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How hard were the Jura mountains pushed?

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Key words: palaeopiezometry, calcite twinning, Jura mountains

ABSTRACT

The mechanical twinning of calcite is believed to record past differential stress values, but validating results in the context of past tectonic situations has been rarely attempted. Using assumptions of linear gradients of stress components with depth, a stress gradient based on twinning palaeopiezometry is derived for the Swiss Molasse Basin, the indenter region to the Jura fold and thrust belt. When integrated into a model of the retrodeformed Jura-Molasse system, allowing horizontal stress concentration and conservation along the original taper geometry, the stress profile proves consistent with the position of the Jura-Molasse (ftb-indenter) transition. The model demonstrates mechanically why the Plateau Molasse portion of the Molasse Basin remained relatively undeformed when transmitting tectonic forces applied to the Jura mountains.

Introduction

The dynamics of mountain belts present many challenges to geologists seeking to understand their evolution. Whilst studies from many regions have successfully constrained the amounts of and variation of finite shortening within mountain chains (e.g. Affolter & Gratier 2004; Lacombe 2007), the amount that a mountain belt was 'pushed' (i.e. the force or maximum force it was subjected to during its evolution) remains a more difficult question. Whilst present day differential stress levels in the earth's upper crust can be measured directly or inferred by many methods (Engelder 1993), states of stress over geologic time are not so easily determined, and results often have substantial uncertainties. Palaeostress magnitudes have been examined in foreland regions (Lacombe and Laurent, 1996; Craddock and der Pluijm, 1999) and also across continental interiors (van der Pluijm et al. 1997) leading to an observation of regional scale stress attenuation with distance away from orogenic belts. Studies of stress levels associated with fold-thrust development in foreland fold-thrust belts have been less common however (Lacombe 2001). One of the major problems associated with studying stresses within a fold-thrust belt is the heterogeneity of stresses due to the influence of faults cutting the upper crust. Variations of stress magnitudes and orientations over time can also lead to significant difficulties interpreting palaeostress indicators (Lacombe 2001, 2007).

As part of a wider examination of strain variation across the Tertiary western alpine foreland (Swiss Molasse Basin) (Hindle & Burkhard 1999) palaeostress magnitudes from several sites and depths have been measured (figure 1). The Swiss Molasse Basin was originally part of a wedge of Meso-Cenozoic material which thinned broadly northwest towards the european foreland, and was later shortened up to ~30 km by northwest directed thrusting above a regional detachment horizon in Triassic evaporites, forming the Jura fold-thrust belt (Burkhard & Sommaruga 1998; Affolter & Gratier 2004). Significant tectonic shortening in the Jura appears to have started post-Serravalian (~10 Ma) (Sommaruga 1999; Becker 2000) and ceased ~3–4 Ma (Becker 2000). GPS data suggest motions today are close to or below measurement errors (~1 mm/yr or less) (Walpersdorf et al. 2005), though Pliocene-Recent, possibly thick-skinned, ongoing deformation at sub-GPS detectable rates has now been suggested along the northernmost Jura border with the Rhine-Bresse transfer zone and Upper Rhine Graben (Ustaszewski & Schmid 2006, 2007). A cross section through the Jura-Molasse system (figure 2a) shows shortening is concentrated in the northwest, near the wedge toe (Jura fold-thrust belt), whilst the deeper-filled portion of the alpine foreland basin to the south-

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east (so-called Plateau Molasse region) was translated ~30 km northwest without undergoing major deformation (Burkhard 1990; Laubscher 1992; Sommaruga 1999; Burkhard & Sommaruga 1998; Affolter & Gratier 2004). The Plateau Molasse region is thus considered to have acted as a form of indenter to the Jura mountains (Burkhard 1990). Forces involved in deforming the Jura fold-thrust belt must have been transmitted through this indenter with little dissipation by frictional resistence of a very weak (shear strength ~1 MPa or less) basal detachment, from the western Alps. Hence, the palaeostress measurements presented here can potentially be interpreted in the geodynamic context of stress transmission into an evolving fold-thrust belt.

