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Development of systematic joints in response to flexure-related fibre stress in flexed foreland plates: the Apulian forebulge case history, Italy

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Abstract

Starting from Pliocene times, the Apulian foreland in southern Italy has undergone a flexural process underneath the Apennines thrust-fold belt. Mesozoic carbonate beds from the exposed Apulian forebulge are intensely dissected by systematic vertical joints striking parallel to the NW-trending flexure hinge. The sedimentary cover involved in the flexure consists of a 5.5 km thick succession of Mesozoic-Cenozoic carbonate beds strongly interpenetrated along bedding surfaces and overlying Triassic anhydrites and dolomites. On the assumption of the applicability of the linear elastic theory, the flexural curve of the Apulian foreland is reconstructed by best fitting a set of data derived from logs of oil wells and referring to the height of the base of Pliocene sediments. A set of flexural parameters is obtained from the reconstructed flexural curve. By using these parameters in solving the flexure equations for the fibre stress, we obtained a flexure-related hinge-perpendicular fibre stress in the outer arc of the Apulian forebulge in excess of −100 MPa. This value is far greater than the tensile strength of the exposed carbonate rocks. This result supports the hypothesis that the flexure-related fibre stress in the Apulian forebulge can have driven the initiation of the observed regional systematic joints. This model may be applied to any flexed foreland plate and constitutes an alternative to the classical model of elastic response of rocks to the variations of lithostatic loads through time that has been often invoked to explain sets of systematic joints over large areas of foreland regions.

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1. Introduction

Most foreland regions are traditionally depicted as consisting of undeformed or poorly deformed rocks under brittle conditions. Despite the substantial lack of thrust-and-fold-related deformations, systematic sets of solution cleavages or joints have been often observed to intensely dissect the flat-lying sedimentary successions of foreland regions (e.g. Sheldon, 1912a,b; Parker, 1942; Ver Steeg, 1942, 1944; Hodgson, 1961a,b; Nickelsen and Hough, 1967; Stearns and Friedman, 1972; Babcock, 1974; Reches, 1976; Geiser and Sansone, 1981; Engelder, 1982; Hancock and Bevan, 1987; Lorenz and Finley, 1991; Lorenz et al., 1991; Rawnsley et al., 1992; Salvini et al., 1999). Solution cleavages are commonly interpreted as forming by layer-parallel shortening (e.g. Engelder and Geiser, 1979; Geiser and Sansone, 1981; Engelder, 1984), whilst joints are often interpreted as forming in response to tensile stresses generated by the elastic reaction of rocks to the variations of the lithostatic load through time. Alternatively, joints are also interpreted as forming in response to tensile stresses generated by an increased pore pressure (e.g. Crosby 1882; McGee, 1883; Hopkins, 1841; Parker, 1942; Price, 1959; Wise, 1964; Secor, 1965; Engelder and Geiser, 1980; Engelder, 1985; Engelder and Oertel, 1985; Hancock, 1985; Suppe, 1985; Davis and Reynolds, 1996). Alternative mechanisms, such as folding-related tensile stresses occurring perpendicularly to the fold hinge in the outer arc of folds (e.g. Murray, 1968; Wiltschko et al., 1985; Narr, 1991; Gray and Mitra, 1993; Gutiérrez-Alonso and Gross, 1999) may be deemed inefficient in foreland areas, where rock successions are flexed on the scale of tens or hundreds of kilometres (i.e. the width perpendicular to the flexure hinge) and hence they may appear as substantially flat-lying over large regions. The hinge-perpendicular width of a foreland flexure is typically between 60 and 470 km, depending upon the flexural rigidity of the plate (DeCelles and Giles, 1996). The flexure of foreland plates occurs in approaching the orogenic wedge by a combination of topographic and subduction loads. It has been demonstrated that the flexure of a foreland plate can be properly simulated by using the equations of the flexure of a thin elastic sheet subject to an end load (e.g. Walcott, 1970; Beaumont, 1978, 1981; Turcotte, 1979; Karner and Watts, 1983; Royden, 1993). Such a flexural process generates a fibre stress, i.e. the stress that develops parallel to the flexed fibres or layers as tensile in the outer arc and compressive in the inner arc (Turcotte and Schubert, 1982). The fibre stress values in a bending plate can be easily resolved from the flexure equations when the use of the linear elastic theory is justified by appropriate boundary conditions (e.g. Turcotte, 1979; Turcotte and Schubert, 1982; Schmalholz and Podladchikov, 1999, 2000).

