PERGAMON

Journal of Structural Geology 26 (2004) 203–206

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Validity of the microboudin method for palaeo-stress analysis: application to extraordinarily long sodic amphibole grains in a metachert from Aksu, China

Toshiaki Masuda[a,*], Nozomi Kimura[a], Bihong Fu[a], Xiangdong Li[b]

[a]*Institute of Geosciences, Shizuoka University, Shizuoka 422-8529, Japan*
[b]*Xinjiang Institute of Geology, Urumqi 830000, China*

Received 31 March 2003; received in revised form 15 July 2003; accepted 25 July 2003

Abstract

This paper deals with microboudin structures of sodic amphibole in a metachert collected from the Aksu terrane, Xinjiang, China. The pre-boudinage sodic amphibole grains of the metachert have large aspect ratios of up to 100, providing a rare opportunity to test the validity of the microboudin method for palaeo-stress analysis. The test was performed by comparing the measured proportions of boudinaged grains at aspect ratios of 2–25 with the theoretically predicted proportions, and the comparison was statistically revealed to be excellent. This result further supports the reliability of the microboudin method.

Keywords: Microboudin; Palaeo-stress; Sodic amphibole; Metachert; Aksu

1. Introduction

Progress in modern structural geology can be largely attributed to the quantification of two parameters of plastic deformation: stress that affected the rocks, and the strain to which the rocks were subjected. Many methods have been established for estimating strain, whereas only a few methods have been attempted for estimating differential stress (e.g. Ramsay and Huber, 1983; Passchier and Trouw, 1996). Stress analysis is far behind strain analysis, and thus the invention of reliable methods for stress estimation will form an important part of further progress.

Recently, Masuda et al. (2003) refined the microboudin method for the palaeo-stress analysis of metamorphic tectonites. Design of the microboudin method (Masuda et al., 1989, 1990) was motivated by a series of studies by Ferguson and Lloyd (e.g. Ferguson, 1981; Lloyd et al., 1982), and the capacity for further refinement was suggested by the studies of Ji and coworkers (e.g. Zhao and Ji, 1997). The microboudin method involves measurement of the proportion of boudinaged columnar mineral grains with respect to the aspect ratio and theoretical prediction of the proportion as a function of a stress parameter. The stress parameter for each sample is determined by the least-square difference between the measured data and the theoretical prediction, and gives the relative magnitude of the far-field differential stress.

In this study, the microboudin method of Masuda et al. (2003) was applied to sodic amphibole grains within a metachert collected from Aksu, China. The sample is highly unusual in that the sodic amphibole grains have aspect ratios of up to 100, about four times greater than all other samples analysed by the microboudin method to date. Thus, as the fundamental data for the microboudin method is the proportion of boudinaged grains with respect to the aspect ratio, the advantage of this sample is that it provides plentiful measurement data for comparison with the theoretical prediction. This sample is therefore not only suitable for obtaining a stress parameter by this method, but also provides a rare opportunity to test the validity of the microboudin method itself. The aim of this paper is to further evidence the reliability of this method by statistical analysis.

* Corresponding author. Tel.: +81-54-238-4794; fax: +81-54-238-0491.
E-mail address: setmasu@ipc.shizuoka.ac.jp (T. Masuda).

0191-8141/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2003.07.001

2. Sample

The Aksu blueschist terrane is situated between the Tienshan range and the Tarim Basin (41.1N, 80.3E). The metamorphic age of the Aksu has been dated at 700 Ma by Rb–Sr and K–Ar methods (Nakajima et al., 1990), and is consistent with stratigraphic evidence (Liou et al., 1989, 1996). The Aksu terrane is divided into two metamorphic zones based on mineral assemblages: a winchite zone and a Na–amphibole zone. The present sample was taken from the Na–amphibole zone. The approximate temperature and pressure conditions for the sample are 450 °C and 1 GPa (Liou et al., 1996).

The sample exhibits well-developed foliation defined by parallel alignment of muscovite and thin banding of various colours, as well as an obvious mineral lineation defined by parallel alignment of columnar sodic amphibole grains on the foliation surface. The concentration parameter of the lineation, κ (Masuda et al., 1999), is 2.7. No folding is apparent in the sample.

