DISCLAIMER:

This document does not meet the current format guidelines of the Graduate School at The University of Texas at Austin.

It has been published for informational use only.

Copyright

by

Sarah Jean Stacy

2012

The Thesis Committee for Sarah Jean Stacy Certifies that this is the approved version of the following thesis:

Evidence from high-temporal-resolution strain rates for strain softening due to episodic fluid influx at Passo del Sole, Central Swiss Alps

APPROVED BY SUPERVISING COMMITTEE:

Supervisor:

William D. Carlson

Mark Cloos

Richard A. Ketcham

Evidence from high-temporal-resolution strain rates for strain softening due to episodic fluid influx at Passo del Sole, Central Swiss Alps

by

Sarah Jean Stacy, B.S.

Thesis Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Geological Sciences

The University of Texas at Austin December 2012

Dedication

I would like to dedicate this thesis to my family.

Acknowledgements

Expressing my thanks to those who helped me complete this project is a task that will reach far beyond this page into the relationships I've built while at UT and those that endured the challenges presented by the undertaking of this project.

First, I would like to thank Bill Carlson, who always had my best interest in mind and would stop at almost nothing to help me out. I would also like to thank my committee members, Mark Cloos and Rich Ketcham. Discussions with them never failed to lead to new insights and good humor.

I am indebted to those who helped me at the Jackson School. Donggao Zhao was committed to helping me and all students learn (sometimes clumsily) how to collect EPMA data. This project could not have been completed without Matt Colbert and Jessie Maisano, who helped me collect and understand HRXCT data. Greg Thompson's help in making thin sections was invaluable. Philip Guerrero prevented logistical matters from becoming obstacles and was always up for a little fun.

The Carlson research group lent companionship and insight in the pursuit of research in metamorphic petrology, as did other students at the Jackson School.

Perhaps most importantly, I would like to thank my family and friends for their unconditional encouragement.

Abstract

Evidence from high-temporal-resolution strain rates for strain softening due to episodic fluid influx at Passo del Sole, Central Swiss Alps

Sarah Jean Stacy, M.S. Geo.Sci.

The University of Texas at Austin, 2012

Supervisor: William D. Carlson

Berg (2007) determined hand-sample-scale high-temporal-resolution strain rates from rotated garnet for two samples of quartzose pelitic gneiss at Passo del Sole, Central Swiss Alps, documenting a correlation between dramatic increases in strain rate and compositionally anomalous garnet growth zones. Considering additional evidence that these anomalous zones resulted from externally derived ephemeral fluid flow, he concluded that increased strain rates at Passo del Sole are the result of strain softening caused by fluid influx.

This study tests Berg's interpretation by calculating new hand-sample-scale hightemporal-resolution strain rates for two additional samples of the same gneiss: a control sample (Sample PDS 03-30) that shows no unusual zoning patterns, implying that it was unaffected by fluids; and another (Sample PDS 03-2) that features a prominent Ca spike, suggesting that it has been affected by fluid influx. Unique features of garnet from this locality—contemporaneity of chemical zones, near-simultaneous nucleation, sizeproportional growth, and rock-wide chemical equilibrium—were exploited to calculate strain rates of unprecedentedly high temporal resolution. Thermodynamically modeled temperatures for several growth-zone boundaries in each garnet crystal were combined with a regional heating rate of 11.5 ± 3.5 °C/Myr (presumed constant) and measured deflections of inclusion trails in each zone to calculate strain rates for several discrete time increments during garnet growth.

Sample PDS 03-2 displays a 2- to 16-fold increase in strain rate that correlates with growth of the high-Ca zone; strain rates are $0.4 \times 10^{-14} \text{ s}^{-1}$ to $4.1 \times 10^{-14} \text{ s}^{-1}$ for zones with normal Ca concentration and $9.1 \times 10^{-14} \text{ s}^{-1}$ to $17.9 \times 10^{-14} \text{ s}^{-1}$ for the high-Ca zone. Distinct amongst all analyzed samples from Passo del Sole, Sample PDS 03-30—which has not been affected by fluid influx—shows no fluctuations in strain rates, which remain low and similar ($0.2 \times 10^{-14} \text{ s}^{-1}$ to $2.6 \times 10^{-14} \text{ s}^{-1}$) across all zones. Results from this study therefore further substantiate the correlation of high strain rates with compositionally anomalous zones, strengthening the interpretation that elevated strain rates at Passo del Sole result from strain softening caused by episodic, externally controlled flow of fluids through the system during synkinematic garnet growth.

