Journal of Structural Geology, Vol. 6, No. 6, pp. 679 to 685, 1984
Printed in Great Britain.

0191-8141/84 $03.00 + 0.00

Solution transfer syn-S_2: an inferred means of deriving fault fill in the Lake Moondarra area, Mt. Isa, Queensland, Australia, based on oxygen isotope results

C. N. Winsor*

Department of Geology, James Cook University, Queensland 4811, Australia

(*Received* 4 *October* 1982; *accepted in revised form* 23 *April* 1984)

Abstract—Many of the faults within the Lake Moondarra area crop out as wide zones which are filled with massive or fibrous milky quartz. Additionally, a variety of rock fragments from the surrounding metasediments are present in the fault zones. The second regional slaty cleavage, S_2, is locally observed through the quartz and country rock fragments within some of the zones, indicating that these fault fills originated pre- or early syn-S_2. The absence of the first regional slaty cleavage, S_1, suggests that the fault fills developed post or late syn-S_1. Evidence supporting an early syn-S_2 timing for the development of these fills is provided by the results of oxygen isotope analysis carried out on quartz specimens collected from the faults and also by the nature of the quartz. Specimens of quartz taken from the various fault zones have $\delta^{18}O$ values between 12.4 and 14.5‰. This suggests that metamorphic water isotopically equilibrated with connate formation water was the aqueous fluid which transported the silica. $\delta^{18}O$ values for the silica in the quartz-rich, sometimes dolomitic, metasediments of the Mount Isa and Haslingden Groups within the Lake Moondarra area are similar to the quartz within the fault fills. The lack of any metamorphic event between the first and second deformation, together with the sometimes fibrous nature of the fault-filling material with fibres parallel to the mineral elongation in S_2 (i.e. L_2^1), suggests that the quartz in the faults was derived syntectonically at grain to grain contacts in the metasediments within the Lake Moondarra area, early in the development of S_2. The quartz is believed to have moved by the process of solution transfer to the faults as they underwent dilation during D_2. Subsequently the quartz was precipitated as a result of a chemical potential gradient.

INTRODUCTION

Many of the macroscopic faults in the Lake Moondarra area near Mount Isa, Australia are quite remarkable in their upstanding character. They have been infilled with large amounts of quartz and consequently outcrop as 'buck quartz' ridges. Three regional fold and cleavage producing events have affected this area (Winsor 1983, in prep.). Evidence is being compiled (Winsor in prep.) which shows that the fill of some faults was introduced before or early in the development of a regional N–S trending cleavage, S_2. This evidence is illustrated in Fig. 1, which shows photomicrographs of a quartz, specimen from the Kingfisher Fault fill. A weak fracture/slaty cleavage passes through the quartz and under crossed polars this cleavage is seen to consist of elongate quartz fibres with a variety of different orientations but with a preferred alignment parallel to the S_2 cleavage in the surrounding metasediments. A number of periods of syntectonic crystallization are suggested by the interpenetrative nature of the quartz. The milky quartz fault fill locally includes fragments of the adjacent country rocks which are metashales, metasiltstones and metasandstones of middle Proterozoic age from within the Mount Isa and Haslingden Groups as described by Mathias & Clark (1975). This material outcrops in fault zones up to 20 m wide with notable variations in thickness along strike. The faults are usually thickest where they trend E–W, that is where they had a suitable orientation for maximum dilation during the D_2 and D_3 deformations.