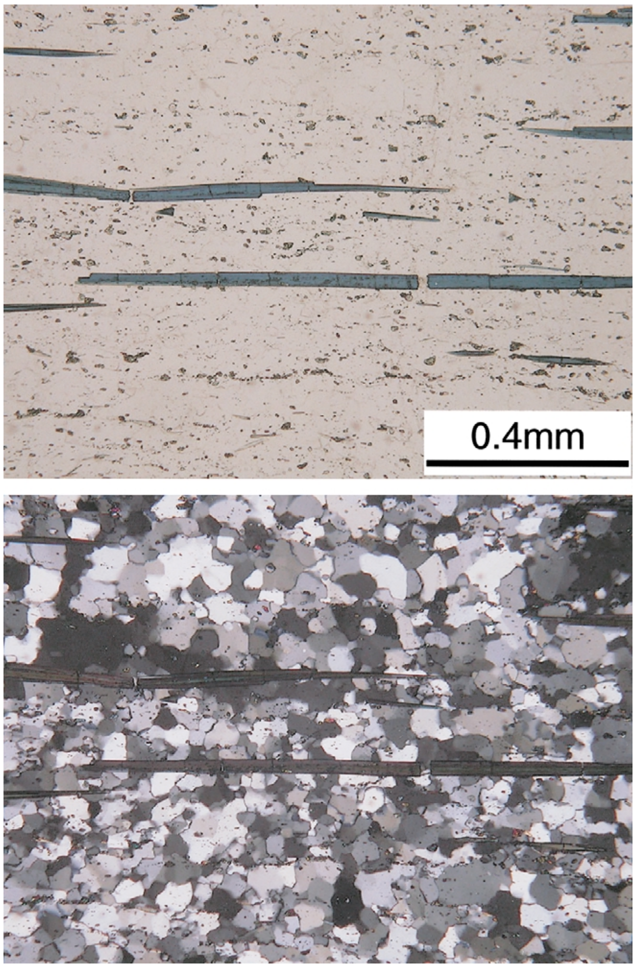

Fig. 1. Photomicrographs of the Aksu metachert. (a) Open nicols. Extraordinarily elongated sodic amphibole grains (blue) are embedded in a quartz matrix (colourless). Sodic amphibole boudins are observed. (b) Crossed nicols. Quartz grains are equant and polygonal. Interboudin gaps between sodic amphibole boudins are occupied by quartz.

3. Microscopic observation

The metachert (Fig. 1) consists predominantly of quartz, with minor amounts of sodic amphibole, epidote, muscovite, and opaque minerals. Observation of thin sections cut parallel to the lineation and perpendicular to the foliation reveals that quartz is equant, equigranular and polygonal, with an average grain size of 80 μm. Undulatory extinction is not obvious in these quartz grains. Sodic amphibole grains are needle-like, with both ends tapered. The width of sodic amphibole grains falls mainly in the range 5–20 μm, and lengths range from 100 to 2000 μm. The aspect ratio (ratio of length to width) ranges widely from 1 to 96.

4. Microboudin structures

Some sodic amphibole grains exhibit microboudin structures (Fig. 1). Fracturing is apparent perpendicular to the long axis, and microboudins were pulled apart in the direction of the long axis. These structures indicate that the microboudinage occurred in a co-axial strain field. The inter-boudin gap distances are small in contrast to the length of the grain, and are occupied by quartz.

The length, width and inter-boudin gap distances (Fig. 2) were measured according to the method of Masuda et al. (1989), and a frequency distribution of length, width and aspect ratio was produced (Fig. 3). The frequencies of boudinaged and intact grains with respect to the aspect ratio were also calculated using the strain-reversal method (Ferguson, 1981; Lloyd and Condliffe, 2003). In this procedure, all the grains that existed in the sample are counted: if one grain is boudinaged into two segments, it is counted as one boudinaged grain and the two intact grains remaining after the boudinage. Histograms of the boudinaged and intact grains with respect to aspect ratio are shown in Fig. 4, and the proportion of boudinaged to total grains at each aspect ratio is plotted in Fig. 5. As can be clearly seen, larger proportions of boudinaged grains are

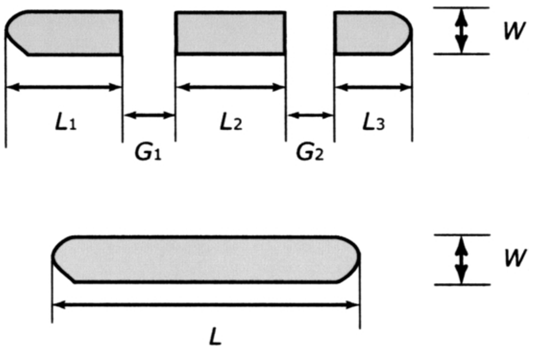

Fig. 2. Measurement of grain size for microboudinaged grains (top) and intact grains (bottom). L = length; W = width. The aspect ratio is calculated as $r = L/W$. L in the top grain is calculated as $L = \Sigma L_i$. L_i and G_i are used to restore the history of microboudinage by the strain reversal method.

