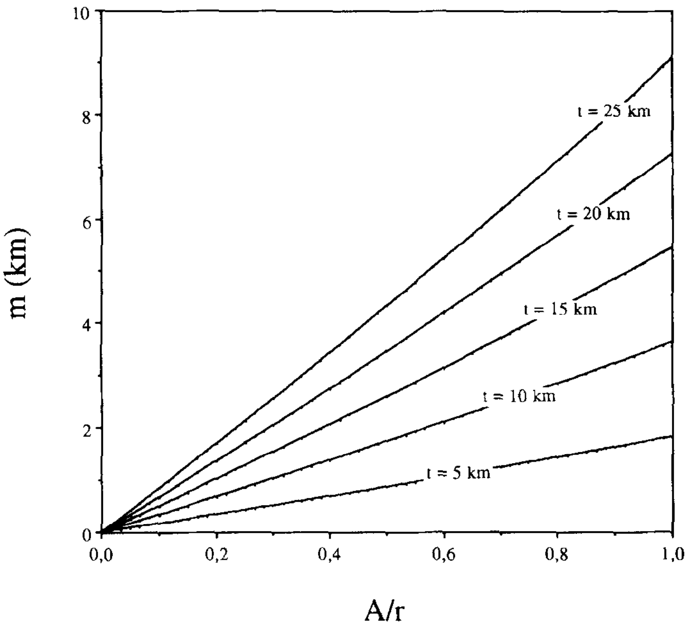

Fig. 6. Diagram showing the amount of material (m) removed from within the roof sequence vs amplification ratio (A/r) of the antiformal stack, for different thicknesses (t) of the roof sequence.

DISCUSSION

In western Tuscany, structures resulting from extension of the Tuscan nappe and Liguride units (refer to Fig. 2) appear to be good analogues of those modeled in Fig. 3 (b), where stretching of the roof sequence occurs above a growing antiformal stack. For this reason, we chose to compare geologically-derived extension values from this area with those computed from our kinematic model. Extension values obtained from detailed structural analysis and section balancing of the complete succession of the Tuscan nappe and of the associated *serie ridotta* are of about 60% (Bertini *et al.* 1991), whereas our model results suggest that, for a fully developed ($A/r = 1$) antiformal stack, a comparable amount of extension (57%) can be reached. The similarities between computed and measured values also suggest that a 2D analysis, carried out assuming plane strain conditions, can confidently be applied to areas characterized by unidirectional extension.

As concerns the evidence of a 'normal-sense' pressure break across the contact between the Alpi Apuane and the overlying roof sequence (Tuscan nappe and Liguride units), our results also indicate a good agreement between geologically-based and computed pressure values. The metamorphic signature of both the roof and duplex sequences of the western Tuscany antiformal stack, suggests, in fact, that the removal of 5–7 km of material from within the roof sequence has occurred. This yields a likely pressure break of 1.5–2 kbar across the base of the roof sequence. Applying our model results to the field example above, in which the original thickness of the roof sequence is in the range of 15–20 km, it follows that, for a fully developed antiformal stack, 5–7 km of material are removed by tectonic excision. This yields a 'normal-sense' pressure break of comparable amount to that observed in western Tuscany.

CONCLUSIONS

This short note and the companion paper on the kinematics of primary contacts between low- and relatively high-pressure rocks (Cello & Mazzoli 1996) discusses the nature of both extensional and compressional contacts in orogens within the framework of subduction–collision tectonics. In this note, we focus on modelling layer-parallel extension within the roof sequence of a growing antiformal structure, and on the comparison between the model results and those obtained from structural studies in western Tuscany.

The main conclusions that may be drawn from our study are summarized as follows:

(1) Geologically-derived extension values characterizing the Tuscan core complex, in central Italy, are comparable with those obtained from simple calculations based on our kinematic model.

(2) Extension values computed for the roof sequence are sufficient to generate the 1.5–2 kbar 'normal-sense' pressure break existing between the Tuscan nappe and the underlying Alpi Apuane.

(3) Removal of material from within the roof sequence by tectonic excision of part of the Tuscan nappe (accounting for the development of tectonically reduced successions known as the *serie ridotta*; Bertini *et al.* 1991 and references therein) may have possibly occurred as a result of collisional processes responsible for the growth of major deep-seated antiformal stack structures.

The above results seem, therefore, to corroborate the possibility that 'normal-sense' pressure breaks and, more in general, syn-collisional extensional contacts in orogens, can result from localized deformation associated with underplating and duplexing within growing subduction–collision complexes.

Acknowledgements—We are grateful to A. J. Barker, Richard Lisle and an anonymous reviewer for their useful comments on the manuscript.

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