Possible origins for the fault fill are quartz derived via: (1) a magmatic water component, (2) a geothermal water component, (3) a meteoric water component, (4) a 'connate' formation water component and (5) a metamorphic water component. Although there is a likelihood of a magmatic component in concentrating the Mt. Isa ore bodies, the source of this magmatic activity was probably situated to the west of the Mt. Isa Fault Zone (MIFZ). As there are no magmatic rocks in the Lake Moondarra area it would appear unlikely that there has been any magmatic water involvement in this area. Purely on geological grounds it is possible to remove the 'geothermal water component' possibility. The other three origins for the movement of the silica remain feasible. Within the Lake Moondarra area quartz veins are abundant at all scales, providing evidence for substantial fluid motion through the rocks. Winsor (1983) observed a geometrical/genetic relationship between some veins and the last two regional deformations (i.e. D_2 and D_3). This indicates that a metamorphic component was involved in the transport of fluid through the rock mass. It should, however, be appreciated that the width of the syntectonic veins discussed by Winsor (1983), are approximately 100–1000 times thinner than the width of the faults which are infilled with quartz. The fault zones often crop out as massive quartz blows, up to 20 m wide and several kilometres in length. It should also be noted that whereas the quartz veins are post S_2, or S_3 and geometrically related to D_2 or D_3, the quartz in the faults may be pre- or early syn-S_2, from the evidence illustrated in Fig. 1. Therefore it would appear that the transport system was

*Present address: Department of Geology, The University of Western Australia, Nedlands, Western Australia, 6009.

operating at a different, but still relatively close, time during dilation of the veins and faults.

Using the oxygen isotope ratio experimentally determined for the oxygen in the quartz fault fill, it is possible to determine the change in the ^{18}O species in the quartz. The values established for a number of different faults can be used to obtain a control on the origin of the fluid and set up a model to establish the way in which the silica was derived.

Oxygen isotope results are useful in determining the primary origin of quartz in a number of different geological environments (cf. Taylor & Epstein 1962a,b, Garlick & Epstein 1967, Clayton *et al.* 1972, Taylor 1974, Becker & Clayton 1976, Taylor 1977, 1979). Garlick & Epstein (1967 p. 188) have suggested that ". . . isotopic records in metamorphic rocks reflect the initial bulk isotopic composition of the precurser rock, the extent of isotopic exchange during metamorphism and the relative temperature at which rocks crystallized". Consequently the oxygen isotopic values for quartz filling a number of faults and within the metasediments were investigated in order to determine the origin of the fault fill and its relationship, if any, to the surrounding country rocks.

NATURE OF THE FAULT FILL

A detailed examination of the fault fill and timing within the Lake Moondarra area, has been made by Winsor (in prep.). It has been established that most of the macroscopic faults within the area developed post or late syn- the first regional deformation (D_1), which is associated with relatively tight, rarely developed folds and a locally penetrative slaty cleavage. The quartz fill in the North Stone Axe, Spillway, Kingfisher, Moondarra Faults and Fault C (Fig. 2), was introduced pre- or early syn- the second deformation, because S_2 passes through country rock, quartz fill and fragments within the fill in the same orientation. This evidence is presented in Fig. 1 and in Winsor (in prep.). The Transmitter Fault is believed to post-date S_2 and is interpreted by Winsor (in prep.) as a possible residual D_3 fault, as it has an orientation approximately subparallel to S_3. Quartz has been found in association with country rocks as gouge filling the Transmitter Fault and this has been analysed for the oxygen isotopic value ($\delta^{18}O$).

The quartz fault fills usually contains evidence of having been crystallized under tectonic conditions. It is common to observe that the quartz consists of fibres parallel