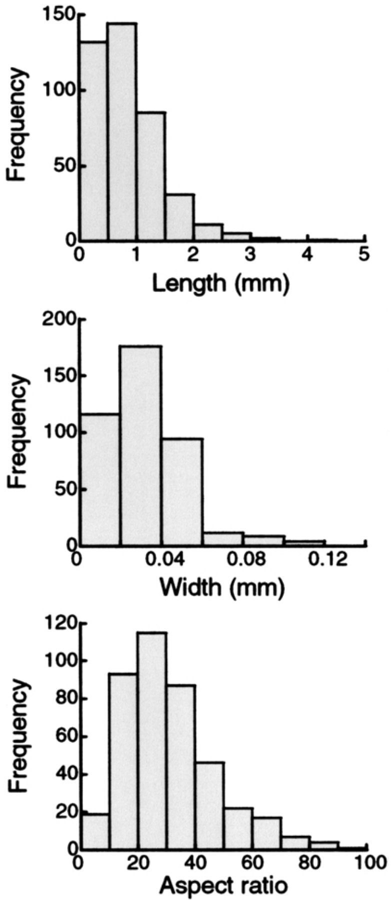

Fig. 3. Frequency distribution of pre-boudinage length, width and aspect ratio.

scored at larger aspect ratios. The plotted data in Fig. 5 is designated as $M(r)$, which is used in later analysis.

5. Application of the microboudin method

The microboudin method (Masuda et al., 2003) compares the theoretical proportion of boudinaged grains with the measured proportion, in this case as shown in Fig. 5. The

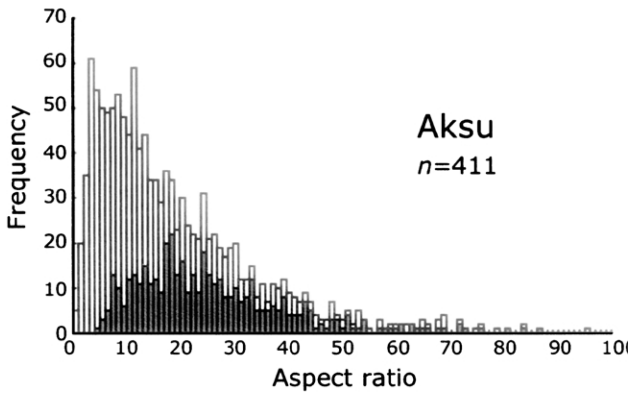

Fig. 4. Frequency distribution of aspect ratio after microboudinage. Boudinaged grains are in black, intact grains are in white.

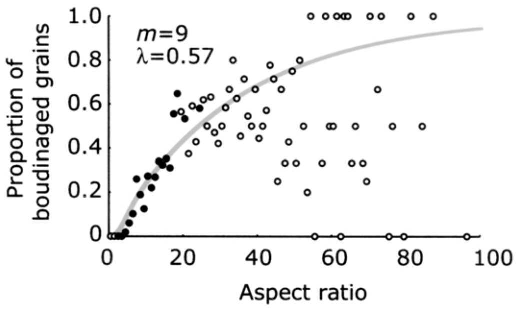

Fig. 5. Proportion of boudinaged grains with respect to aspect ratio. Solid circles = reliable data, open circles = unreliable data. Reliable data includes more than 25 grains. The solid curve shows the best-fit theoretical prediction of boudinaged grains: $G(r, 0.57)$ at $m = 9$.

theoretical proportion is expressed by:

$$G(r,\lambda) = 1 - \exp\left[-\frac{m-1}{m} r\lambda^m \left(\frac{E_f}{E_q}\right)^m \left\{1 - \left(1 - \frac{E_q}{E_f}\right)\frac{1}{\cosh(Ar)}\right\}^m\right] \quad (1)$$

where r is the aspect ratio, λ is the stress parameter, m is the Weibull modulus of the fibre material, E_f and E_q are the elastic constants of the fibre and matrix, and A is a constant. The interface between the fibre material and the matrix is assumed to be mechanically welded. In this case, the fibre material is sodic amphibole and the matrix is quartz. E_f/E_q and A can be properly given for sodic amphibole and quartz in the same way as shown in Masuda et al. (2003) by using the data of Simmons and Wang (1971): $E_f/E_q = 1.2$ and $A = 0.5$. The stress parameter λ is expressed as:

$$\lambda = \frac{\sigma_0}{S^*} \quad (2)$$

where σ_0 is the magnitude of the far-field differential stress, and S^* is the modal fracture strength of sodic amphibole at $r = 1$.