Table of Contents

List of tablesxii
List of figuresxiii
Introduction1
Background: Local strain rates in metamorphic rocks
Geologic background7
Geologic overview: Central Swiss Alps7
Lepontine Dome
Passo del Sole17
Structural features
Unit descriptions
Unique features in Orange Gneiss garnet: Implications for strain-rate calculations23
Contemporaneity of growth zones
Near-simultaneous nucleation of garnet crystals
Size-proportional zones
Chemical equilibrium
Implications for strain-rate calculations
Previous work: Berg (2007)
Unique garnet zoning: A result of episodic channelized external fluid flow34
Strain rates and interpretation of variations

Methods	40
Strain rate equation	40
Samples	42
Sample preparation: Making central sections	43
Electron probe microanalysis	46
Definition of growth zones	46
Measurement of deflections: Determining ω	53
Thermodynamic modeling: Determining ΔT	55
Thermodynamic models	56
Determining bulk compositions	59
Heating rate: Determining h	66
Results	67
Sample PDS 03-30	67
Temperatures	67
Deflections	69
Strain rates	71
Sample PDS 03-2	74
Temperatures	74
Deflections	74
Strain rates	77
Uncertainties	80

Rotation angle measurements	80
Thermodynamic modeling	81
Heating rate	84
Discussion	85
Evidence for strain softening caused by channelized, episodic, fluid flow	85
Strain rate elevations: An artifact of heating-rate increases?	88
Further implications	90
Conclusion	91
Appendix A: Sample descriptions	92
PDS 03-30	92
PDS 03-2	93
Appendix B: EPMA analysis conditions	95
EPMA quantitative analysis conditions	95
EPMA X-ray map conditions	97
Appendix C: Garnet EPMA results	
PDS 03-30	
PDS 03-2	107
Appendix D: EPMA quantitative analyses of minerals other than garnet	115
PDS 03-30	115
PDS 03-2	119

Appendix E: Isochemical phase diagrams12
PDS 03-3012
Garnet 212
Garnet 512
Garnet 713
Garnet a14
PDS 03-214
Garnet 13014
Garnet 19715
Garnet 40915.
Garnet Berg15
Appendix F: Central inclusion orientations16
Appendix G: Determination of uncertainty due to central-section misorientation16
Appendix S1: Supplementary disc168, attached
References16

List of Tables

Table 1:	Deformational events in the Lepontine Dome	15
Table 2:	Sample PDS 03-30 thermodynamic model inputs	68
Table 3:	Sample PDS 03-30 results	70
Table 4:	Sample PDS 03-2 thermodynamic model inputs	75
Table 5:	Sample PDS 03-2 results	76

List of Figures

Figure 1:	Schematic tectonic map of the Alps	8
Figure 2:	Timeline of major pre-Alpine and Alpine events recorded in the Central	
	Swiss Alps	9
Figure 3:	Geologic cross-sections across the Western Alps, reconstructing the	
	evolution of the Alpine orogeny	.10
Figure 4:	Geologic map of the area between Lukmanier Pass and Passo del Sole,	
	with a cross-section through Passo del Sole	18
Figure 5:	Thin-section photograph of a rotated garnet crystal from the Orange	
	Gneiss	21
Figure 6:	Concentric Ca zoning in Sample AG-4	.24
Figure 7:	Quantitative EPMA traverses of garnet crystals in Sample PDS 03-30	.26
Figure 8:	X-ray maps of a partially replaced garnet, Sample PDS 02-12	.36
Figure 9:	Strain-rate results of Berg (2007)	.38
Figure 10:	Outcrop map showing sample locations	.44
Figure 11:	Ca X-ray maps showing zones in PDS 03-30	.48
Figure 12:	Quantitative EPMA traverses showing zones in PDS 03-30	.49
Figure 13:	Ca X-ray maps showing zones in PDS 03-2	51
Figure 14:	Quantitative EPMA traverses showing zones in PDS 03-2	.52
Figure 15:	Measurement of deflections in inclusion trails	.54
Figure 16:	Extraction of <i>P</i> - <i>T</i> estimates from isochemical phase diagrams	.57

