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► To cite this version:

Cyril Durand, Emilien Oliot, Didier Marquer, Jean Pierre Sizun. Chemical mass transfer in shear zones and metacarbonate xenoliths: a comparison of four mass balance approaches. *European Journal of Mineralogy*, 2015, 27 (6), pp.731-754. 10.1127/ejm/2015/0027-2475 . hal-01260258

HAL Id: hal-01260258

<https://hal.science/hal-01260258v1>

Submitted on 6 Oct 2022

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Chemical mass transfer in shear zones and metacarbonate xenoliths: a comparison of four mass balance approaches

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Abstract: Mass balance calculations have been performed through a comparison of published graphical and statistical approaches applied to two contrasted geological settings: (i) the development of a greenschist-facies ductile shear-zone that recorded a weak volume change but significant mass transfers, and (ii) the formation of exoskarns in metacarbonate xenoliths that recorded a large volume decrease related to huge mass transfers. The comparison of the four mass-balance approaches shows that, if uncertainties are ignored, (1) they yield similar results concerning the mobile vs immobile behaviour of many components; (2) they yield similar mass-change values on bulk rock and on individual chemical elements (bulk-rock mass-change values differ by a maximum of *ca.* 15 % between graphical and statistical treatments of the metacarbonate xenolith evolution). The main difference concerns the uncertainties on mass changes (for bulk rocks and individual elements), which are much larger with the graphical than with the statistical approaches when uncertainties on chemical elements are taken into account, as they should be.

The main advantage of the graphical methods is their rapid implementation and the clarity of the diagrams. Their main disadvantages are that uncertainties on each chemical element and bulk compositions are not taken into account and the difficulty in choosing an accurate immobility field to precisely define errors. Graphical methods need to be completed by a statistical treatment that gives absolute mass transfer results. The statistical approaches have the advantage of taking into account the chemical heterogeneities of the compared populations, in conjunction to a precise data treatment. The statistical treatment is an important and necessary step to decipher and to be pertinent in interpreting mobility/immobility of chemical elements, and, thus, in the absolute quantification of mass and volume changes.

Key-words: chemical mass transfer; mass balance calculation; metasomatism; ductile shear zone; exoskarn; Aar Massif; Quérigut Massif.

1. Introduction

Mass balance calculation is a useful tool to quantify absolute mass and volume changes that occur during geological processes involving chemical mass transfers in the lithosphere. Numerous mass balance approaches have been developed over 50 years (Gresens, 1967; Grant, 1986; Brimhall & Dietrich, 1987; Potdevin & Marquer, 1987; Potdevin, 1993; Ague, 1994; Baumgartner & Olsen, 1995; Ague & van Haren, 1996; Sturm, 2003; Grant, 2005; Coelho, 2006; Lopez-Moro, 2012). Applications concern a wide variety of geological topics, for example regional metamorphism (Ague, 1991; Ferry & Dipple, 1991; Ague, 1994, 2000, 2003), contact metamorphism (Vidale, 1969; Thompson, 1975; Abu El-Enen *et al.*, 2004; Durand *et al.*, 2009), ore-deposit formation (Einaudi & Burt, 1982; Harris & Einaudi, 1982; Brown & Essene, 1985;

Kalczynski & Gates, 2014), shear-zone development (O'Hara, 1988; Marquer, 1989; McCaig, 1997; Hippertt, 1998; Steyrer & Strum, 2002; Oliot *et al.*, 2010; Goncalves *et al.*, 2012b), migmatite formation (Olsen & Grant, 1991; Chavagnac *et al.*, 2001), hydrothermal alteration (Harper, 1997; Mori *et al.*, 2003), penetrative cleavage development (Wright, 1982; Bell, 1985; Beutner & Charles, 1985; Henderson *et al.*, 1986; Wintsch *et al.*, 1991) and weathering alteration and soil formation (Brimhall & Dietrich, 1987; Brimhall *et al.*, 1988; Soler & Lasaga, 2000; Carrasco & Girty, 2015).

Chemical mass transfers are basically quantified by comparing the bulk chemical composition of unaltered samples with that of altered samples. The terms “unaltered sample” or “initial rock”, used in this article, refer to a sample that was not affected by the geological event studied (*e.g.* contact metamorphism). However,