Journal of Structural Geology 31 (2009) 749–751

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Folding with thermal–mechanical feedback: Discussion

Susan H. Treagus [a,*], Peter J. Hudleston [b]

[a] School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Rd, Manchester M13 9PL, England, United Kingdom
[b] Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455, USA

ARTICLE INFO

Article history:
Received 25 February 2009
Accepted 28 March 2009
Available online 15 April 2009

Keywords:
Folding
Thermal–mechanical feedback

ABSTRACT

A recent paper in this Journal by Bruce Hobbs, Klaus Regenauer-Lieb and Alison Ord [Hobbs, B., Regenauer-Lieb, K., Ord, A., 2008. Folding with thermal–mechanical feedback. Journal of Structural Geology 30, 1572–1592] presents an alternative theory to the traditional Biot-Ramberg theory for folding of viscous rocks that involves non-equilibrium thermodynamics and thermal–mechanical feedback. The authors convey a strong message throughout their paper that the folds produced by this theoretical and numerical modelling are geologically realistic and provide a better explanation for many natural folds than the traditional theory. They promise the same approach for boudinage, and present this folding paper as part of a "unified framework for rock deformation processes". Readers of the *Journal of Structural Geology* might be led to conclude that this paper provides a good alternative model for folding of rocks. Our discussion will disagree, on four counts.

1. Folding of a single layer

Hobbs et al. (2008) provide a comprehensive review of folding theory, but one that exclusively addresses folding of a *single layer* in a quasi-infinite matrix. They usefully examine differences according to the boundary conditions of constant force, constant velocity, constant strain rate and of both viscous and viscoelastic media: yet, extraordinarily, they pay no attention to justifying using a single layer folding model in support of their general argument. Their Discussion begins: "This paper has been concerned with the deformation of layered rocks …". This is not strictly true: all their theory, and most of their modelling, concern folding of one layer! Except for one small paragraph (Section 5.2) and two figures presenting finite element models of two and ten (eight?) layers, with little discussion, all the theory and modelling in Hobbs et al. (2008) concern a single layer in a semi-infinite matrix, even when the words "single layer" are not explicitly stated.

Hobbs et al. (2008) authoritatively claim (*Q1*): "*Natural folds are rarely, if ever, strictly periodic; that is, they are rarely characterised by a single dominant wavelength or a narrow distribution around a dominant wavelength. A clear example here is the ubiquitous existence in Nature of parasitic folds*" (p. 1578). These are bold statements, unsupported by any references, and they differ from our own observations in the field. These authors make several sweeping statements about folds in "Nature", and yet provide no justification for using single layer theory to model folding in the middle to lower crust. In the field, single layer folds of primary bedding are rare, especially on a large scale. Rocks are stratified and multilayered; accordingly, *folds* are usually multilayered. Where single layer folds do occur in nature, it is typically on a small scale, in thin rock layers or mineral or pegmatite veins (e.g. Ramsay and Huber, 1987, pp. 385–393; Price and Cosgrove, 1990, pp. 277–279); the quasi-periodic nature of folding is clearly revealed, countering *Q1* above. Furthermore, it is a red herring to include parasitic folds as a reason to question the periodic nature of single layer folding and the concept of a dominant wavelength, when there are logical explanations for parasitic folding applying established theory (Ramberg, 1964; Frehner and Schmalholz, 2006).

2. Wavelength–thickness values of geological folds

Hobbs et al. (2008) make another claim about folds in rocks, and one that appears to underpin their new approach to folding, and their criticism of the traditional Biot-Ramberg model. Calling this quotation (p. 1575) *Q2*: "*One should note that typical values of λ/h [wavelength/thickness] for real rocks are in a narrow range of 2–7* (see Sherwin and Chapple, 1968; Smith, 1979; Price and Cosgrove, 1990; Johnson and Fletcher, 1994; Patton and Watkinson, 2005, for reviews)." Ignoring the apparent inconsistency with *Q1*, above, nor quibbling that their quoted range and Eq. (1) omitted to qualify that they refer to *single layer folds*, we will simply argue the facts. The five citations listed as reviews do not contain a wealth of

* Corresponding author. Tel.: +44 161275 3822
E-mail addresses: susan.h.treagus@manchester.ac.uk (S.H. Treagus), hudle001@umn.edu (P.J. Hudleston).