In this paper, we investigate the possibility of failure in the extension of foreland carbonate rocks subject to flexure and hence to intervening fibre stresses. In particular, we modelled the flexure of the Adriatic foreland plate under the Apennines thrust-fold belt in southern Italy (Fig. 1), and verified whether the observed hinge-parallel joint fabric in the forebulge region (i.e. the Apulian forebulge) could be simply interpreted as the rock response to the flexure-related fibre tensile stress. The resulting flexural curve is very similar to those proposed by Royden and Karner, (1984a,b), Royden et al. (1987), Royden (1988), and Albarello et al. (1990) in the same region. This similitude supports the adequacy of the physical parameters used for the subsequent estimate of the flexure-related fibre stress. Despite the aforementioned vast literature on systematic joints across foreland areas, the model presented in this paper represents, at least to the best of our knowledge, the first attempt of quantitatively correlating the origin of regional systematic joints in flexed foreland regions with the flexure-related fibre stress (for a review on jointing see: Friedman, 1975; Kranz, 1983; Engelder, 1987; Pollard and Aydin, 1988).

2. Tectonic setting

The Apennines form the NW–SE-trending foreland thrust-fold belt along the Italian peninsula (Fig. 1). The Apennines orogen developed on top of the Adriatic plate that constituted the foreland plate. Starting from the late Miocene, the Apennines foredeep migrated eastward with the progressive retreat of the foreland flexural monocline (Scandone, 1979; Malinverno and Ryan, 1986; Ricci Lucchi, 1986; Patacca et al., 1990). The flexural process involved the present Apulian-Adriatic region in Pliocene-Pleistocene times (Patacca and Scandone, 2001). The Apulian region in the southern Apennines is the actual on-shore forebulge of the Adriatic foreland (Fig. 1). In this area, a more than 6 km thick Mesozoic sedimentary cover occurs over a Variscan crystalline basement (D'Argenio, 1974). The Puglia 1 deep well near Brindisi (Fig. 1a) drilled through, from bottom to top, Permo-Triassic red beds, Triassic evaporites and dolomites (1 km thick) and well-bedded shallow-water Mesozoic carbonates (5.5 km thick). Tertiary marine deposits overlay the Mesozoic carbonates. The lithospheric thickness of the Apulian foreland is greater than 100 km (Calcagnile and Panza, 1981). The wide NW–SE-trending Apulian antiform is segmented by NW–SE-striking extensional faults with down-faulted blocks both south-westward and north-eastward, for a total vertical displacement (i.e. throw) of about 1 km. In the Gargano area, a transpressional belt associated to the left-lateral strike-slip Mattinata Fault system transversally dissects the Apulian foreland (Salvini et al., 1999; Billi and Salvini 2000, 2001). The foreland basin is approximately 50 km wide as measured on the topographic surface from the Apennines

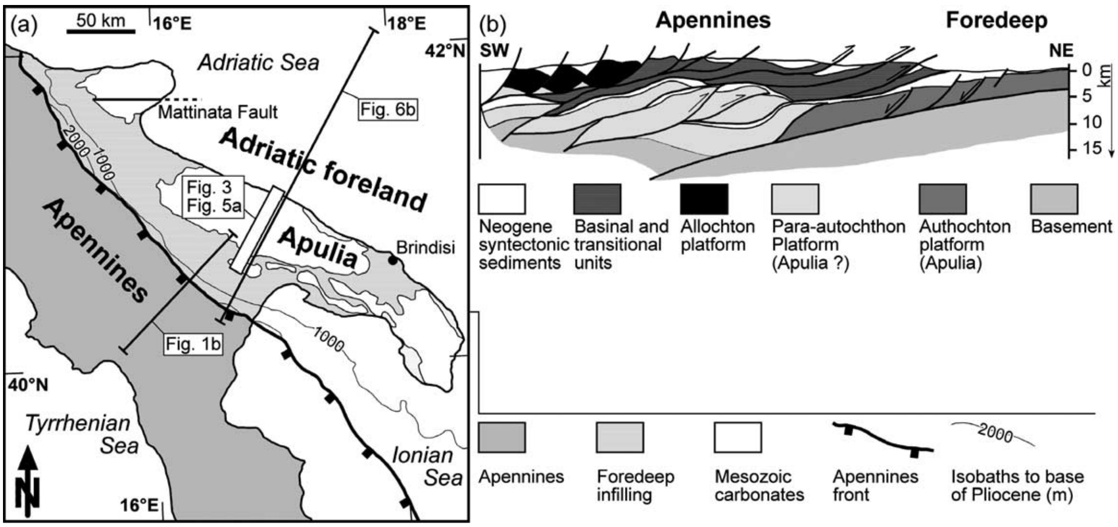

Fig. 1. (a) Structural map of southern Italy. Note the location of the transect in which data shown in Figs. 3 and 5b have been collected, and the location of cross-section shown in Fig. 6. (b) Geological cross-section through the southern Apennines (after Roure and Sassi, 1995).