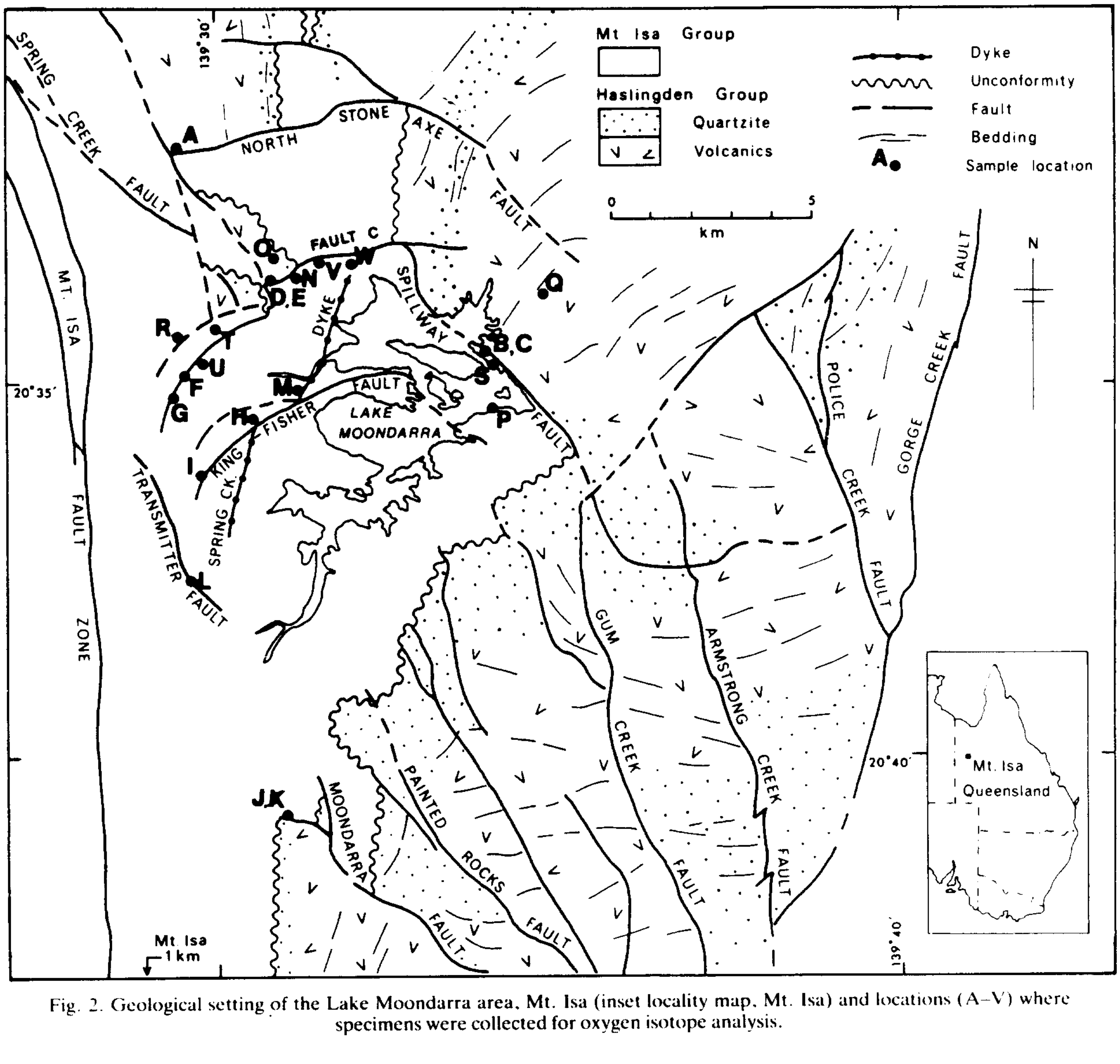

Fig. 2. Geological setting of the Lake Moondarra area, Mt. Isa (inset locality map, Mt. Isa) and locations (A–V) where specimens were collected for oxygen isotope analysis.