Figure 17:	Example of image analysis	63
Figure 18:	Measured deflections: PDS 03-30	72
Figure 19:	Strain rate results: PDS 03-30	73
Figure 20:	Measured deflections: PDS 03-2	78
Figure 21:	Strain rate results: PDS 03-2	79
Figure 22:	Location map with strain-rate profiles	86

INTRODUCTION

Local strain rates in metamorphic rocks are important for understanding structural, petrologic, and metamorphic processes and have been applied to interpret geologic histories in numerous localities (e.g., Christensen et al., 1994; Selverstone et al., 1995; O'Hara, 2007; Rey et al., 2009a; Braid et al., 2010). Until recently, however, the methods used for determining strain rates on a local (hand-sample) scale (e.g., Mueller et al., 2000; Biermeier and Stüwe, 2003) yielded strain rates averaged over periods of time no shorter than the growth period of garnet, precluding insights into processes that occur on shorter time scales.

In the method of Biermeier and Stüwe (2003), strain rates are determined by relating the differences between thermodynamically determined temperatures for cores and rims of garnet crystals to heating rates and deflections in inclusion trails in the porphyroblasts, allowing for calculation of strain rates over the growth period of a garnet at the hand-specimen scale. Berg (2007) advanced the method of Biermeier and Stüwe by developing a technique that entails determining temperatures and measuring deflections corresponding to several zones in the *interiors* of garnet crystals in addition to the cores and rims. This method yields strain rates of unprecedentedly high temporal resolution, permitting investigation of structural and metamorphic processes over time increments as small as 300,000 years. Berg took advantage of this ability by calculating strain rates from two samples from Passo del Sole in the Central Swiss Alps, leading to the

interpretation that strain-rate fluctuations observed in garnet from Passo del Sole are the result of strain softening caused by episodic channelized external fluid flow.

This study tests the interpretation of Berg (2007), using the same method to calculate local strain rates from two additional samples from Passo del Sole: a control sample that has not been affected by episodic channelized fluid flow, and another sample that has experienced ephemeral fluid influx. Calculation of strain rates is implemented by combining thermodynamically modeled temperatures for concentric annuli in rotated garnet, measured deflections of inclusion trails between annuli, and a regional heating rate determined by Janots et al. (2009). The results broaden the suite of high-temporal-resolution strain-rate data, allowing for new insights into the variation of strain rates in space and time, and permitting more perceptive interpretations of the causes of these variations.

BACKGROUND: LOCAL STRAIN RATES IN METAMORPHIC ROCKS

Because strain rate affects the deformational response of rocks, it is a quantitative characteristic of metamorphic systems that can be as useful for understanding their history as other more commonly quantified characteristics such as temperature and pressure. Local strain rates from metamorphic rocks-those that characterize a handsample-sized specimen rather than an entire region-have been applied to geological problems to shed light on structural and tectonic histories in numerous localities. For example, Christensen et al. (1994) and Selverstone et al. (1995) used local strain rates to further the understanding of the kinematics of the Tauern Window in the Swiss Alps. O'Hara (2007) used local strain rates to characterize the petrologic history of the Blueridge-Piedmont crystalline thrust sheet in the southern Appalachian Mountains. Rey et al. (2009b) developed a model to predict crystallization versus exhumation histories of metamorphic core complexes using strain rate as a parameter. They applied it to understand the role of partial melting in the Shuswap metamorphic core complex in British Columbia, Canada and the Ruby Mountains in Nevada. Changes in local strain rates observed in the Pulo do Lobo Zone in southern Iberia by Braid et al. (2010) helped to constrain the nature of collision of the paleo-continents Gondwana and Laurussia.

