Pergamon

Journal of Structural Geology, Vol. 17, No. 12, pp. 1793 to 1795, 1995

0191–8141/95 $9.50+0.00

0191–8141(95)00079–8

Practical stress analysis using piedmontite microboudinage structures

TOSHIAKI MASUDA,* TOMOKI SHIBUTANI† and HARUKA YAMAGUCHI

Institute of Geosciences, Shizuoka University, Shizuoka 422, Japan

(*Received* 21 *September* 1994; *accepted in revised form* 4 *July* 1995)

Abstract—This paper proposes a practical method for inferring the relative magnitude of differential stress during plastic deformation using piedmontite microboundinage structures in quartz schists. The method only deals with the proportion (p) of broken grains of piedmontite, and demonstrates that an increase in p value is roughly indicative of a larger differential stress. If the number of measured grains exceeds 100, the confidence interval of the p value becomes less than 0.1, providing a first approximation of the relative magnitude of the differential stress.

INTRODUCTION

Boudinage is a very important deformation mechanism for structural geologists, because it provides information on stress and strain (e.g. Ramberg 1955, Ramsay 1967, Hossain 1971, Beach, 1979, Ferguson 1981, Ferguson & Lloyd 1982, 1984, Lloyd *et al.* 1982, Lloyd & Ferguson 1989). Here we focus on the stress analysis method developed by Masuda *et al.* (1989), which modifies that presented by Lloyd *et al.* (1982) and Ferguson & Lloyd (1982). It suggests a method for inferring the relative magnitude of differential stress using piedmontite microboudinage structures. The method is based on two assumptions: (i) piedmontite grains possess elastic, welded contacts with the quartz matrix, and (ii) the number of imperfections in the grains is proportional to the aspect ratio. The method can be applied to non-steady state flow, and has been extended to infer the relative magnitude of differential stress with increasing strain (stress–strain curve) during microboudinage (Masuda *et al.* 1990, in press).

The analysis by Masuda *et al.* (1989, 1990, in press), however, is time consuming because it requires intensive measurement of the length and width of several hundred piedmontite grains to obtain reliable readings plus complicated data processing. Hence, their method may not be suitable for analysing numerous samples from many areas in a short period of time. This paper proposes a less quantitative but much more practical method that uses microboudinage structures to compare the magnitude of differential stress during plastic deformation.

BRIEF DESCRIPTION OF MICROBOUDINAGE STRUCTURE IN QUARTZ SCHISTS

Piedmontite-bearing quartz schists occur in the high P/T metamorphic belts in Japan (Kamuikotan, Yamagami, Sambagawa and Nagasaki; for the detailed geological setting and observations of these schists, see Masuda *et al.* 1989, 1990). These schists are highly foliated and lineated. The foliation is usually defined by parallel alignment of flaky minerals such as muscovite and biotite, and the lineation is defined by parallel alignment of needle-like minerals such as epidote (piedmontite) and amphibole. The samples mostly consist of quartz with subordinate piedmontite, epidote, amphibole, muscovite, biotite, chlorite, apatite, calcite and opaque minerals.

Observations have been made under the optical microscope on thin sections cut perpendicular to the foliation and parallel to the lineation. Piedmontite grains, enclosed within the quartz matrix, are more or less columnar, with both ends tapered. Their width is usually less than 0.1 mm, and their length less than 0.3 mm. The proportion of microboudinaged grains differs from sample to sample. The fracture planes of the microboudins develop almost perpendicularly to the lineation, and the separation either approximately or precisely follows the lineation. Piedmontite grains show various stages of microboudinage; some grains are unbroken, some have just started to separate into two microboudins, and some are widely separated. Many broken grains have separated into two or three microboudins, and a few have split into between six and nine. Inter-boudin gaps are occupied mainly by quartz.

A NEW PRACTICAL METHOD

The method proposed here only requires determination of the proportion of broken to total piedmontite

---

*Present address: Department of Earth Sciences, James Cook University of North Queensland, Townsville, Q.4811, Australia.

†Present address: Power Reactor & Nuclear Fuel Development Corporation, Tokai-mura, Ibaraki 319-11, Japan.

grains. We count the number of broken grains (f) and the number of total (broken plus intact) grains (n). The proportion, here denoted as p, is simply defined by f/n. When counting, we do not consider the grain size or aspect ratio of piedmontite grains. We also ignore the stage of microboudinage. Hence, even when a grain is separated into several microboudins, we regarded the grain as 'one' broken grain.

RELIABILITY OF THE p VALUE

Figure 1 shows the stability of p with increasing n. The p value becomes stable with increasing n when n exceeds 50. The true proportion of broken grains (μ) is estimated with a confidence interval

$$\left(t\sqrt{\frac{f/n(1-f/n)}{n}}\right)$$

as:

$$f/n - t\sqrt{\frac{f/n(1-f/n)}{n}} < \mu < f/n + t\sqrt{\frac{f/n(1-f/n)}{n}}$$

where t is Student's t, which is related to the size of the critical region and degree of freedom $n - 1$ (e.g. Cheeney 1983). If we take the critical region as 0.05, and $n > 100$ for each sample, the confidence interval of our data is less than 0.1.