thrust front to the Apulian foreland. This basin consists of an asymmetric trough deepening towards the Apennines and containing a more than 8 km thick succession of Pliocene-Quaternary sediments. Pliocene sediments (i.e. carbonate packstones and grainstones) in the Apulian region deposited before the onset of the lithosphere flexure in a marine shallow-water environment (Patacca and Scandone, 2001). For this reason, the base surface of Pliocene sediments can be used as the reference horizon to draw the flexure of the Adriatic lithosphere during Pliocene-Quaternary times (e.g. Royden and Karner, 1984a; Royden et al., 1987). By referring to the base of the Pliocene sediments, the height of the present forebulge is estimated in about 2 km (Bigi et al., 1992). By subtracting to this value 1 km of assessed cumulative throw on extensional faults (Billi, 2000), we obtain 1 km of vertical upward deflection (amplitude) of the Apulian forebulge.

3. Meso-structural fabric of the Apulian forebulge

A NE–SW transect survey (i.e. perpendicular to the flexure hinge, see Fig. 1a for location) was performed across the central Apulian forebulge (i.e. Murge area) for a total length of 85 km, with the aim of recording meso-structural deformations on the exposed Mesozoic carbonate rocks. Fig. 2 shows a set of photographs displaying some examples of meso-structural deformations from the investigated area. Fig. 3 shows the related structural data as projected in rose and Schmidt diagrams. In the Apulian forebulge, the meso-structural fabric consists of closely spaced unfilled systematic joints (Fig. 2a and b), which are persistent throughout the entire surveyed transect. On the investigated exposures, carbonate beds deeply interdigitate along sutured stylolitic bedding surfaces (Fig. 2b). The high-frictional profile of bedding surfaces should have prevented significant flexural-slip folding (i.e. layer-parallel slip) during foreland flexure, as suggested also by the substantial absence of evidence of slip (e.g. striations) over the exposed bedding surfaces.

NW-striking extensional faults with displacements spanning from a few centimetres to a few tens of metres, rarely occur (Figs. 2c and 3b). Crosscutting relationships indicate that the extensional faults substantially post-date the joint formation, as demonstrated by some faults cutting through and displacing joint surfaces that are sheared or dilated in approaching the faults (e.g. Peacock, 2001).

Joints in the Apulian forebulge are sub-vertical, intra- and more rarely inter-bed surfaces striking NW–SE (Figs. 2 and 3a). A sub-ordered family of NE-striking cross-joints abutting against the NW-striking family is also present (Fig. 3a). Joints affect Mesozoic carbonate beds, which are flat-lying (bedding dip $\leqslant 4^\circ$) and 0.2 m to more than 2 m in thickness (Figs. 2 and 3c). Joint surfaces are commonly between 0.01 and 0.10 m in spacing (Fig. 4a), but may also reach 2 m, depending upon the bed thickness (e.g. Rabinovitch and Bahat, 1999; Bai et al., 2000). In order to assess the joint spacing and aperture (i.e. opening displacement) in relation with the bed thickness, a series of scan-lines were performed along exposures of jointed carbonate beds. Each scan-line includes data coming from a single bed. In Fig. 4a, the average values (i.e. from Gaussian fitting of data) of joint spacing data sampled along 46 scan-lines are plotted against the relative bed thickness. This graph shows that the average spacing of joints is in the 0.02–0.75 m range and that it increases with increasing the bed thickness in the 0.05–1.2 m range. In Fig. 4b,