Palaeostress from calcite twinning and stress gradients

Palaeostress and strain analyses have been carried out in the relatively undeformed Plateau Molasse region of the Molasse Basin. Five samples from the Lower Miocene, marine littoral, lumachellic sandstone, Upper Marine Molasse (OMM) lying at the present day surface and one sample from a borehole (Schafisheim) from Triassic (Muschelkalk) limestones lying ~1300 metres below surface have been used.

Mechanical twins in calcite grains in naturally deformed rocks have been used as both a strain and differential stress gauge (Groshong 1972; Spang 1972; Jamison & Spang 1976; Rowe & Rutter 1990; Laurent et al. 1990; Lacombe & Laurent, 1992). The Groshong (1972) technique has been used in this study to find principal strain orientations from the relatively undeformed (kilometric scale open folding suggest ~1–2% shortening; Hindle & Burkhard 1999) Plateau Molasse region. Principal strain axes (figure 1) are found to lie close to horizontal (maximum shortening strain) and close to vertical (minimum shortening strain), with very low principal strain values (strain components ~0.1%). The very low deformation of the Plateau Molasse region and the generally high quality of twin data which have negative expected values (Groshong 1972) <20% indicate near co-axial deformation (Hindle & Burkhard 1999). Consequently, principal stress and strain axes are considered to have approximately the same orientations and thus, principal stresses are considered close to horizontal ($\sigma_H \approx \sigma_1$), and close to vertical ($\sigma_V \approx \sigma_3$).

Several methods of determining past differential stress levels from calcite twinning exist (Jamison & Spang 1976; Rowe & Rutter 1990; Laurent et al. 1990; Lacombe & Laurent, 1992). This study uses the Jamison & Spang (1976) (J&S) method, based on a theoretical relationship between percentages of calcite grains displaying 1, 2 or 3 active twinsets and the differential stress needed to make these reach a critical resolved shear stress (CRSS) in the direction of twinning assuming a large population of randomly oriented calcite crystals, and a value of 10 MPa for the CRSS. The magnitude of the CRSS has been quoted differently in several studies applying various methods to palaeostress analysis. (e.g. between 5 and 10 MPa; Lacombe