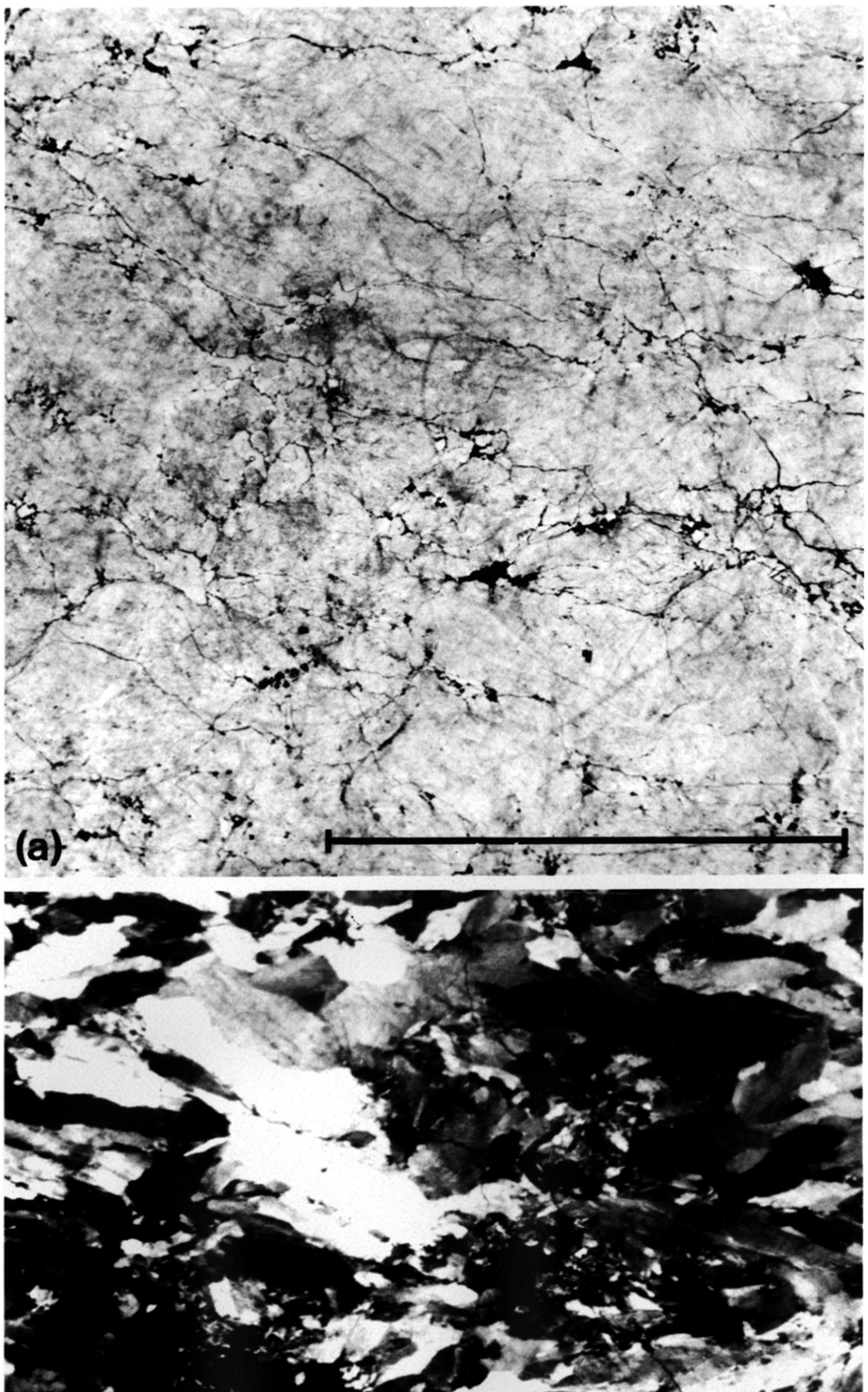

Fig. 1. Photomicrographs of quartz from the Kingfisher Fault, horizontally oriented, (a) Plane polarised light, (b) Crossed polars. At a mesoscopic scale a weak fracture cleavage, corresponding to the S_2 slaty cleavage in the adjacent country rocks, is evident through the fault fill, demonstrating that the fault underwent dilation pre- or early syn-S_2. Under crossed polars elongate quartz crystals are aligned parallel and sub-parallel to the fracture cleavage. The scale bar is 2 cm long.

to the mineral elongation directions, which have been active during D_2 and D_3 (i.e. L_2^2 or L_3^3 using the terminology of Bell & Duncan 1978). Both these lineations are found to plunge steeply to the south (Winsor 1983). Traverses across the fault fill at a number of locations indicate that the proportion and nature of country rock incorporated into the faults is quite variable. Complex changes in the proportion of country rock and quartz have been noted along the lengths of faults, as well as across fault zones. There is generally a higher percentage of country rock incorporated into the fault zones on the western side of Lake Moondarra, that is closer to the MIFZ, where there is greater evidence of ductile deformation.