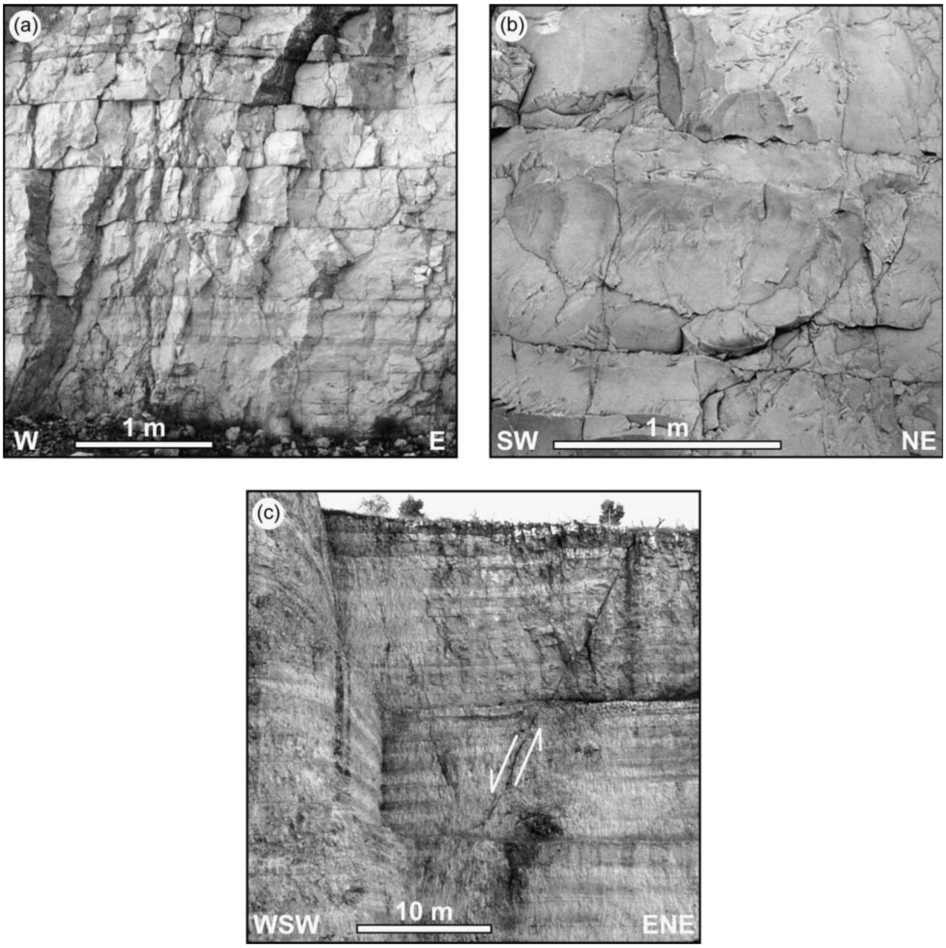

Fig. 2. (a) Photograph of Mesozoic flat-lying carbonate beds containing intra-bed joints (Apulian forebulge). (b) Photograph of jointed carbonate beds from the Apulian forebulge. Note the sutured stylolitic interdigitations along the bedding surfaces. The high-frictional profile of the bedding surfaces inhibits flexural slip along them. (c) Photograph of a NW-striking extensional fault cutting through and displacing the jointed carbonate beds exposed in the Apulian forebulge.

the average values (i.e. from Gaussian fitting of data) of joint aperture data sampled along 19 scan-lines are plotted against the relative bed thickness. This graph shows that the aperture of joints varies, as average value, between 0.002 and 0.06 m for bedding thickness varying between 0.1 and 0.9 m. The aperture of joints tends to increase with increasing the bed thickness, according to a rather poor correlation.

In Fig. 5b, the same structural data as in the graphs of Fig. 4 are plotted against the distance of the SW–NE transect whose swath is shown in Fig. 1a and topography in Fig. 5a. These data show that there are no significant changes both in the joint spacing and in the joint aperture across the Apulian forebulge. An overall slight increase of joint aperture and density (i.e. decrease of joint spacing) occurs in coincidence with the forebulge region.