The quantification of local strain rates in metamorphic rocks has been approached using several different techniques, including Rb-Sr dating of strain fringes formed around pyrite grains (Mueller et al., 2000) and area-perimeter fractal analysis of quartz grains from quartzite (Mamtani, 2010). These techniques have proven useful in certain localities. However, in most cases, garnet crystals that display evidence of rotation have become the tool of choice for determining local strain rates in metamorphic rocks because these remarkable porphyroblasts commonly preserve continuous records of pressure, temperature, rotation—and less explicitly—time. The following methods couple measurement of apparent rotation of inclusion trails in garnet porphyroblasts with various techniques for determining a time component to yield strain rate.

Isotopic ages of cores and rims of garnet porphyroblasts have been correlated with measured deflection of inclusion trails between cores and rims to determine strain rate (Christensen et al., 1989; Christensen, 1992; Vance and O'Nions, 1992; Baxter, 2004). This technique is useful for calculating an average strain rate over the entire growth interval of a porphyroblast, but it is time- and resource-intensive, works best with large porphyroblasts (at least 25 mm in diameter) or porphyroblasts with datable inclusions in their cores and rims, and may yield results with very high uncertainties (Lapen et al., 2004; Dickin, 2005).

In response to the challenges imposed by such methods, Biermeier and Stüwe (2003) developed a method that provides a simpler, more readily available, and more widely applicable means of determining local strain rates. They combined thermodynamically determined growth temperatures of garnet cores and rims with a constant heating rate to determine the garnet growth rate. Using the growth rate—which provides a time component—and measured deflections of inclusions in garnet porphyroblasts, they derived strain rates. A significant advantage of this method is the ability to determine strain rates for small porphyroblasts, which are more common than

the large ones required for isotopic dating. However, all of the methods described above simply compare core conditions to rim conditions, so they are limited to determining strain rates averaged over the interval between the time when garnet crystals began to nucleate in a rock and the time when garnet crystallization terminated.

The method used in this study is that of Berg (2007), which is a modification of Biermeier and Stüwe's (2003) approach. It extracts much higher-time-resolution strain rates with much lower uncertainties, by exploiting unusual features of garnet from the Passo del Sole region in the Central Swiss Alps: nearly simultaneous nucleation of garnet crystals and distinctive zoning patterns developed under rock-wide chemical equilibrium. This is accomplished by calculating strain rates that correspond to several individual time increments within the garnet growth period, rather than just cores and rims, and precisely calculating effective bulk compositions. Berg (2007) used THERMOCALC (Holland and Powell, 1990, 1998; Powell et al., 1998) to thermodynamically model temperatures of formation of several compositional annuli in the interiors of garnet crystals. In a manner similar to Biermeier and Stüwe (2003), Berg combined these temperatures with measured deflections of inclusion trails between concentric annuli and a regional heating rate, presumed to be constant. Berg (2007) approximated the heating rate (10-20 °C/Myr) by assuming, following Biermeier and Stüwe, that heating rates during regional metamorphism are equivalent to cooling rates, and by taking into consideration published heating rates based on geochronology for the western Lepontine Alps. This study uses the 11.5 \pm 3.5 °C/Myr heating rate of Janots et al. (2009), determined by combining ages and temperatures of formation for monazite and allanite. This procedure yields strain rates for several zones in each sample, thus resulting in high-time-resolution strain rates; it is described in detail in the Methods section.

GEOLOGIC BACKGROUND

Geologic Overview: Central Swiss Alps

Rocks in the Central Swiss Alps (Fig. 1) have a long and complicated pre-Cretaceous tectonic history (Fig. 2), much of which is overprinted by deformation and metamorphism associated with the Cretaceous-Tertiary Alpine Orogeny, which characterizes the present-day region most prominently.