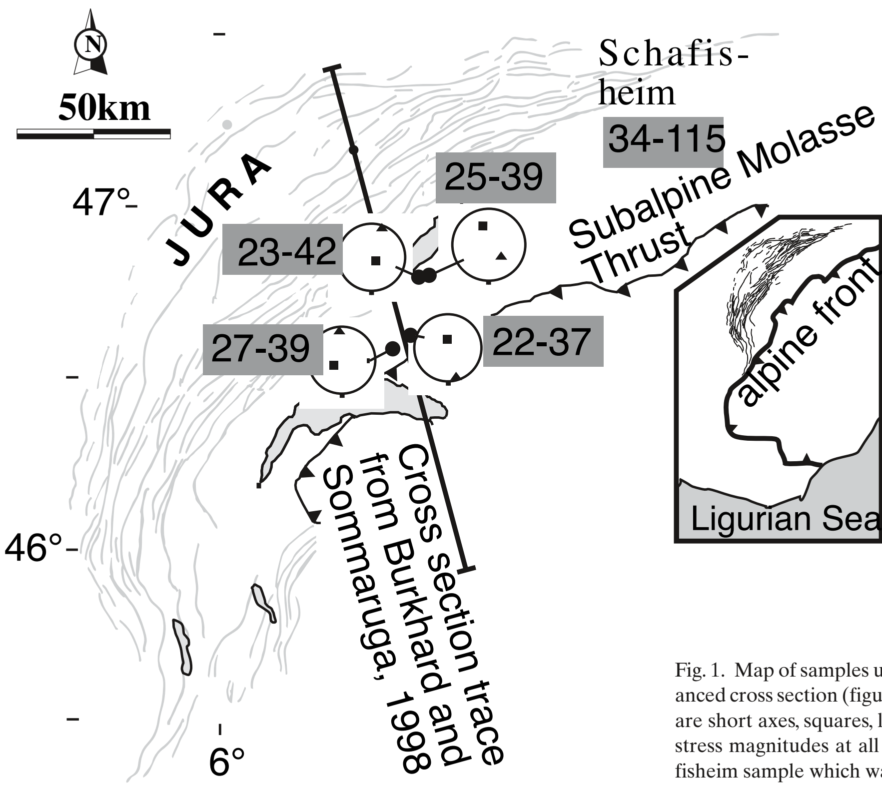

Fig. 1. Map of samples used for twin analyses, results of analyses, and trace of balanced cross section (figure 2a). Stereograms show strain axes from twins, triangles are short axes, squares, long. Numbers on grey background show the differential stress magnitudes at all sites. No axes orientations are available from the Schafisheim sample which was not oriented.

2001, 2007). The 10 MPa value used here is considered most appropriate when applying the J&S technique to low strain samples with near co-axial deformation such as those found in the Plateau Molasse. This is also in accordance with J&S's original experimental calibration of the technique at low temperature, and small, uniaxial strain (Jamison & Spang 1976).

OMM sediments lying at the surface today are estimated to have undergone ~2.3 km burial from vitrinite reflection data (Schegg et al. 1997). Overburden removal estimates for the region of the borehole sample (Kaelin et al. 1992), which lies ~1300 m below the OMM at present, are less certain, with porosity/decompaction calculations yielding values ~1.5–4 km. Regional geology suggests the lower values are more likely. This study uses 2 km as a value of overburden removal. The original depths of OMM (~2.3 km) and borehole (~3.3 km) samples are thus used to estimate the vertical stress component assuming $\sigma_3 \approx \sigma_V \approx \rho g z$. Timing of overburden removal is linked to evolution of the Jura mountains (Laubscher 1992), with exhumation and erosion starting as Jura shortening begins. Thus, in the initial stage of stress transmission across the Molasse Basin, we assume that maximum burial depths apply to the samples.

The differential stresses (σ_D) determined from OMM samples (figure 1) are very similar at all sites (average one twinset values ~25 MPa, average two twinset values ~40 MPa), whilst the deeper, borehole shows higher values (~34 MPa for one twinset, ~115 MPa for two). A 2 dimensional state of stress at the two sample depths has been estimated by adding differential stress from twin analysis to σ_V estimated from overburden to give the maximum principal stress. The states of stress corresponding to the lower stress values at the two depths are shown in figure 3b.

Many measurements of variations in contemporary principal stress magnitudes and orientations with depth in the earth's crust have been made, and approximately linear increases in stress components with depth in the upper ~10 km of the crust have been suggested (McGarr & Gay 1978; McGarr 1980). By assuming linear increase of stress components with depth, differential stress functions have been created based on the palaeostress values from the study (figure 3a). The minimum σ_D values at paleodepths 2.3 and 3.3 km are the only combination which give a σ_D curve that intercepts the surface with a positive value (~4 MPa). Applying the higher σ_D values gives large negative surface values under the assumption of a linear stress gradient. Present day stress measurements from the Jura Mountains and Plateau Molasse (Becker 1999, 2000) record surface σ_H values ~5 MPa. Hence, the uncertainties in stress profiles are shown only based on depth ranges (±0.5 km) applied to the lower set of σ_D values from the study, yielding surface stresses with a positive σ_H value, also in accorance with the compressive setting of the Jura-Molasse system.

Strength of the Jura-Molasse system

A theoretical upper limit on the strength of the upper crust was derived by Byerlee (1978) assuming the strength of the upper crust to be governed by friction, and giving a non-linear strength relationship with depth. Other rock strength criteria are based on Coulomb failure, the loading required to generate new fractures in a particular rock type, which is sample specific. Comparison of the palaeostress values from this study to these criteria (figure 3b) shows that stresses remain well below yield levels.