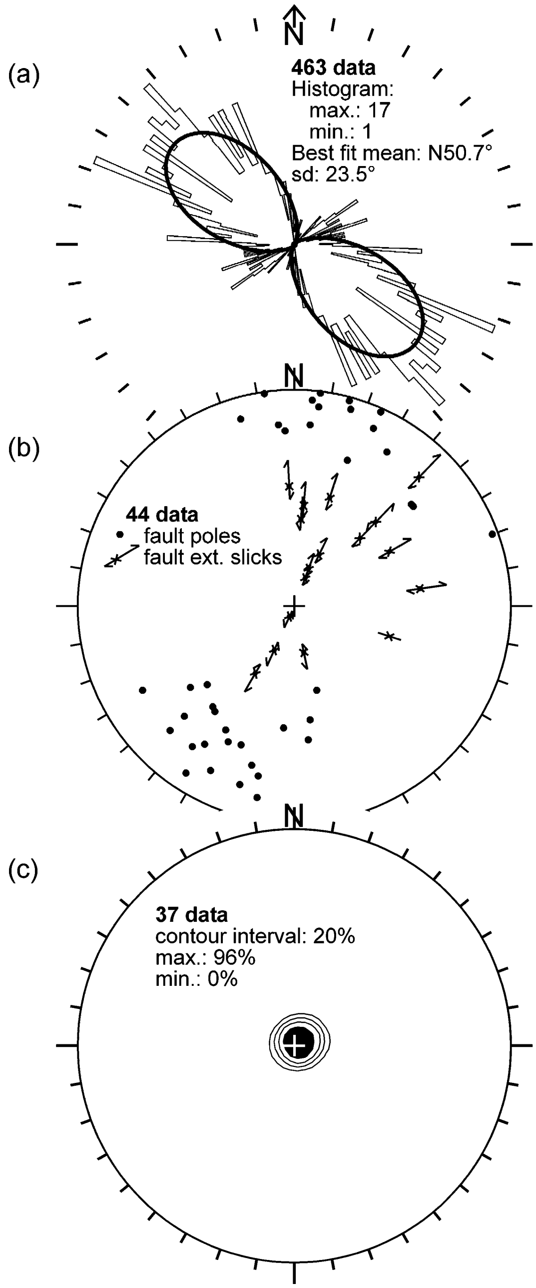

Fig. 3. Joints, faults and bedding data collected within a SW–NE transect across the Apulian forebulge (see Fig. 1a for transect location). (a) Rose diagram displaying the histogram and Gaussian best fit of joint azimuths. (b) Poles of extensional faults and related slickenlines projected on a Schmidt net (lower hemisphere). (c) Contours to poles of bedding surfaces (Schmidt net, lower hemisphere).

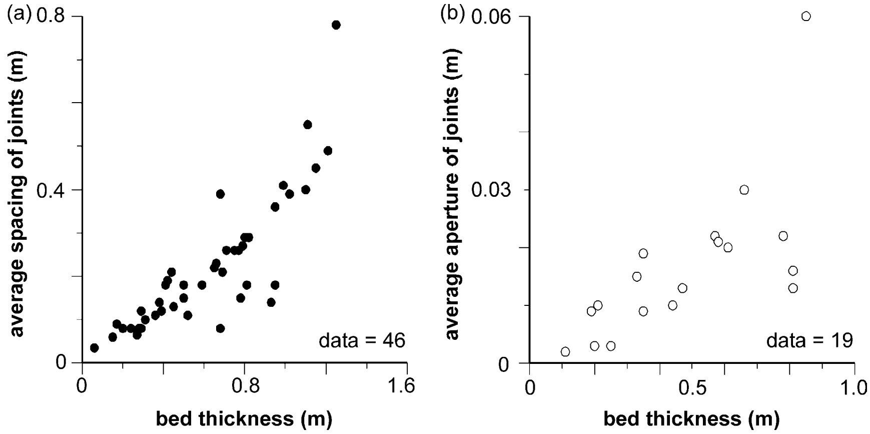

Fig. 4. (a) Graph of the average spacing of joints against the relative bed thickness. (b) Graph of the average joint aperture (i.e. opening displacement) against the relative bed thickness. Note that each datum in these graphs (average spacing or average aperture of joints) comes from a Gaussian best fitting over a population of data sampled along a scan-line (46 scan-lines for joint spacing and 19 scan-lines for joint aperture) on a single bed cross-section.

4. Flexure-related fibre stress in the Apulian forebulge

We simulated the flexure of the Adriatic foreland plate by using the function of the flexure of a thin elastic plate subject to a linear end load V_0 (e.g. Turcotte, 1979; Turcotte and Schubert, 1982; Ranalli, 1994, 1995). In such a deforming system (Fig. 6a), the vertical deflection, w, of the elastic plate is defined as a function of the spatial co-ordinate, x, by the following equation:

$$w = e^{-x/\alpha}(c_1 \ \cos x/\alpha + c_2 \ \mathrm{sen} x/\alpha) \tag{1}$$

where α is the flexural parameter and c_1 and c_2 are constants determined by the boundary conditions (Turcotte and Schubert, 1982). In this system, the maximum fibre stress, σ_{xx}, is given by the following equation:

$$\sigma_{xx} = -6 \ M/h^2 \tag{2}$$

where M is the flexural moment and h is the effective elastic thickness of the plate. We henceforth use negative values for tensile stresses. The flexural moment in the forebulge (M_b) is given by the following equation:

$$M_b = -\left(\pi^2/8\right)\left[D \ w_b/(x_b - x_0)^2\right] \tag{3}$$

where D is the flexural rigidity and w_b is the vertical upward deflection of the forebulge (x_b). D is given by the following equation:

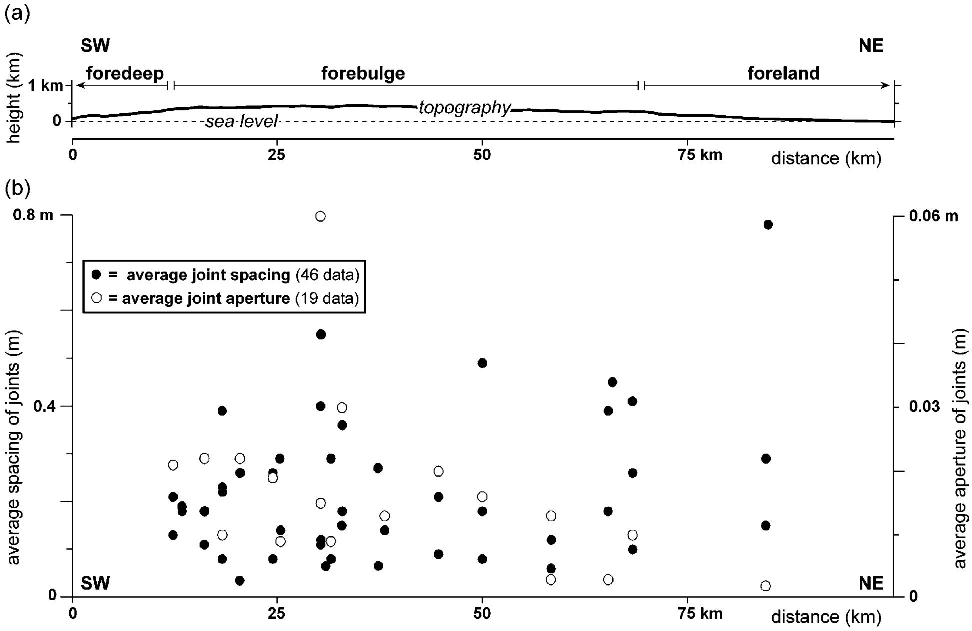

Fig. 5. (a) SW–NE topographic cross-section along the studied transect (see Fig. 1a for transect location). The foredeep, forebulge and foreland domains are shown, from SW to NE, on the cross-section. (b) Same data as of Fig. 4a and b (i.e. average spacing and aperture of joints) plotted against the distance of the SW–NE cross-section of Fig. 5a.

$$D = (E\ h^3)/[12(1 - \nu^2)] \tag{4}$$

where E is the Young's modulus and ν is the Poisson's ratio.

In applying these equations, it is assumed that the plate is thin compared with its width (i.e. $h \ll L$) and the vertical deflection of the plate is small compared with its width (i.e. $w \ll L$) (Fig. 6a). This assumption is necessary for justifying the use of the linear elastic theory (Turcotte and Schubert, 1982). According to this theory, in the outer arc of the flexed plate (i.e. the forebulge point), the fibre stress coincides with the maximum tensile stress (σ_3) and the fibre strain coincides with the maximum stretch (ϵ_3). The fibre stress and the fibre strain are parallel by definition.

In modelling the flexure of the Adriatic lithosphere, it is assumed a Young's modulus of 70 GPa and a Poisson's ratio of 0.25 (Royden and Karner, 1984a; Royden et al., 1987). In order to define the flexural curve of the Adriatic foreland plate, by using Eq. (1), we operated a best fitting process on depth vs. distance data of the base of Pliocene sediments along a SW–NE cross-section (Fig. 6b), whose trace is shown in Fig. 1a. Fitted data are extracted from Bigi et al. (1992) and from logs of public oil wells in the Adriatic offshore (e.g. de Dominicis and Mazzoldi, 1987). The resulting best fitting flexural curve is drawn in Fig. 6b. From this curve, a set of flexural parameters necessary to compute the fibre stress in the forebulge, is obtained: (1) $(x_b - x_0) = 60$ km; (2) $\alpha = 43.29$ km; (3) $D = 8.6044 \times 10^{21}$ Nm; (4) $h = 11.139$ km; (5) the hinge-perpendicular width of