Prior to the Alpine Orogeny, rocks that are now exposed in the Alps experienced a series of orogenic events. The Pan-African Orogeny (Neoproterozoic) (Mercolli et al., 1994) was followed by the Caledonian Orogeny (Ordovician) (Schaltegger, 1994; Biino et al., 1997) and the Variscan Orogeny (Carboniferous) (Coward and Dietrich, 1989; Schaltegger, 1994). A period of extension associated with the formation of the Tethys Ocean during the Mesozoic (165-160 Ma from U-Pb zircon geochronology, Coward and Dietrich, 1989) followed the Variscan orogeny and immediately preceded the Alpine Orogeny (Coward and Dietrich, 1989). The current configuration of the Alpine chain is derived from the paleomorphology of the Tethys Ocean (Coward and Dietrich, 1989). During the same extensional period, another smaller ocean, the Valais Ocean, formed to the north of the Tethys Ocean. Microcontinental fragments, including the Briançonnais terrane, separated the two oceans (Stampfli et al., 1998) (Fig. 3a).

When discussing the Alpine Orogeny, it is useful to subdivide rocks in the Central Swiss Alps into three different paleogeographic domains: (1) the Helvetic domain, which consists of rocks that were initially part of the European plate; (2) the Austroalpine



Figure 1: Schematic map of the Alps from Pfiffner (1993) showing major features and tectonic blocks, including those discussed in the text. The orange star marks the approximate location of the field area investigated in this study.



Figure 2: Timeline from Berg (2007) showing timing of metamorphism, deformation, subduction, rifting, and depositional events for which there is evidence in the Central Swiss Alps. HP = high-pressure metamorphism, Lep. = Lepontine metamorphism

Figure 3 (next page): Cross sections through the Western Alps showing the evolution of the Alpine Orogeny, from Berg (2007) after Marthaler (2002). (a) 100 Ma: initiation of subduction at the southern margin of the Tethys Ocean, when the Valais basin still contained an active spreading center. (b) 60 Ma: closure of the Tethys Ocean and subduction of the Briançonnais microcontinent while the Austroalpine nappes are overthrusting the accretionary prism. (c) 50 Ma: closure of the Valais Ocean, and onset of the Alpine continental collision, as the southern margin of the European continent enters the subduction zone. (d) 35 Ma: near the peak of the Alpine orogeny, as the basement massifs of the European continent are thrust out of the subduction zone.



domain, which includes rocks that were originally part of the Apulian plate (a microplate that broke away from the African plate during the Cretaceous); and (3) the Penninic domain, which is made up of rocks derived from paleogeographic domains between the European and Apulian plates (Coward and Dietrich, 1989) (Figs. 1 and 3).

The precursor to the Alpine Orogeny is the subduction of the Tethys Ocean (Gebauer, 1999). Subduction began on the margin of the Apulian plate about 76 Ma (Brouwer et al., 2004) and continued until about 65 Ma (Brouwer et al., 2004) (Fig. 3a). An accretionary prism formed during this stage on the margin of Apulia. As subduction continued, the Tethys Ocean closed and continent-continent collision-along with the Alpine Orogeny-began with subduction of microcontinental fragments, including the Briançonnais terrane, beneath the accretionary prism during the early Tertiary (Stampfli et al., 1998) (Fig. 3b). During this stage, the Austroalpine nappes were incorporated into the accretionary prism (Coward and Dietrich, 1989). Alpine deformation and metamorphism began about 50 Ma with the entrance of the European plate into the subduction zone on the margin of the Apulian plate (Coward and Dietrich, 1989). The European plate's position immediately below the Valais Ocean during subduction resulted in overthrusting of ophiolite sequences onto the southern margin of the European plate (Coward and Dietrich, 1989) (Fig 3c). The European plate was subducted between 50 and 100 km during the Alpine Orogeny, resulting in high-pressure metamorphism (Marthaler, 2002). Continental crust began to obstruct the subduction zone by the mid-Tertiary, causing backthrusting of continental basement nappes and massifs from the lower part of the accretionary prism (Fig. 3d). This backthrusting also resulted in highpressure metamorphism.