The point of transition from the Molasse to the Jura also marks a mechanical transition from Coulomb failure and shortening (Jura) to sliding without Coulomb failure (Plateau Molasse). The retro-deformed Jura-Molasse profile shows the restored position of the transition and hence the point of onset of Coulomb failure. Molnar & Lyon-Caen (1988) proposed that in systems with low shear stresses at the base, and relatively gentle

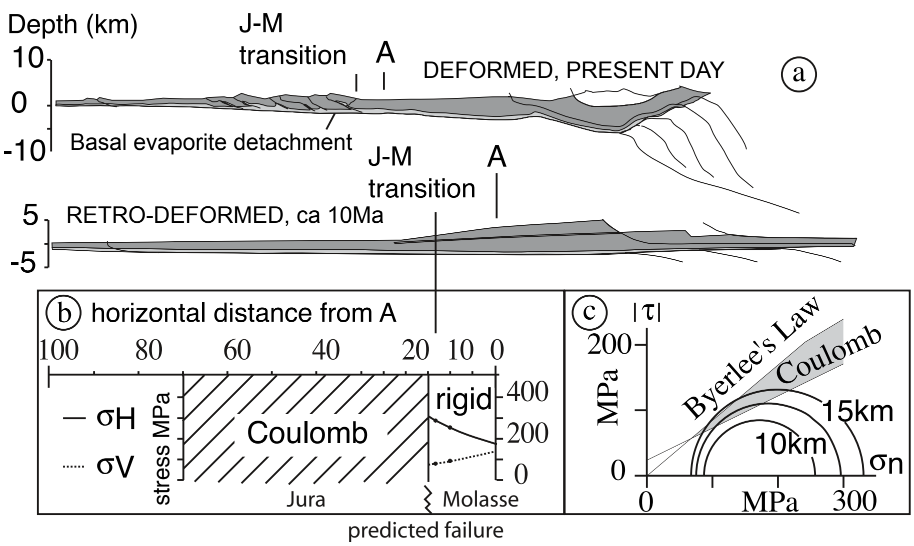

Fig. 2. a) Balanced and restored profile across the Jura and Molasse Basin (adapted from Burkhard and Sommaruga (1998)). A is the approximate position of the stress profiles shown in figure 3a. Jura-Molasse transition is shown in both the present day and restored configurations. b) horizontal and vertical stresses calculated by conserving the integral horizontal force at A derived from calcite twin palaeopiezometry. c) Mohr circles shown for 10, 13 and 15 km horizontal positions along the restored profile at $z = z_{max}$. Comparison is made to yield criteria from Byerlee's law and Coulomb failure.

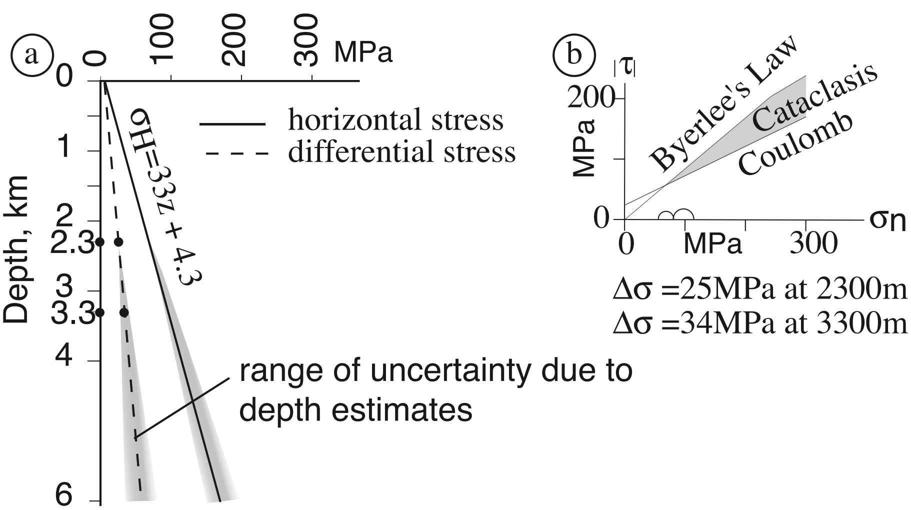

Fig. 3. a) Stress gradients from minimum differential stress values from J & S technique. Shaded area shows approximate uncertainties due to depth estimates b) Mohr circle plots of the states of stress from twin data from samples at estimated depths of 2.3 and 3.3. km respectively.

changes of topography, horizontal stress would be conserved over a vertical crustal profile, above that weak base.