OXYGEN ISOTOPE RESULTS

Specimens of quartz from a number of faults in the Lake Moondarra area were collected at the locations shown in Fig. 2. The specimens were selected so that the quartz was visually as pure as possible with few ferruginous impurities. Care was taken to obtain quartz of the same generation, that is avoiding secondary veins. A specimen was collected from a 5 cm thick ore-stage quartz vein within the Mount Isa Mine (18B sublevel) for comparison. This specimen by analogy with other chalcopyrite bearing quartz veins, appeared to be silicified quartz in a former dolomitic pseudo breccia (Perkins pers. comm. 1984) and showed no evidence of having predated any cleavages. Most of the replacive hydrothermal quartz within the mine has been interpreted as being post-D_2, syn-D_3. Swager (1983), however, has found localized areas of syn-D_1 quartz which would predate S_2, but there are no large bodies of quartz which have been positively identified as being pre-S_2. This is very different to the Lake Moondarra area where large amounts of pre- or early syn-S_2 quartz fills a number of faults. The quartz associated with a N–S trending dolerite dyke in the Lake Moondarra area has also been analysed. This dyke is interpreted (Winsor in prep.) as having been intruded at a late stage during or after a regional folding event (D_2), possibly as a relaxation effect. Following analysis of the quartz from the faults and the dyke, representative specimens were collected from within the quartz-rich metasediments of the Mount Isa and Haslingden Groups. All specimens were analysed by the bromine penta-fluoride method (Clayton & Maydeda 1963), whereby oxygen is liberated from the quartz by reaction with BrF_5 at 500–600°C in nickel reaction vessels. Table 1 shows the values determined from the analysis of the quartz filling the faults, the quartz plus silicates (feldspar and muscovite) within the metasediments of the Lake Moondarra area and the ore stage quartz vein from the Mount Isa Mine. The $\delta^{18}O$ values have been determined relative to the value in standard mean oceanic water (S.M.O.W.). As the values are relatively consistent (mean 13.2 ± .72‰), they provide important information concerning the processes involved in transporting and deriving the quartz filling the faults.

Table 1. Oxygen isotope specimens and results

Location/Specimen	$\delta^{18}O(\pm.1)$ relative to S.M.O.W. Silicate + Qtz.	
A Quartz from the North Stone Axe Fault	13.4	
B Quartz from the Spillway Fault	13.1	
C Quartz from the Spillway Fault	12.6	
D Quartz from Fault C	12.8	
E Quartz from Fault C	14.4	
F Quartz from Fault C	13.7	mean 13.2 ± .72‰ (A–K)
G Quartz from Fault C	12.6	
H Quartz from the Kingfisher Fault	14.5	
I Quartz from the Kingfisher Fault	12.5	
J Quartz from the Moondarra Fault	12.4	
K Quartz from the Moondarra Fault	13.7	
L Quartz from the Transmitter Fault	19.1	
M Quartz from the Spring Creek Dyke	18.3	
N Quartz adjacent to N–S trending dyke	14.3	
O Lena Quartzite	14.2	
P Warrina Park Quartzite	13.6	
Q Haslingden Group Quartzite	13.7	
R Moondarra Siltstone	12.6	
S Breakaway Shale	16.6	
T Breakaway Shale	15.7	
U Breakaway Shale	17.3	
V Dolomitic Siltstone	10.1	
W Dolomitic Siltstone	11.1	
Quartz veins from within the Mt. Isa Mine (18B Sublevel, P428E Decline 1, 14.8 metres)	12.3	

DISCUSSION

The results of oxygen isotope analysis of a variety of rocks from different geological environments have been summarized by Taylor (1974, 1979). Sedimentary rocks have a wide range of values from $\delta^{18}O = +5$ to $+35$‰. Shales, limestones and cherts generally fall within the range $\delta^{18}O = +15$ to $+35$. Igneous rocks, sandstones, greywackes, arkoses and volcanogenic sediments usually have values between $\delta^{18}O = +5$ to $+13$. It has been established that commonly the $\delta^{18}O$ values for volcanic and plutonic rocks fall within the restricted range $\delta^{18}O = +5.5$ to $+10.0$‰, while granitic rocks have $\delta^{18}O$ values within the range +7 to +10‰. Regional metamorphosed rocks usually have a range of $\delta^{18}O$ values from +5 to +25‰. This wide range can be expected because to a large extent metamorphic rocks retain their original connate water values. The effect of metamorphism is depletion of the ^{18}O species, so that the higher the grade the greater is the tendency for the isotopic values of metamorphic rocks to approach the range of values of igneous rocks.