Peak metamorphic temperatures in the Central Swiss Alps range from ~500 °C to 675 °C, and increase from north to south (Kamber, 1993; Todd and Engi, 1997). Pressures reach a maximum of about 7 kbar about 20 km north of the southern border of Alpine metamorphism and decrease to the north and to the south (Todd and Engi, 1997). Fluid chemistry of veins in the Central Swiss Alps is neither homogeneous nor consistent with expected fluid compositions derived from plutons in the region, implying that fluids present during metamorphism in the Central Swiss Alps were not derived from a homogeneous source or from local plutons (Todd and Engi, 1997).

Lepontine Dome

The Lepontine Dome is a window of tectonic uplift that is the dominant metamorphic and structural feature in the Central Alps. Structural and metamorphic features that resulted from metamorphism and deformation in the Lepontine window are the most prominent characteristics of Passo del Sole, the region of interest in the present study.

In contrast to the rest of the Alpine chain, the configuration of the Lepontine Dome was not dictated by the location of the Tethys Ocean. Rather, it resulted from the mid-Tertiary counter-clockwise rotation of the African Plate, which caused a gradual change from north- to west-northwest-oriented collisional structures, imposing a dextral sense of shear along the suture zones (Merle et al., 1989). The radial motions involved in this rotation, along with backthrusting, may have created a zone of extension parallel to the arc, retarding crustal thickening and allowing for uplift of the Lepontine Dome. Metamorphic isograds associated with Lepontine metamorphism crosscut tectonic domains in the Lepontine dome (Frey and Ferreiro Mählmann, 1999), indicating that Lepontine deformation and metamorphism postdate metamorphism and emplacement of nappes related to subduction. Although several mechanisms have been proposed to account for metamorphism in the Lepontine Dome (Bradbury and Nolen-Hoeksema, 1985; Becker, 1993; Engi et al., 1995; Frey and Ferreiro Mählmann, 1999; Brouwer et al., 2004), the most widely accepted theory is that a slab-breakoff or detachment event that post-dates nappe emplacement brought heat into the region from plutons and buoyant pieces of subducted continental crust (Frey and Ferreiro Mählmann, 1999; Brouwer et al., 2004). This process would have created rapid transient heating of overlying materials, which is consistent with observed conditions in the Lepontine Dome (Janots et al., 2009).

The Lepontine Dome consists mainly of Helvetic and Penninic Nappes; the Penninic nappes have been tectonically emplaced above the Helvetic nappes. Also in the Lepontine Dome are the Gotthard and Lucomagno nappes. These nappes have been interpreted to straddle the transition zone between the allocthonous Penninic nappes and the semi-allocthonous Helvetic nappes. For this reason, the Gotthard and Lucomagno nappes are sometimes referred to as Subpenninic or Infrapenninic nappes (Milnes, 1976; Grujic and Mancktelow, 1996).

Deformation in the Lepontine Dome can be divided into three main phases, or five generations of deformation (outlined in Table 1): (1) early thrust emplacement and

	D1	D2	D3	D4	D5
Main structures	thrusting/ isoclinal folding	main post- nappe folding	cross-folds	northern backfolds	collapse folds
Main features		main regional schistocity	crenulation cleavage	weak crenulation	
Tectonic setting	thrusting, crustal thickening	gravitational collapse	unclear	dextral transpression, exhumation	tectonic exhumation
Mineral growth		mica, grt, stt, ky, czo in schist; hbl in amphibolite	poikiloblastic plagioclase, grt, ky, czo in schist	mica	mica, vein systems
Time	late Eocene - Oligocene	Oligocene (pre-Bergell)	late Oligocene (pre- to syn- Bergell	Neogene onset ~20 Ma	Neogene
Chadwick (1968)	nappe transport	В		V	
Thakur (1973)	F1	F2		F3	
Milnes (1974)	early overthrusting	main nappe emplacement	regional isoclinal folding	late-stage deformation	late-stage deformation
Huber et al. (1980)	D1	D2	D3	D3	
Baudin et al. (1993)	D1	D2	D3 (?)	D4	
Shreurs (1993)	D1	D2	D3 (?)		