EVALUATION OF THE p VALUE AS A DIFFERENTIAL-STRESS GAUGE

To evaluate p, it first must be calibrated. For this purpose, the p values were correlated with B values (Fig. 2), where B is a dimensionless parameter linearly related to the differential stress; i.e. $B = (E_f/E_m)(S_{bulk}/S^*)$, where E_f is the Young's modulus of the boudins (piedmontite), E_m is Young's modulus of the matrix (quartz), S_{bulk} is the external differential stress imposed on the sample, and S^* is the average fracture strength of a piedmontite grain with an aspect ratio of 1 (Masuda *et al.* 1989). We currently cannot estimate quantitatively the magnitude of differential stress from B, because E_f and S^* are not known for piedmontite. Thus, B is only regarded as a relative indicator of differential stress. However, Fig. 2 demonstrates that p is systematically related to B and therefore to the differential stress. Some uncertainty occurs at low p values where the relationship becomes non-linear. This figure strongly suggests that a large p value is the result of a large differential stress.

CONCLUDING REMARKS

The present method is simple and needs at most one hour to obtain a reliable p value, whereas it takes at least one week to obtain a reliable B value for each sample. Hence, if one wants to quickly get a rough estimate of relative differential stress, this method is very useful.

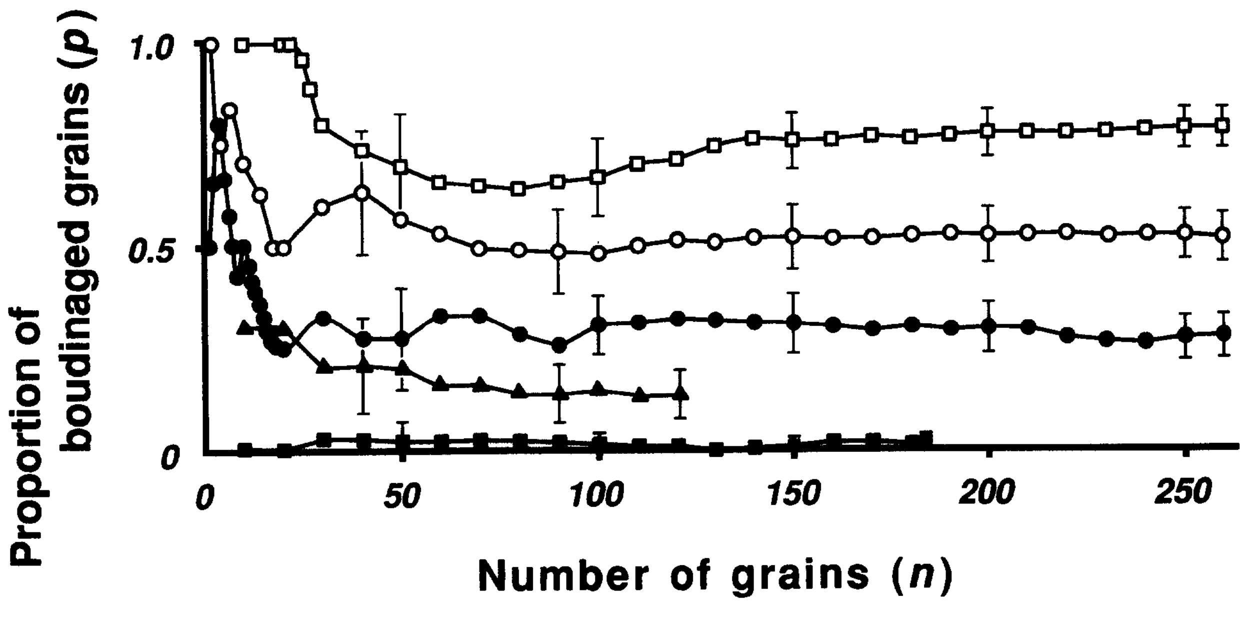

Fig. 1. Reliability of proportion of boudinaged grains (the p value) for 5 samples. These samples come from the Kamuikotan metamorphic belt (Nuporomaporo, open square), and the Sambagawa metamorphic belt (Wakayama, open circle; central Shikoku, solid circle, solid triangle and solid square). The error bars represent the confidence interval. The measured proportion of boudinaged grains becomes stable and the confidence interval becomes less than ±0.1 when the measured number of grains exceeds 100.