Although the oxygen isotope values for rocks of different environments (igneous, metamorphic or sedimentary) have restricted ranges, it is clear that some overlap will inevitably occur when solutions of different sources come into contact. For example, the $\delta^{18}O$ values for quartz are low in metamorphosed carbonate rocks which have been influenced by high temperature (and/or pressure) water from an igneous source. An influx of meteoric water into buried rock masses may also significantly alter the values. Taylor (1974) indicated that $\delta^{18}O$ values for meteoric water have a wide range and are normally negative. Problems may also arise in the determination of isotopic values due to isotopic fractionation and contamination. Another factor which should be considered when relating isotopic values is secular changes in the $^{18}O/^{16}O$ ratio. Becker & Clayton (1976) noted that for ancient oceans the $\delta^{18}O$ value was lower than that for modern seas. The $\delta^{18}O$ values for Precambrian rocks are commonly found to lie within the range of +15 to +26‰.

As shown in Table 1, the results of oxygen isotope analysis of quartz from faults within the Lake Moondarra area, which contain evidence of the S_2 cleavage, are relatively consistent, ranging from $\delta^{18}O$ = 12.4 to 14.5‰, with the average value = 13.2 ± .72‰. This suggests that the water necessary as a transport medium to move the silica in solution into the fault zone was metamorphic water as the average of these values does not lie within the normal igneous range of $\delta^{18}O$ = +5.5 to +10.0‰. A connate water component cannot be entirely ruled out, but appears unlikely from the consistency of the results. Table 1 shows that two of the highest $\delta^{18}O$ values are from quartz specimens collected from the Transmitter Fault fill (J) and the Spring Creek Dyke (M). Both the fault and the dyke are interpreted as post-S_2 effects (Winsor in prep.), whereas the quartz within the other faults has been introduced during dilation of the faults, pre- or early syn-S_2. The higher $\delta^{18}O$ value for the quartz associated with the Transmitter Fault fill and the dyke are here interpreted to be a result of the different $\delta^{18}O$ value of the metamorphic water late during D_3. The quartz collected from a vein within the Mount Isa Mine has a relatively low value possibly as a result of the influx of a magmatic water component in the mine. As mentioned previously, however, it is difficult to make any sweeping conclusions concerning the origin of quartz in the mine from the results of only one specimen. The slightly higher $\delta^{18}O$ values for quartz collected at locations E and H, may also be a result of a local influence or some contribution from D_3 quartz. The $\delta^{18}O$ values for the quartz plus silicate in the country rocks within the Lake Moondarra area (Table 1) ranges from 10.2–17.3‰. This possibly reflects an originally wider variation of sedimentary $\delta^{18}O$ values and the homogenizing influence of metamorphically derived water originating during the regional deformations. Smith *et al.* (1978) suggested from the results of analysis of Mount Isa Group carbonates that the $\delta^{18}O$ values determined, which ranged from 10.8 to 15.9‰ S.M.O.W., indicated isotopic variation in the original connate water as a result of low-grade metamorphism. This is a conclusion also reached from the oxygen isotope results in the Lake Moondarra area. The oxygen isotope values are considerably higher at the McArthur River deposit to the northwest of Mount Isa, in the Northern Territory, where similar sediments (i.e. McArthur River Group sediments) are unmetamorphosed (Smith *et al.* 1978).

