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Combining microstructural analysis with EPMA monazite geochronology to constrain progressive stages of orogenesis in the Appalachians

Volume I: Text.

Thesis submitted by

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STATEMENT ON THE CONTRIBUTION OF OTHERS

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THESIS INTRODUCTION AND OUTLINE

Introduction

Microstructural relationships between porphyroblasts and the matrix have been frequently used to infer the relative timing of porphyroblast growth in deformed and metamorphosed terrains (Bell and Rubenach, 1983; Bell et al., 1986; Schulz, 1990; Barker, 1994; Williams, 1994). Although the interpretation of inclusion trail geometries is still controversial (Bell et al., 1992; Passchier et al., 1992; Williams and Jiang, 1999; Ikeda et al., 2002), quantification, by way of foliation intersection/inflection axes preserved in porphyroblasts (FIAs), has shown that long histories and multiple periods of growth can be preserved (Bell and Hayward, 1991; Bell et al., 1995; Bell et al., 1998). As such, inclusion trails have been used to locally track the deformation and metamorphic history that predates the development of the matrix foliations that are finally preserved in rocks (Bell and Hickey, 1999; Stallard and Hickey, 2001; Stallard et al., 2003; Bell et al., 2004; Cihan and Parsons, 2005).

Whilst relative timing constraints on numerous sample suites have been obtained using the FIA method, chemical and absolute time data for these interpretations is required. Microstructurally, successive portions of garnet porphyroblasts generally do not correlate with the chemical zoning patterns of major cations, despite these porphyroblasts preserving a multi-stage growth history (e.g. Bell and Kim, 2004). One explanation for this has been based around the effects of deformation partitioning and reactivation of pre-existing foliations controlling the location and timing of porphyroblast growth (Bell et al., 2004). In these models, differentiated crenulation cleavage development stops porphyroblast growth because the resultant strain softening prevents microfracture, which is essential for the rapid access of components to and from the growth site. When later deformation resumes, porphyroblast growth resumes provided the deformation partitions through that location, until differentiated cleavage again begins to develop, and growth again ceases. If no significant changes have occurred in temperature (T), pressure (P) or composition (X), then on resumption of growth there should be no (or little) effect on compositional zoning. The ability to constrain absolute time and test whether this is the case is, therefore, very important. Fine-scale isotopic dating of garnet is difficult and expensive, particularly when inclusion-rich porphyroblasts are the subject of study (e.g. DeWolf et al., 1996; Vance et al., 1998; Prince et al., 2000). The dating of accessory minerals such as monazite provides a viable alternative for constraining different generations of porphyroblast growth and/or foliation development.

Monazite [(LREE)PO_4] incorporates appreciable amounts of Th and U and is highly resistant to Pb-loss through either volume diffusion (Seydoux-Guillaume et al., 2002; Cherniak et al., 2004), or metamictisation (Ewing and Haaker, 1980; Meldrum et al., 1997). Consequently, it is widely used to date metamorphic, igneous and hydrothermal events. Monazite contains little or no common Pb (Parrish, 1990). Therefore, it can be chemically dated in-situ on the electron probe microanalyser (e.g. Suzuki and Adachi, 1991; Montel et al., 1996; Rhede et al., 1996; Cocherie et al., 1998; Crowley and Ghent, 1999; Williams et al., 1999; Jercinovic and Williams, 2005; Pyle et al., 2005). Advantages of the electron probe microanalyser (EPMA) include the small spatial resolution (down to 1 μm), minimal sample damage and the ability to get compositional data for each spot analysed. High detection limits (which generally preclude dating monazites younger than approximately 50 Ma), large errors in precision, and the inability to assess potential discordancy between ^{238}U-^{206}Pb and ^{235}U-^{207}Pb ages, are some potential problems (Montel et al., 1996; Cocherie and Albarede, 2001). However, used within its limits, monazite dating on the EPMA has the potential to provide crucial absolute time constraints on both porphyroblast growth and foliation development (Bell and Welch, 2002; Williams and Jercinovic, 2002).

Whilst monazite is an ideal accessory mineral to date garnet growth events, it is not necessarily present around the garnet isograd. The monazite stability field in metapelites commonly appears to be at a higher grade than that of garnet. Consequently, it is mostly present as inclusions in garnet porphyroblast rims and/or higher grade phases. This restricted one of the aims in this study, the dating of FIA events, which, at present, has only been attempted by Bell and Welch (2002). Nevertheless, both detailed microstructural and monazite analyses have been combined to solve particular metamorphic and deformation timing problems within the Appalachians of eastern North America. Three different areas are examined, two in the southern Appalachians and the third in the New England. Between these regions, over 150 million years of orogenesis, within three major events are recorded. The protocol for analysing monazite was (and still is) a continual process of refinement and learning. As such, the data presented here reflects this natural progression, and some of the methods used during the early parts of this project were improved on in the later parts. The data presented here has been obtained as accurately as possible and where any doubts existed regarding the results they were either re-checked using the current EPMA setup or addressed within the thesis.

Thesis Outline

The thesis consists of four sections, each written as independent bodies of work with the intention that they will be submitted as papers for publication in international journals. The chapters follow a progression from early work involving data handling and determining the precision of EPMA monazite ages, to combining monazite and garnet chemistry, microstructural classification and chemical ages to interpret the metamorphic and deformational history of the study areas. The main text of the thesis is in Volume I and figures and tables are presented in Volume II. References are given at the end of each section in Volume I and appendices are included at the end of Volume II.

The first chapter addresses how different studies have quoted precision errors in EPMA monazite ages, particularly with the “single-spot” method (where an “age” is calculated from the Pb, Th, U concentration for each data point). Two different techniques have been used, one utilising counting statistics and the other the variation within a group of individual ages/dates. By comparing the methods with a dataset from a homogeneous monazite grain, the potential underestimation of precision from counting statistics is highlighted. This chapter is a major revision of a manuscript submitted to Chemical Geology in late 2004.

The second chapter follows on from above by evaluating a non parametric (bootstrap) method for calculating precision errors in heterogeneous monazite grains/domains. Methods to chemically and microstructurally interpret individual grains in metamorphic rocks are also presented. These techniques are applied to data from the Murphy Syncline, North Carolina with the results addressing previous uncertainties as to whether regional metamorphism was Taconic (Ordovician), Acadian (Silurian-Devonian), or a combination of both events.

A narrow, fault-bounded belt of meta-sediments and meta-volcanics that extends across northern Georgia is the subject of Chapter 3. These rocks have an uncertain metamorphic age, although they contain excellent microstructures, both within garnet porphyroblasts and the matrix that potentially record a prolonged metamorphic history. Whilst the rare monazite inclusions prevented a detailed study of the porphyroblast history, the data that was obtained provides interesting insights into the metamorphic and structural development of the region.

The final chapter presents the results of an extensive study to determine the earliest stages of porphyroblast growth within meta-pelites from north-central Massachusetts. The rocks here contain multiple FIA sets within the porphyroblasts, despite the matrix having been heavily sheared late in the metamorphic history. Qualitative analysis of garnet-monazite equilibrium was undertaken in some samples to correlate monazite ages to periods of garnet porphyroblast growth. The results are interpreted with respect to the possible pattern of early metamorphism and the also the tectonic setting of metamorphism prior to shearing.

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