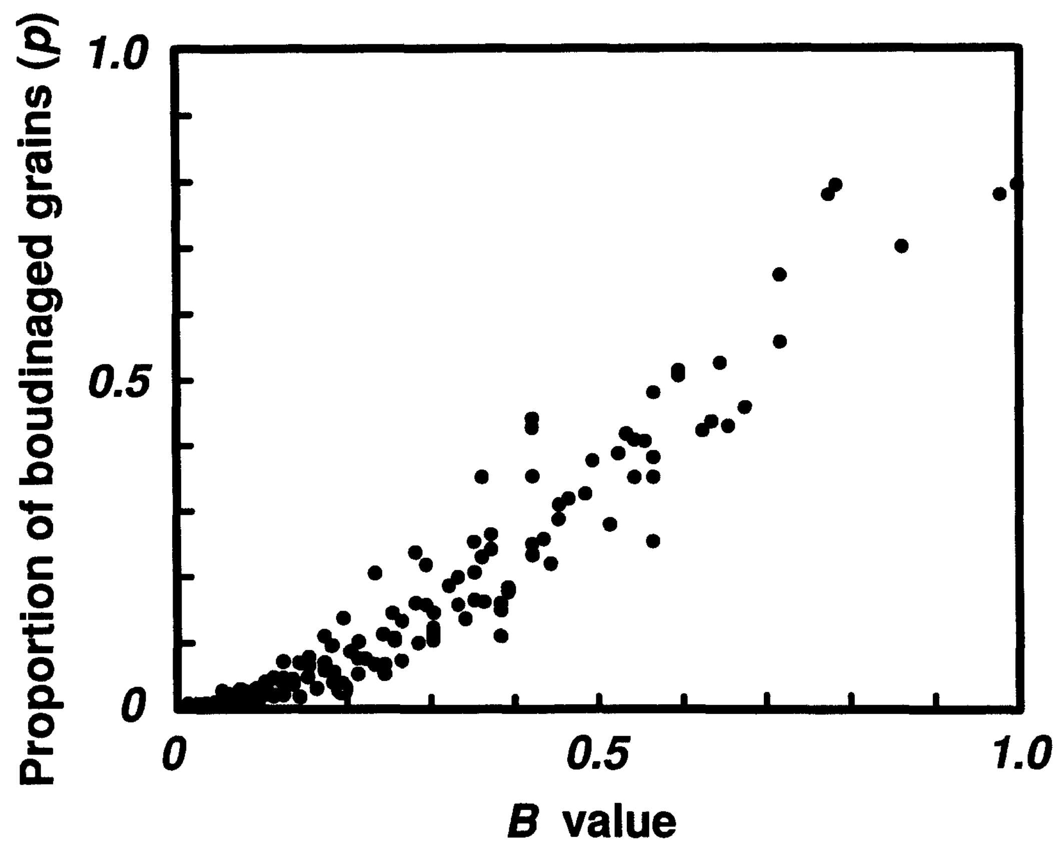

Fig. 2. Relationship between proportion of boudinaged grains (the p value) and the B value. These data come from samples described in Masuda *et al.* (1989, 1990). The p values are positively related to the B values. For definition of the B value, see text.

Acknowledgements—Final revision of the manuscript was done in the James Cook University of North Queensland. We thank Tim Bell for correcting the English and for constructive comments. We also thank Geoff Lloyd for giving helpful and encouraging comments, R. J. Lisle for constructive editing and Robert Twiss and Katzu Michibayashi for critically reading an early version of the manuscript.

REFERENCES

Beach, A. 1979. The analysis of deformed belemnites. *J. Struct. Geol.* **1**, 127–135.

Cheeney, R. F. 1983. *Statistical Methods in Geology*. George Allen & Unwin, London.

Ferguson, C. C. 1981. A strain reversal method for estimating extension from fragmented rigid inclusions. *Tectonophysics* **79**, T43–T52.

Ferguson C. C. & Lloyd, G. E. 1982. Paleostress and strain estimates from boudinage structure and their bearing on the evolution of a major Variscan fold-thrust complex in southwest England. *Tectonophysics* **88**, 268–289.

Ferguson, C. C. & Lloyd, G. E. 1984. Extension analysis of stretched belemnites: a comparison of methods. *Tectonophysics* **101**, 199–206.

Hossain, K. M. 1979. Determination of strain from stretched belemnites. *Tectonophysics* **60**, 279–288.

Lloyd, G. E. & Ferguson, C. C. 1989. Belemnites, strain analysis and regional tectonics: a critical appraisal. *Tectonophysics* **168**, 239–253.

Lloyd, G. E., Ferguson, C. C. & Reading, K. 1982. A stress-transfer model for development of extension fracture boudinage. *J. Struct. Geol.* **4**, 355–372.

Masuda, T., Shibutani, T., Igarashi, T. & Kuriyama, M. 1989. Microboudin structure of piedmontite in quartz schists: a proposal for a new indicator of relative palaeodifferential stress. *Tectonophysics* **163**, 169–180.

Masuda, T., Shibutani, T., Kuriyama, M. & Igarashi, T. 1990. Development of microboudinage: an estimate of changing differential stress with increasing strain. *Tectonophysics* **178**, 379–387.

Masuda, T., Shibutani, T. & Yamaguchi, H. In press. Comparative rheological behaviour of albite and quartz in siliceous schist revealed by the microboudinage structure. *J. Struct. Geol.*

Ramberg, H. 1955. Natural and experimental boudinage and pinch and swell structures. *J. Geol.* **63**, 512–526.

Ramsay, J. G. 1967. *Folding and Fracturing of Rocks*. McGraw-Hill, New York.