Table 1: Deformational events for which there is evidence in the Lepontine Dome, along with the terms by which they are referred in studies where they are discussed (from Berg, 2007).

superposition of nappes (D1 in Table 1); (2) intense development of foliation and regional scale folding, during which two generations of deformation developed (D2 and D3 in Table 1); and (3) formation of large-scale back-folds (D4 in table 1). These deformational phases were followed by the tectonic exhumation of the Lepontine Dome, which resulted in local collapse folds (D5 in Table 1) (Chadwick, 1968; Thakur, 1973; Milnes, 1974; Huber et al., 1980; Baudin et al., 1993; Richter et al., 1993; Schreurs, 1993).

The first phase, emplacement of nappes (D1 in Table 1), began with tectonic nappe transport starting in the Miocene (Huber et al., 1980). Uplift of the Lepontine dome at ~ 30 Ma also contributed to the emplacement of nappes in the Lepontine region. This event raised the Penninic nappes relative to the Helvetic nappes (Ridley, 1989).

The second structural phase, during which foliations and large-scale regional folding occurred, can be divided into two generations of deformation. The first (D2 in Table 1) characterizes the current landscape prominently and is defined by multiple large-scale tight folds and well-developed foliation and lineation fabrics (Thakur, 1973; Milnes, 1974). In the Passo del Sole region, on the northern margin of the Lepontine Dome, the D2 event produced an east-west trending schistosity and north-plunging mineral stretching lineations (Lambert et al., 1992). Large-scale folds produced by the D2 event include the Scopi and Piora synforms and the Val de Campo antiform. The Piora Synform is one of the most conspicuous features at Passo del Sole. The D3

event is a less pervasive folding event associated with the folding phase of deformation in the Lepontine Dome. This event produced a crenulation cleavage in the Passo del Sole region (Thakur, 1973). Peak Lepontine metamorphism is thought to be coincident with D2, D3, or with the lull between these two events (Thakur, 1973; Frey et al., 1980).

Lepontine deformation following the folding event was primarily brittle, but the margins of the Lepontine dome, including the Northern Steep Belt and Passo del Sole, acted ductily. Marginal ductile deformation takes the form of backfolding in the Passo del Sole region. This backfolding rotated isograds and deformation indicators like foliations and stretching lineations, so that isograds now dip 35° to the north (Fox, 1975) and fabrics that were originally sub-horizontal are now nearly vertical and commonly overturned (Rosenfeld, 1978, 1985; Merle et al., 1989).

Passo del Sole

Passo del Sole is the specific area of focus of the current study. It is located about 75 km southeast of Luzern on the Northern Steep Belt of the Lepontine Dome (Fig. 4) (Berg, 2007). Rocks at Passo del Sole can be separated into three structural domains: (1) the pre-Mesozoic gneisses of the Gotthard Massif; (2) the metasedimentary Mesozoic cover of the Gotthard Massif; and (3) the pre-Mesozoic gneisses and amphibolites of the Lucomagno nappe, which were tectonically emplaced above the Mesozoic cover sequence (Berg, 2007).

Figure 4 (next page): (a) Regional geologic map of the area between Lukmanier Pass and Passo del Sole, Central Swiss Alps from Berg (2007), based on field relationships observed by Berg (2007) and Chadwick (1968). The black rectangle highlights the Passo del Sole field area and roughly correlates to the outcrop map presented in Figure 10. (b) Chadwick's (1968) N-S cross-section of the Passo del Sole, from Berg (2007). The filled red circle in (b) schematically represents a section through a garnet porphyroblast from the Orange Gneiss. The circular arrow shows a counter-clockwise rotation direction. The white dashed line within the circle represents approximate inclusion trail orientations in garnet crystals from the Orange Gneiss.





Structural features

The most prominent structural features at Passo del Sole are the Piora synform and the tectonic boundary between the Lucomagno nappe and the Mesozoic cover of the Gotthard Massif (Fig. 4) (Berg, 2007). Note that the entire sequence described here and shown in the cross section in Fig. 4 has been overturned by the backfolding event described above.