0191-8141/$ – see front matter Crown Copyright © 2009 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2009.03.015

different datasets from which the summary range of $\lambda/h = 2$–7 could be deduced. Furthermore, none of these publications quotes this exact range, either as a range of mean values from different examples, or as the range of all λ/h measurements within one dataset. So where has this narrow 2–7 range come from, especially the lower value of 2?

The only reference among the five cited in *Q2* that gives *primary measurements* of wavelength–thickness ratios, strictly arclength/thickness, is the seminal Sherwin and Chapple (1968) study. Their data reveal mean λ/h values of 4.0–6.8, not 2–7. Most of the Sherwin and Chapple folds are in quartz veins, 1 mm–1 cm thick, in slate or phyllite matrix; but similar mean values are found for carbonaceous siltstone layers in slate, and for greenish quartzite in phyllite, where the layers are thicker ($\sim$5–16 cm). Let us now examine published measurements of arclength–thickness of folds that were *not* cited by Hobbs et al. (2008), to provide a more representative survey of folds in rocks.

Shimamoto and Hara (1976, Figs. 9–12) present four histograms of arclength–thickness measurements for folded quartz veins in mafic schist, psammitic schist and pelitic schist, with mode values of 5.5, 8 or 8.5 and 14.5, respectively. The slightly larger mean values are $\sim$7, 10 or 12, and 15, respectively. This 7–15 range is far from the narrow 2–7 range stated by Hobbs et al. One reason why the mean values of Shimamoto and Hara are higher than those of Sherwin and Chapple (4.0–6.8), when the datasets appear to be lithologically similar (quartz veins in slate, phyllite or schist matrix), could relate to their higher metamorphic grade and increased rheological contrasts.

In addition to these two major studies, there are other recordings of arclength–thickness ratios in natural folds that we can use to test the validity of the "typical" 2–7 range claimed by Hobbs et al. Hudleston (1986, Fig. 7) provides arclength–thickness measurements for 233 folds of calcite veins and limestone beds in slate matrix. His values range from 2 to 16, with mean and mode slightly above 7. Ramsay and Huber (1987, Fig. 19.3) illustrate a fold train in a mm-scale quartz–feldspar pegmatite vein in a biotite-rich granite host, which forms their Question 19.2, to measure wavelength–thickness relationships. The rocks here are quite different from all the previous examples, so make an interesting comparison. Answer 19.2 (Ramsay and Huber, 1987, p. 390–391) shows 35 fold measurements (half wavelengths) that give a mean wavelength (arclength)–thickness value of 9.2.

The conclusion from this discussion is that *mean* arclength–thickness ratios for recorded single layer folds "in Nature" occupy a range from 4 to 15 for quartz veins in different host rocks, $\sim$7 for calcite or limestone in slate, and $\sim$9 for a pegmatite vein in granite. The range of 2–7 quoted by Hobbs et al. does not emerge as representative, either from the five citations they give (*Q2*), or from this more comprehensive look at recorded measurements of natural single layer folds. It is possible that the authors are confusing discussions of values for *real* folds with processes discussed in *theory*, such as: (a) Smith's (1979) 'resonance folding' in layers with strongly non-linear rheology, with dominant wavelength–thickness ratio of 4; or (b) Patton and Watkinson (2005), who refer to a range of 2.8–5.4 where they are addressing folding in the lithosphere.

We remain bemused by the lower value of 2, in the range of $\lambda/h = 2$–7 stated by Hobbs et al. We can find no evidence of single layer folds with representative arclength–thickness ratios of 2 from any published studies of folded rocks, nor from any of our own field observations. However, Hobbs et al. (2008, p. 1584 and Fig. 5) do have an explanation for $\lambda/h = 2$, in their thermal–mechanical model: that this value occurs because folds are localised where shear zones, crossing layers at 45°, intersect top and bottom boundaries. The important point of conclusion, here, is that we know of no published evidence for such low values in natural single layer folds in "real rocks".

3. Adequacy of existing theory

Hobbs et al. (2008) give several reasons for questioning the adequacy of traditional (e.g. Biot, 1961; Ramberg, 1963; Sherwin and Chapple, 1968; Fletcher, 1974; Smith, 1977, 1979) folding theory. They claim that growth rates according to this theory are too small to account for folds with what they state are typical values (2–7) of λ/h, and they claim that fold profiles are less regular than this theory predicts. We believe both criticisms are unfounded.