$$\frac{\partial}{\partial x}\int_0^{z(x)}\sigma_H(x,z)dz \approx 0 \tag{1}$$

Though the model of Molnar & Lyon-Caen (1988) was for the entire crust, the Jura-Molasse system is a small scale analogue with low shear stresses at its base, lubricated by a weak décollement layer in Triassic salt (depth independent shear strength ~1 MPa (Davis & Engelder 1985)), and with a relatively gentle variation in topography from a maximum ~6.25 km of original Ceno-Mesozoic section in the southeast extremity of the Plateau Molasse to a minimum of ~1.2 km, ~130 km northwest in the proto-Jura mountains (figure 2a). Point A (figure 2a) is taken as the approximate average position at which the OMM samples used to constrain the stress-depth function (figure 3b) were located at the beginning of Jura shortening. A coordinate system is defined with $x = 0$ km = A (figure 2b). The horizontal stress (σ_H) depth function (equation 1 and figures 2b and 3b) at this point becomes,

$$\sigma_H \approx \sigma_{xx}(x_0, z) \approx 33z + 4.3 \tag{2}$$

Since total horizontal force must be conserved along the profile, at any point (x) we know from equations (1) and (2) that

$$\int_0^{z_{\max}(x)}\sigma_{xx}(x,z)dz \approx \int_0^{z_{\max}(x_0)} 33z + 4.3dz = F \tag{3}$$

where F is the integral horizontal force transmitted along the profile from point A with restored thickness of Ceno-Mesozoic material $z_{max}(x_o) \approx 5.25$ km. F is thus the horizontal force applied to the Jura-Molasse fold-thrust system derived from the palaeostress gradients estimated from calcite twin paleopiezometry. Assuming that the general form of the equation of horizontal stress variation with depth remains linear, and the constant term in equations (2) and (3) (surface horizontal stress) does not vary along the profile, approximations to the horizontal stress gradient at any point (x) are derived from equation (3).

$$\sigma_{xx}(x,z) = 2\left[\frac{F - 4.3z_{\max}(x)}{z_{\max}(x)^2}\right]z + 4.3 \tag{4}$$

At any point (x) on the profile, applying $z = z_{max}$ (the original Ceno-Mesozoic thickness) to equation (4) yields an estimate of horizontal stress and by factoring in the vertical stress gradient, the 2 dimensional state of stress, at the base of the wedge of material, above the Triassic décollement. The non-linear variation of wedge taper (figure 2b) is also modeled by including a thickness of 2.25 km at $x = 20$ km. The results are shown as a function of position (x) in figure 2b. The predicted stress states at various points along the profile are compared to Coulomb failure and frictional strength envelopes in figure 2c, indicating at what point along the restored geometry of the profile failure might be expected based on the palaeostress estimates from the Molasse basin and the model assumptions listed above. Thus, an estimate of the position of the Jura-Molasse transition can be derived. Predicted failure occurs at $\sim x = 13$ km. This point lies very close to the restored position of the present day Jura-Molasse transition. The remaining portion of the Jura to the northwest is considered to be a region of pervasive Coulomb failure. The integral force applied to the Jura (F) above the Triassic décollement, and apparently sufficient to cause their deformation, based on the palaeostress data, is 4.3×10^{11} N. Such a value specific to a thin-skinned fold-thrust belt and derived from palaeostress measurements is rarely given. Probably the most commonly calculated force in tectonics is ridge push which is considered to be $\sim 2 \times 10^{12}$ Nm^{-1} (Richter & McKenzie 1978).

Discussion

The integration of palaeostress data with a simple stress propagation model appears consistent with the position of the Jura-

Molasse transition which is the predicted point of onset of Coulomb failure, whilst the state of stress derived from samples in the Plateau region is well within the envelope of sliding without Coulomb failure as would be expected in a region that has not undergone pervasive faulting. The palaeostress measurements from the Plateau Molasse region can be interpreted as stresses in an oversteepened wedge, whose geometry was generated by the flexure of the Tertiary alpine foreland generating a short wavelength, high amplitude basin (Burkhard & Sommaruga 1998). The taper geometry of Tertiary overburden and the widespread, weak basal detachment provided by Triassic salt layers (Laubscher 1992; Affolter & Gratier, 2004) thus stabilizes the Plateau Molasse and the rapidly thinning taper of the Plateau Molasse causes a stress concentration, leading to an increase in horizontal and differential stresses in the direction of narrowing of taper at the base of the system. The weak base plays an important role by stopping stress dissipation along the length of the profile, and in the model, allowing for all the transmitted stress to concentrate along the narrowing taper.