The implication from the $\delta^{18}O$ values that the water transporting silica in solution into some of the faults in the Lake Moondarra area was dominantly metamorphically derived water is of considerable significance with respect to the timing of emplacement, mechanism of production and transport of this silica. It will be shown (Winsor in prep.) that the quartz filling most faults in the Lake Moondarra area was introduced pre- or early syn-S_2, that is post-S_1. Very low-grade metamorphism occurred during D_2 and there is no local or regional evidence of any metamorphic event between D_1 and D_2, even in the higher-grade rocks to the west of the MIFZ (Weniger pers. comm. 1982). Therefore it is possible that a process which began early in the development of S_2 moved the quartz in solution from a source, through the metasediments, into the faults as they underwent dilation. It is interpreted that due to an applied stress field during D_2, dissolution of quartz and mica occurred, particularly within the D_2 plane of compression. This was accompanied by nucleation and growth of micas parallel to S_2 with only minor rotation of earlier micas into that plane. The quartz thus dissolved, moved along grain boundaries and micro-fractures to regions of lower mean stress such as the dilatant areas associated with the faults and fractures. The isotopic analysis of the quartz in faults indicates that the most likely source for this filling material, if metamorphic fluids are involved, is the quartz-rich metasediments of the Mount Isa and Haslingden Groups. The oxygen isotope results therefore point towards solution transfer (Durney 1972) as being the mechanism for dissolution, transport and precipitation of quartz from the country rocks to the fault zones.

The pH of water, which is temperature dependent, may have an important influence on the solubility of minerals with which it comes into contact. The solubility of quartz is found (Fyfe *et al.* 1978) to be almost independent of pH, while the pH remains below about 9. At pH = 9 the solubility of silica is found to increase rapidly. It has been noted by Fyfe *et al.* (1978), that in highly alkaline solutions or at higher temperatures, silica solubility increases. Beach (1979) has also indicated that metamorphic reactions exist which buffer the pH to such a level that silica solubility increases. The subsequent precipitation of quartz within the fault zones would have occurred as a result of a chemical potential gradient.

The dilation of faults within the Lake Moondarra area was initiated during the early stages of D_2 prior to S_2 development and possibly continued throughout D_2 (Winsor in prep.). Secondary quartz veins with fibres oriented at a slightly different angle to the predominant fibres developed through the quartz were occasionally noted. This suggests that secondary growth occurred within a reactivated stress field when axes changed from those previously active. It is thus apparent that quartz has been incorporated in the fault zones at different stages of S_2 development. Most of the faults therefore have been sinks for the dissolved material originating from the D_2 plane of compression. Similar situations have been recognised by Brace *et al.* (1966) and Fyfe *et al.* (1978). The quartz filling the faults has most likely been emplaced as a result of dilation of the faults parallel to and possibly also perpendicular to L_2^2, during D_2 (Winsor in prep.). It would appear likely from the presence of secondary veins within the 'buck quartz' filling material, that there have been a number of pulses of fluids moving silica from the country rocks into the fault zones. Possible pulses are also suggested by the different $\delta^{18}O$ values for the D_2 quartz compared to D_3 quartz. Sibson *et al.* (1975) have also reached the conclusion that pulses of fluid injection may occur in relation to 'seismic pumping' which has been recognized as a significant mechanism involved in solution transfer. The results of oxygen isotope analysis in the Lake Moondarra area indicate that all the pulses of solution transfer recognized had a major component of metamorphic water associated with them (i.e. either D_2 or D_3 water).

CONCLUSIONS

The results of oxygen isotope analysis of the quartz filling some faults and of the silica in the weakly metamorphosed country rocks within the Lake Moondarra area, Mount Isa, are consistent with the quartz in the faults being transported firstly through pore spaces and along microfractures, secondly by an aqueous fluid of metamorphic origin and thirdly from the metasediments of the Mount Isa and Haslingden Groups. Locally, the fault filling material contains the S_2 regional slaty cleavage but not the S_1 regional slaty cleavage. Solution transfer accompanying the formation of S_2 is considered to be the mechanism responsible for the dissolution, transport and redeposition of the quartz. This is because (a) the oxygen isotope results are not compatible with a magmatic origin or with meteoric water involvement; (b) the fibrous oriented character of the quartz within the faults is parallel to L_2^2 in the surrounding country rocks; and (c) there is no metamorphic event between D_1 and D_2.