The measured proportion of boudinaged grains with respect to the aspect ratio, $M(r)$, was compared with the theoretically predicted proportion, $G(r, \lambda)$. The value of λ is determined so as to minimize $T(\lambda)$, which is defined as:

$$T(\lambda) = \sum_r [G(r,\ \lambda) - M(r)]^2 \quad (3)$$

However, m for sodic amphibole is not known. Thus, m is regarded as a variable in Eq. (1) and both m and λ are determined so as to minimize $T(m, \lambda)$, which is defined as:

$$T(m,\ \lambda) = \sum_r [G(r,\ m,\ \lambda) - M(r)]^2 \quad (4)$$

The obtained values of λ and m are $\lambda = 0.57$ and $m = 9$. Substituting these values into Eq. (1) gives the line $G(r, \lambda)$, which is drawn in Fig. 5. The curve of $G(r, \lambda)$ appears to fit the reliable $M(r)$ data plotted in Fig. 5 quite well. A χ^2-test was performed to determine whether the fitting is statistically warranted (e.g. Cheeney, 1983). The result of 23.8 lies within the critical region of 0.05 with 18 degrees of freedom, and as such the fitting is considered to be excellent. Then, if S^* is known, σ_0 can be obtained from Eq. (2).

In Fig. 5, the data points at $r > 30$ are mostly smaller than $G(r, \lambda)$. This can be explained by loss of cohesion at the interface between the quartz matrix and the sodic amphibole fibres. However, without cohesion at the interface, no extensional stress can be applied to the fibres resulting in no microboudinage of the fibres. Thus, the loss of cohesion appears to occur partially or locally at the interface for fibres with $r > 30$. Such a partial loss of cohesion will reduce the stress applied to the fibre, resulting in a smaller number of microboudins than predicted theoretically. The partial loss of cohesion may be caused by partial interfacial slip due to high shear stress concentration at the interface (Ji et al., 1998).

6. Summary

The microboudin method proposed by Masuda et al. (2003) was successfully applied to sodic amphibole grains with aspect ratios of up to 25 in the Aksu metachert. The results support the reliability and applicability of the microboudin method, which is expected to contribute to progress in structural geology.

Acknowledgements

The authors thank Aaron Stallard, Tadashi Maruyama, and Jianming Guo for assistance on the field trip in the Aksu area, and Shaocheng Ji and Daniel Koehn for constructive comments on the manuscript. The authors also thank Hideki Mori for preparing thin sections. This study was financially supported by the Japan Society for the Promotion of Science.

References

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.

Ji, S., Zhu, Z., Wang, Z., 1998. Relationship between joint spacing and bed thickness in sedimentary rocks: effects of interbed slip. Geological Magazine 135, 637–655.

Liou, J.G., Graham, S.A., Maruyama, S., Wang, X., Xiao, X., Carroll, A.R., Chu, J., Feng, Y., Hendrix, M.S., Liang, Y.H., McKnight, C.L., Tang, Y., Wang, Z.X., Zhao, M., Zhu, B., 1989. Proterozoic blueschist belt in western China: best documented Precambrian blueschists in the world. Geology 17, 1127–1131.

Liou, J.G., Graham, S.A., Maruyama, S., Zhang, R.Y., 1996. Characteristics and tectonic significance of the Late Proterozoic Aksu blueschists and diabasic dikes, northwest Xinjiang, China. International Geology Review 38, 228–244.

Lloyd, G.E., Condliffe, E., 2003. 'Strain Reversal': a Windows™ program to determine extensional strain from rigid-brittle layers or inclusions. Journal of Structural Geology 25, 1141–1145.

Lloyd, G.E., Ferguson, C.C., Reading, K., 1982. A stress-transfer model for the development of extension fracture boudinage. Journal of Structural Geology 4, 355–372.

Masuda, T., Kimura, N., Hara, Y., 2003. Progress in microboudin method for palaeo-stress analysis of metamorphic tectonites: application of mathematically refined expression. Tectonophysics 364, 1–8.

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., Kugimiya, Y., Aoshima, I., Hara, Y., Ikei, H., 1999. A statistical approach to determination of mineral lineation. Journal of Structural Geology 21, 467–472.

Nakajima, T., Maruyama, S., Uchiumi, S., Liou, J.G., Wang, X., Xiao, X., Graham, S.A., 1990. Evidence for late Proterozoic subduction from 700-Myr-old blueschists in China. Nature 346, 263–265.

Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics, Springer, Berlin.

Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology. Vol. 1: Strain Analysis, Academic Press, London.

Simmons, G., Wang, H., 1971. Single Crystal Elastic Constants and Calculated Aggregate Properties: A Handbook, MIT Press, Cambridge.

Zhao, P., Ji, S., 1997. Refinements of shear-lag model and its applications. Tectonophysics 279, 37–54.