As already noted, typical or mean values of λ/h are in the range 4–15 rather than 2–7. They can readily be explained by traditional theory, which accounts for folds with low values of λ/h and at low viscosity contrasts developing as a result of: 1) reduction with shortening of the preferred wavelength (λ_P/h) from the Biot dominant wavelength (λ_B/h) (Sherwin and Chapple, 1968); and 2) sufficient amplifications at low values of λ/h for low viscosity contrasts if the layers follow non-linear flow laws (Fletcher, 1974; Smith, 1977). As an example, folds with $\lambda_P/h = 7$ can be produced in a layer following a power law with $n = 3$ and with a viscosity ratio of about 10 (see Fletcher, 1974, Fig. 5). This involves an amplification of 40 and a layer shortening of about 20% to bring the folds from their initial state to limb dips of about 15°, at which stage the linear theory of fold initiation ceases to apply and other processes take over as the folds grow to large amplitude (Sherwin and Chapple, 1968; Hudleston, 1973; Fletcher, 1974; Schmalholz and Podladchikov, 2000; Schmalholz, 2006). All of the above values seem to us realistic.

On the questions of the regularity of fold profiles, Hobbs et al. (2008) make statements about traditional theory that are at best misleading. They state that according to Biot's theory, (*Q3A*) "*one wavelength of perturbation, λ_B, given by equation (1) below, grows preferentially and at an exponential rate; all other perturbations grow relatively slowly. This system is unstable with respect to perturbations of wavelength, λ_B, and the instability exists from the instant the deformation begins*" (p. 1574). Two paragraphs further on they say, (*Q3B*), "*The common result of all such treatments, if the layer or the embedding materials are elastic, linearly viscous or power law viscous, is that just one particular wavelength (the dominant wavelength) is amplified.*" One might deduce from these statements that the instability only exists for perturbations of wavelength, λ_B, when in fact for viscous media (although not elastic) there is instability for all wavelengths, and all grow at an exponential rate. It is just that the dominant wavelength, λ_B, initially grows fastest. There exists, for each set of rheological conditions and given amount of layer shortening, an amplification spectrum, as shown by Sherwin and Chapple (1968) and Fletcher (1974). Because of this, one would expect a fold train to emerge with a profile that results from the superimposition of the amplification spectrum upon a spectrum of initial layer interface irregularities. Fletcher and Sherwin (1978) and Mancktelow (1999), among others, have explored the relationship between amplification spectra and the spectra of observed finite fold wavelengths. The point is, traditional theory would lead one to expect natural folds to show a spectrum of λ/h (or arclength/h) with a spread of values and a fairly well-defined maximum, as is observed in nature (Sherwin and Chapple, 1968, Fig. 2; Hudleston, 1986, Fig. 7). This is also true for analogue models (Hudleston, 1973) and numerical simulations (Mancktelow, 1999; Schmalholz, 2006).

4. How geologically realistic are these models of folds?

The single layer model of Hobbs et al. (2008), termed intermediate scale, represents a 13.2 × 3 km block of rock, comprising a quartz rock matrix that contains a central 300 m thick feldspar layer. The scale of this example, and the two 'rocks' chosen for the layer and matrix, bear no resemblance to any natural single layer folds described in the studies cited above. Where on Earth might one find an enormous single layer fold of a feldpathic layer within a vast quartz matrix? Even if the question of scale is disregarded, it is not explained why the authors chose feldspar for the rheology of the single layer, when all the geological evidence for single layer folding in rocks, including studies cited by Hobbs et al., suggest that quartz is a more likely analogue for a folding layer, than for its matrix. Hobbs et al. also state that their thermal–mechanical coupling folds have wavelengths ranging from 100 s to 1000 s of metres, which is clearly a different scale from most examples of single layer folds "in Nature", as discussed in the preceding sections.

Nevertheless, in their Discussion, Hobbs et al. claim (*Q4A*): "*We have shown that a large range of realistic structures arises through thermal mechanical coupling.*" They elaborate that their folding process is different from the Biot buckling process, their folds being the result of localised shear zones and thermal softening. In the Conclusions, they state (*Q4B*): "*The intersection of these shear zones with layers produces localised areas of weakening that represent embryonic hinges that then buckle. The structures are realistic in that folds develop at a number of wavelengths, are of Type 1A or Type 3 at high strains and have axial plane structures well developed*." These two statements clearly imply that the authors think their structures are geologically realistic, and yet they are totally unsupported by any geological evidence or examples. It is unclear why class 1A or class 3 fold geometry (Ramsay 1967, p. 365) is considered relevant, since most natural single layer folds are approximately class 1B; classes 1A and 3 are indicative of folding in incompetent layers surrounding buckling layers (e.g. Hudleston, 1986, Fig. 8A). No information or examples are presented to prove the assertions in *Q3*.

