Metamorphic chronology—a tool for all ages: Past achievements and future prospects

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ABSTRACT

Metamorphic chronology or petrochronology has steadily evolved over several decades through ever improving analytical techniques and more complete understanding of the geochemical and petrologic evolution of metamorphosing rocks. Here, the principal methods by which we link metamorphic temperatures (T) and ages (t) are reviewed, focusing primarily on accessory minerals. Methods discussed include textural correlation, inversion of diffusion profiles, chemical correlation, and combined chronologic and thermometric microanalysis. Each method demonstrates remarkable power in elucidating petrologic and tectonic processes, as examples from several orogens illustrate, but limitations must also be acknowledged and help define future research directions. Correlation methods are conceptually simple, but can be relatively non-specific regarding pressure-temperature conditions of formation. A new consideration of errors indicates that modeling of chronologic diffusion gradients provides relatively precise constraints on cooling rates, whereas models of chemical diffusion gradients can lead to large (factor of 2 or more) cooling rate uncertainties. Although arguably the best method currently in use, simultaneous T-t measurements are currently limited to zircon, titanite, and rutile. Directions for future improvement include investigation of diffusion profiles for numerous trace element-mineral systems using now-routine depth profiling. New trace element models will help improve chemical correlation methods. The determination of inclusion entrapment P-T conditions based on Raman spectroscopic measurement of inclusion pressures (“thermoba-Raman-try”) may well revolutionize textural correlation methods.

Keywords: Geochronology, monazite, titanite, zircon, trace elements and REE, Zr, zircon, titanite, rutile, metamorphic petrology, UHP, Invited Centennial article

INTRODUCTION

Understanding Earth processes commonly depends on constraining rates. Although the aphorism “No dates, no rates” is disproved by modeling chemical diffusion profiles (see below), improvements in how we date minerals have indeed led to many major advances in petrogenesis and tectonics. In the last couple decades, metamorphic geochronologists have increasingly sought to develop new analytical and theoretical techniques to link ages with temperature and/or mineral reactions and petrologic evolution. Referred to as “petrochronology” in some quarters, this integrative approach culminates a large body of research in metamorphic geochronology, mineral chemistry, and petrogenesis. This review considers four different ways in which we link metamorphic ages (“t”) with temperature (“T”), mainly in the context of accessory minerals: (1) textural correlation between

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1 Engi (2009), but see also Fraser et al. (1997) for the first use in the geosciences literature. Originally (Thompson 1969), petrochronology was defined in reference to a Yoruba (west African) cult of the river god Eyunle, in which the number of stones in a ceremonial earthenware pot was proposed as a possible measure of duration and intensity of devotion, i.e., a sort of “stone-chronometer.” As Thompson wrote (p. 141): “Future research will determine whether there is a mean correlation between years and stones. If there is, we have a [method] for the dating of the pots, a science that we take the liberty of designating in advance petrochronology.”

key minerals and ages; (2) inversion of diffusional zoning, both chemical zoning and chronologic zoning; (3) chemical correlation of ages to mineral growth events; and (4) simultaneous microanalysis of ages and trace-element temperatures in mineral domains. Examples, limitations, and advantages are discussed. Last, some views are presented on research directions with good future potential, including further development of geochemical tracers, new trace element models, and the use of Raman spectroscopy for determining inclusion pressures and temperatures (“thermoba-Raman-try”).

TEXTURAL CORRELATION

Datable inclusions in a petrogenetically diagnostic host

Many textural correlations rely on dating mineral inclusions inside a host mineral whose chemistry or growth is somehow linked to P-T evolution. The most common host mineral is garnet, both because it commonly grows with increasing P or T so its rim may represent the peak of metamorphism, and because its chemistry can be inverted to constrain a P-T path. Thus, the age for a garnet core vs. rim can inform rates of heating or loading, which can be useful for tectonic interpretations and models of mineral growth kinetics. Conceptually, if an accessory mineral continually reequilibrates during metamorphism,