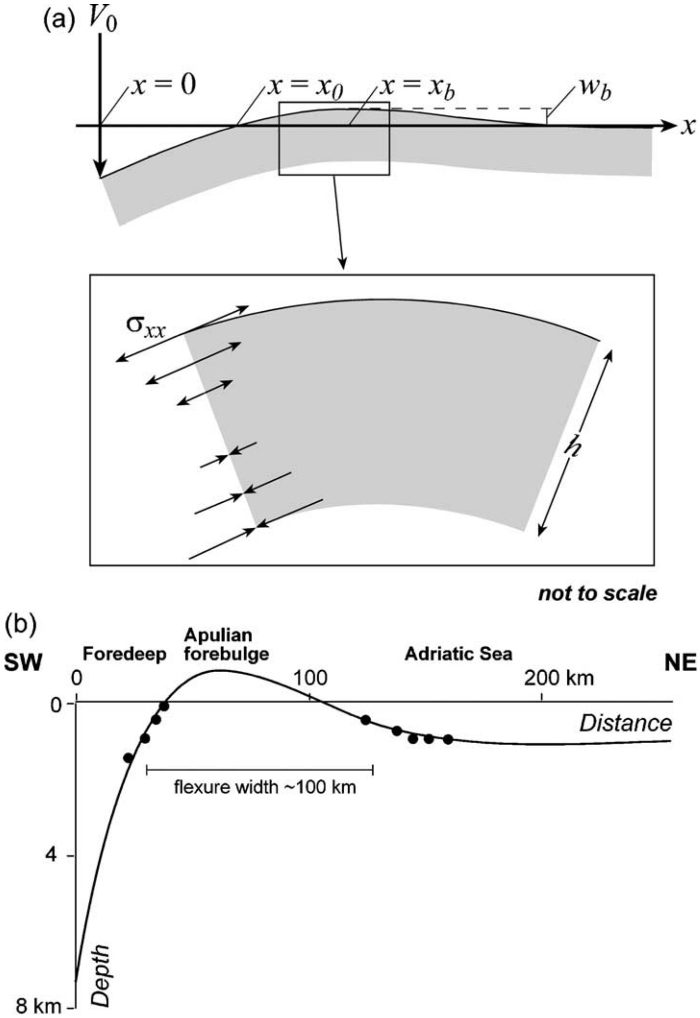

Fig. 6. (a) Cartoon showing the flexure of the lithosphere under a linear end load and the related internal distribution of the fibre stress (modified after Turcotte and Schubert, 1982). (b) Depth vs. distance data of the base of Pliocene sediments across the Adriatic foreland projected along the cross-section whose trace is shown in Fig. 1a. Data are fitted by the adopted equation of flexure (see text for further explanations). The resulting curve approximates the flexed Adriatic foreland plate under the Apennines thrust-fold belt.

the flexure ≈100 km (Fig. 6b). By using these parameters in solving Eqs. (2) and (3) for the fibre stress σ_{xx}, we obtain a fibre stress in the Apulian forebulge in excess of −100 Mpa. This value is far greater than a possible upper-bound estimate of −30 MPa (Paterson, 1978) for the tensile strength of carbonate rocks in standard boundary conditions (i.e. at the Earth's surface on the outer arc of the Apulian forebulge). This result supports the hypothesis that the flexure of the Adriatic plate during Pliocene-Quaternary times can have induced a flexure-related fibre stress in the Apulian forebulge able to drive the initiation of regional systematic jointing parallel to the flexure hinge (i.e. NW–SE).

5. Discussion

The computed flexure-related fibre stress in the Apulian forebulge shows that the Pliocene-Quaternary flexure of the Adriatic lithosphere is a plausible mechanism for explaining the initiation of the observed regional systematic joints striking parallel to the flexure hinge in the outer arc of the Apulian forebulge.

Joint spacing and aperture data indicate that the carbonate beds in the Apulian foreland are rather homogenously deformed. No significant changes are detected in the joint spacing and aperture across the forebulge region except for a slight increase of joint density and aperture towards the highest sector of the forebulge. The homogeneous deformation may be explained by the gentle tightness and the nearly circular concentric shape of the flexure, in which flexure-related fibre stresses suitable for extensional failure of carbonate rocks, may have occurred not only in the forebulge (i.e. hinge) point, where the tensile fibre stress reaches its maximum value, but also in the adjoining regions (i.e. flexure flanks). However, it should be noted that the above discussed model for the flexure of the Adriatic foreland and for the generation of the related fibre stress can explain only the initiation of extensional fracturing in the outer arc of the forebulge. Joint spacing and aperture data may be substantially independent from the flexure mechanism. A comparison between graphs of Fig. 4 (i.e. average joint spacing and aperture vs. bed thickness) and the graph of Fig. 5b (i.e. average joint spacing and aperture vs. transect distance) suggests that, across the Apulian forebulge, the control exerted by the bed thickness on the joint spacing and aperture is far more significant than the control possibly exerted on the same parameters by their location across the flexed foreland (i.e. hinge vs. flank regions). In addition, the occurrence of extensional faults closed to some of the investigated exposures may have biased the joint spacing and aperture data towards lower values of spacing and higher values of aperture (e.g. Peacock, 2001). For these reasons, any speculation over possible homogeneities or secular changes of deformations with the development and migration of the foreland flexure may be poorly suitable if based solely on the discussed joint spacing and aperture data.