The coupling of thermal and mechanical processes in nature is certainly important, and it is encouraging to see Hobbs et al. exploring the implications of models of such behaviour for folding. Their thermal–mechanical model produces fold-like structures, and may have applications to the deformation of some materials, under certain conditions; but they have not demonstrated that their model produces realistic structures in crustal rocks under realistic conditions. The folds illustrated by Hobbs et al. (2008) do not resemble the countless folds, in single layers or multilayers, in sedimentary or metamorphic rocks, that we have observed in the field or seen illustrated in this Journal. Many folds in naturally deformed rocks are regular and quasi-periodic; they are well modelled by Biot-Ramberg sinusoidal buckling theories and their refinements, by a wide range of analogue model materials, and by a range of numerical or finite element models; all without need for coupled thermal–mechanical feedback.

References

Biot, M.A., 1961. Theory of folding of stratified viscoelastic media and its implications in tectonics and orogenesis. Geological Society of America Bulletin 72, 1595–1620.

Fletcher, R.C., Sherwin, J., 1978. Arc lengths of single layer folds; a discussion of the comparison between theory and observation. American Journal of Science 278, 1085–1098.

Fletcher, R.C., 1974. Wavelength selection in the folding of a single layer with power-law.

Frehner, M., Schmalholz, S.M., 2006. Numerical simulations of parasitic folding in multilayers. Journal of Structural Geology 28, 1647–1657.

Hobbs, B., Regenauer-Lieb, K., Ord, A., 2008. Folding with thermal–mechanical feedback. Journal of Structural Geology 30, 1572–1592.

Hudleston, P.J., 1973. An analysis of "single-layer" folds developed experimentally in viscous media. Tectonophysics 16, 189–214.

Hudleston, P.J., 1986. Extracting information from folds in rocks. Journal of Geological Education 34, 237–245.

Johnson, A.M., Fletcher, R.C., 1994. Folding of Viscous Layers. Columbia University Press, New York.

Mancktelow, N.S., 1999. Finite-element modelling of single-layer folding in elasto-viscous materials; the effect of initial perturbation geometry. Journal of Structural Geology 21, 161–177.

Patton, R.L., Watkinson, A.J., 2005. A viscoelastic strain energy principle expressed in fold-thrust belts and other compressional regimes. Journal of Structural Geology 27, 1143–1154.

Price, N.J., Cosgrove, J.W., 1990. Analysis of Geological Structures. Cambridge University Press, Great Britain.

Ramberg, H., 1963. Fluid dynamics of viscous buckling applicable to folding of layered rocks. Bulletin of the American Association of Petroleum Geologists 47, 484–505.

Ramberg, H., 1964. Selective buckling of composite layers with contrasted rheological properties, a theory for the simultaneous formation of several orders of folds. Tectonophysics 1, 307–341.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw Hill.

Ramsay, J.G., Huber, M.I., 1987. Modern Structural Geology. In: Folds and Fractures, vol. 2. Academic Press.

Schmalholz, S.M., 2006. Scaled amplification equation: a key to the folding history of buckled viscous single-layers. Tectonophysics 419, 41–53.

Schmalholz, S.M., Podladchikov, Y.Y., 2000. Finite amplitude folding; transition from exponential to layer length controlled growth. Earth and Planetary Science Letters 179, 363–377.

Sherwin, J.A., Chapple, W.M., 1968. Wavelengths of single layer folds: a comparison between theory and observation. American Journal of Science 266, 167–179.

Shimamoto, T., Hara, I., 1976. Geometry and strain of single-layer folds. Tectonophysics 30, 1–34.

Smith, R.B., 1977. Formation of folds, boudinage, and mullions in non-Newtonian materials. Geological Society of America Bulletin 88, 312–320. Biot, M.A., 1961.

Smith, R.B., 1979. The folding of a strongly non-Newtonian layer. American Journal of Science 279, 272–287.