Acknowledgements—I thank Mount Isa Mines Limited for allowing field work to be carried out in the Lake Moondarra area and for allowing publication of the data collected. The Institute of Nuclear Sciences at Lower Hutt, New Zealand is acknowledged for undertaking the isotopic analysis and useful comments were made by P. Blattner of the Institute during the preparation of the manuscript. T. H. Bell, C. Cuff and C. Swager of the Geology Department, James Cook University and S. H. White of the Department of Geology, Imperial College, are also thanked for constructive comments, as are W. G. Perkins, C. Robertson and C. A. Towsey of Mount Isa Mines Limited. The author was the recipient of a Commonwealth Postgraduate Scholarship during this research.

REFERENCES

Beach, A. 1979. Pressure solution as a metamorphic process in deformed ferruginous sedimentary rocks. *Lithos* **12**, 51–58.

Becker, R. H. & Clayton, R. N. 1976. Oxygen isotope study of a Precambrian banded iron formation Hamersley Range Western Australia. *Geochim. cosmochim. Acta* **40**, 1153–1163.

Bell, T. H. & Duncan, A. C. 1978. A rationalized and unified shorthand terminology of lineations and fold axes in tectonites. *Tectonophysics* **47**, T1–T5.

Brace, W. F., Paulding, B. W. & Scholz, C. 1966. Dilatancy in the fracture of crystalline rocks. *J. geophys. Res.* **71**, 3939–3953.

Clayton, R. N. & Mayeda, T. K. 1963. The use of bromine penta fluoride in the extraction of oxygen from oxides and silicates for isotopic analysis. *Geochim. cosmochim. Acta* **27**, 43–52.

Durney, D. W. 1972. Solution-transfer, an important geological deformation mechanism. *Nature, Lond.* **235**, 315–316.

Fyfe, W. S., Price, N. J. & Thompson, A. B. 1978. *Fluids in the Earth's Crust*. Amsterdam, Elsevier.

Garlick, G. D. & Epstein, S. 1967. Oxygen isotope results in coexisting minerals of regionally metamorphosed rocks. *Geochim. cosmochim. Acta* **31**, 181–214.

Mathias, B. V. & Clark, G. J. 1975. Mount Isa copper and silver–lead–zinc ore bodies–Isa and Hilton Mines. In: *Economic Geology of Australia and New Guinea*, Volume 1 (edited by Knight, C. L.). Australian Institute of Mining and Metallurgy, 351–372.

Sibson, R. H., Moore, J. McM. & Rankin, A. H. 1975. Seismic pumping—a hydrothermal fluid transport mechanism. *J. geol. Soc. Lond.* **131**, 653–659.

Smith, J. W., Burns, M. S. & Croxford, N. J. W. 1978. Stable isotope studies of the origins of mineralization at Mt. Isa 1. *Miner. Deposita* **13**, 369–382.

Swager, C. P. 1983. Microstructural development of the silica-dolomite and copper mineralization at Mt. Isa, NW Queensland with special emphasis on the timing and mechanism of mineralization. Unpublished Ph.D thesis, James Cook University.

Taylor, H. P. & Epstein, S. 1962a. Relationship between O^{18}/O^{16} ratio in coexisting minerals of igneous and metamorphic rocks. *Bull. geol. Soc. Am.* **73**, 461–480.

Taylor, H. P. & Epstein, S. 1962b. Relationship between O^{18}/O^{16} ratio in coexisting minerals of igneous and metamorphic rocks. *Bull. geol. Soc. Am.* **73**, 675–694.

Taylor, H. P. 1974. The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition. *Econ. Geol.* **69**, 843–883.

Taylor, H. P. 1977. Water/rock interactions and the origin of H_2O in granitic batholiths. *J. geol. Soc. Lond.* **133**, 509–558.

Taylor, H. P. 1979. Oxygen and hydrogen isotope relationships in hydrothermal mineral deposits. In: *Geochemistry of Hydrothermal Ore Deposits, 2nd edition* (edited by Barnes, H. L.). Wiley, New York.

Winsor, C. N. 1983. Syntectonic vein and fibre growth associated with multiple slaty cleavage development in the Lake Moondarra area, Mount Isa, Australia. *Tectonophysics* **92**, 195–210.

Winsor, C. N. in prep. Intermittent folding and faulting in the Lake Moondarra area, Mount Isa, Australia. Submitted to *J. Aust. Earth Sci.*