Different flexural models from that used in this paper (i.e. the linear elastic model from Turcotte and Schubert, 1982) may better simulate bending of foreland lithosphere, especially in oceanic and cold continental lithosphere (e.g. Ranalli and Murphy, 1987; Ranalli, 1994). For instance, in the flexure of a viscoelastic plate (e.g. Schmalholz and Podladchikov, 1999, 2000), the amount of flexure-related fibre stress would be reduced as compared with that of a linearly elastic plate. However, even in a rheologically non-linear model of flexure, flexural-slip and/or flexural-flow folding should be reduced to the minimum in a 5.5 km thick succession of Mesozoic carbonate beds (i.e. such as that occurring in the Apulian forebulge) with deep stylolitic interdigitations along bedding surfaces, thus ensuring a tensile fibre stress during flexure far greater than the strength of rocks, at least in the outer arc of the forebulge.

Results from this paper put the question of whether the flexure-related fibre stress is a suitable explanation for regional systematic joints in other flexed foreland regions. Despite very ample flexure widths, the occurrence of stiff and thick sedimentary successions can ensure high values of the effective elastic thickness that, in turn, ensure tensile fibre stresses in the outer arc of the forebulge region far greater than the strength of rocks commonly occurring in foreland regions (e.g. strata of limestone, dolostone, chalk, sandstone or coal). On the contrary, the flexure-related fibre stress may be less efficient in sedimentary successions where soft rocks such as clays or marls alternate with stiff rocks. In such a flexing rock succession, flexural-slip and flexural-flow folding may easily occur, thus drastically reducing the effective elastic thickness of the plate and the flexure-related fibre stress. For these reasons, the proposed mechanism for the development of systematic joints in the Apulian forebulge should be verified in other flexed foreland regions. Should this mechanism be verified as occurring in several other orogenic systems, it would have important impacts on the study of fracture fabrics that develop in orogenic belts during folding and thrusting (e.g. Mitra and Yonkee, 1985; Cooper, 1992; Salvini and Storti, 2001). Deformation mechanisms such as layer parallel shortening and/or thrusting/folding of foreland sedimentary successions (e.g. Rogers, 1987; Mitra and Mount, 1998), commonly interpreted as temporally the first deformations occurring in the orogenic process, may on the contrary be secondary events with respect to the development of the flexure-related deformational fabrics such as that observed in the Apulian forebulge. The development of such pre-contractional fracture fabric would completely change the rheology of the deforming medium before its involvement in the orogenic deformational process (i.e. thrusting and folding), thus invalidating those predictive models of fold-thrust-related deformation that are based on the assumption of pristine undeformed multilayered media (e.g. Chester et al., 1991; Patton et al., 1995).

6. Conclusions

The structural and geodynamic analysis of the Pliocene-Quaternary flexure of the Apulian-Adriatic foreland in southern Apennines allows to conclude that:

1. The exposed Apulian forebulge is affected by regional systematic joints striking parallel to the flexure hinge.
2. Joint spacing and aperture are rather homogeneous across the Apulian forebulge. The average spacing of joints along bed scan-lines increases from 0.02 to 0.75 m for the relative bed thickness increasing from 0.05 to 1.2 m. The average aperture of joints along bed scan-lines increases from 0.002 to 0.06 m for the relative bed thickness increasing from 0.1 to 0.9 m.
3. Depth vs. distance data of the base of Pliocene sediments along a SW–NE cross-section through the Apulian forebulge are satisfactorily fitted by the function of the flexure of a thin elastic sheet subject to an end load.
4. The tensile fibre stress in the outer arc of the Apulian forebulge as computed from the equations of the flexure of the Adriatic foreland, results in excess of -100 MPa. This result confirms that the flexure of the Apulian foreland is a suitable process for explaining the initiation of regional systematic jointing parallel to the flexure hinge in carbonate strata of the forebulge region.

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