Several assumptions are key to both the palaeostress studies and to the model of the Jura-Molasse system. The CRSS value of 10 MPa adopted in this study, a key parameter in deriving stress magnitude estimates, is a much discussed number (Newman 1994). Studies have suggested the CRSS varies, particularly as a function of grain size but also as a function of temperature and strain (Lacombe 2007). The samples from the alpine foreland used here have relatively even grainsizes (sparitic calcite ~200–400 μm) but contain patches of finer grained calcitic and micritic material. Strain values are very low in the Molasse Basin and it is believed the deformation of the region was approximately coaxial, both of which are similar to the experimental conditions used by J&S suggesting their experimentally determined 10 MPa CRSS value is probably appropriate for this study. Whether the 10 MPa represents a real physical constant related to shear stress on individual twin planes or is rather a bulk parameter correlating the effects of a number of processes generating twinning to the ambient differential stress a sample undergoes is not considered here. For studies in more complexly deformed regions (Lacombe 2007), more sensitive consideration of CRSS values are likely to be necessary.

The burial depth of the samples is important for deriving stress states from the differential stresses determined by palaeopiezometry. Burial depth of the Schafisheim sample is uncertain. The sample is also from a position ~100 km northeast of the OMM samples. However, the linear stress gradient models appear to confirm both the lower values of stress from the samples and the most likely burial depths as those giving the most physically realistic stress values. Twinning in all samples, including the borehole, is of type 1 or 2 (mostly type 1) (Burkhard 1993; Ferrill et al. 2004) except for clearly reworked grains from the Helvetic nappes, suggesting low temperature (<150 °C) deformation and hence burial likely < 5 km.

Conservation of stress in a 2D profile directed approximately parallel to the mean shortening direction of the Jura (Affolter & Gratier 2004) is also assumed in this study. Laubscher (1972) examined the plan view form of the Jura chain and suggested the crescent shape defined by significant changes in strike of fold axes, defined a set of divergent stress trajectories emanating from a rigid Molasse indenter pushing into the Jura. Such a model would lead to diminution of integral stress moving northwest along the profile through the Jura. The stress trajectories interestingly become most divergent at the southern and northern extremes of the chain and at the northwestern limit of the Jura. In the central Jura region where the profile for this study is located, the amount of stress divergence is also at a minimum, and thus, 3D effects on stress estimates would be minimal.

Lacombe (2001, 2007) suggested a suite of palaeopiezometry techniques can only give order of magnitude estimates of stress levels from most tectonics situations. However, Lacombe (2001) carried out a study in a polyphase deformation régime, from within a fold-thrust belt. The simplicity of the Jura-Molasse system and the fact that the Molasse region has behaved as a relatively rigid indenter allow the generation of a simple model into which palaeostress estimates can be integrated to provide a test of the results and possibly to constrain them further than would otherwise be the case.

Conclusions

The result of a simple model of stress propagation integrating palaeostress values from the Jamison & Spang (1976) technique seems to agree with the position of the Jura-Molasse transition, and the onset of thrusting in the system. In this model, stress propagation is assumed to have occurred by concentration along the thinning taper of a foreland sedimentary wedge, with no lateral (out-of-plane) stress dissipation. Although speculative, using mechanical models may be a way to assess the quality of palaeostress data, and to further constrain the normally substantial associated uncertainties. An absolute value of the linear force pushing the upper 5–8 kms of the alpine foreland lies, as expected, well below the most commonly calculated plate tectonic driving forces (ridge push) which should be distributed over most of the continental crust, though concentrated in the stronger upper crust and upper mantle.

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