The Piora synform is a tight fold whose axis runs east-west. Foliation-parallel extension, dismemberment of quartz veins, and boudinaged individual layers all increase toward the core of the Piora synform (Berg, 2007). The tectonic boundary between the two nappes is exposed at Passo del Sole as an east-west striking shear zone between the subvertical Mesozoic cover sequence and the Orange Gneiss in the Lucomagno nappe, subparallel to the axis of the Piora synform (Berg, 2007). Shear-sense indicators like delta clasts and sigmoidal inclusion trails in garnet in the Orange Gneiss (e.g., Fig. 5) imply a south-side-up sense of shear on the fault, and indicate that garnet growth took place during the backfolding event and thus post-dated development of the Piora synform (Rosenfeld, 1978, 1985). In its current configuration, a south-side-up motion would imply that the shear zone acted as a normal fault (Fig. 4); however, in its original orientation before the sequence was overturned, it was a thrust fault with the gneisses of the Lucomagno nappe in the hanging wall moving north over the Gotthard Massif and its Mesozoic cover in the footwall.



Figure 5: Thin-section photos in cross-polarized light (top) and plain-polarized light (bottom) of a non-central section of a garnet crystal from Orange Gneiss Sample PDS 03-2 displaying rotation. Red arrows show the south-side-up sense of shear undergone by the Orange Gneiss. This resulted in a counter-clockwise rotation of garnet porphyroblasts in the unit (when facing east), preserved by s-shaped inclusion trails.
Unit descriptions

The Gotthard Massif comprises weakly foliated granitic gneisses (deformed Variscan intrusions) that consist dominantly of quartz + biotite + muscovite + plagioclase \pm potassium feldspar. The Tremola metasediments, which are commonly garnetiferous and hornblende bearing, are also exposed in the Gotthard Massif, though less abundantly than the metagranitic gneisses (Berg, 2007).

The Mesozoic cover of the Gotthard Massif at Passo del Sole consists of the basal dolomite Räuhwacke (which includes evaporites, carbonates, and dolomitic rocks) overlain by a sequence of metamorphosed marls, mudstones, sandstones, and thin carbonates collectively called the Quartenscheifer.

The Subpenninic Lucomagno nappe was tectonically emplaced above the Mesozoic cover sequence. At Passo del Sole, the Lucomagno nappe consists of the Orange Gneiss, the White Gneiss, and the Brönich Gneiss, with thin layers and lenses of amphibolite dispersed throughout the section (Berg, 2007). The Brönich gneiss is a graphitic, garnet-rich, micaceous gneiss that is not exposed abundantly at Passo del Sole. The White Gneiss is a quartzofeldspathic augen gneiss that is pink to white and lacks garnet and iron staining. Samples in this study are Orange Gneiss, which is a quartzose pelitic unit that weathers to a rust color and crops out along the northern boundary of the Lucomagno nappe. The metamorphic foliation dips steeply to the north (Berg, 2007). The Orange Gneiss has a typical assemblage of quartz + biotite + muscovite + garnet \pm plagioclase \pm chlorite with staurolite, kyanite, ilmenite, and apatite sometimes present in very small modal amounts. Spiral inclusion fabrics in garnet porphyroblasts, which

appear in layers of the Orange Gneiss, record a south-side-up sense of apparent rotation (e.g., Fig. 5) (Rosenfeld, 1978, 1985).

Unique features of Orange Gneiss garnet: Implications for strain-rate calculations

Every garnet crystal in each Orange Gneiss sample studied contains entire, sometimes elaborate, *identical* sequences of chemical zones (e.g. Fig. 6) (Meth and Carlson, 2005), which have been interpreted to result from episodic, externally derived fluid flow (Berg, 2007). These unique zoning patterns, along with other compositional features present in samples from the Orange Gneiss, exhibit evidence for contemporaneity of garnet growth zones, nearly simultaneous nucleation of garnet porphyroblasts, size-proportional growth of garnet crystals, and rock-wide chemical equilibrium. Together, these phenomena make possible unprecedented precision and temporal resolution in strain-rate calculations.

Contemporaneity of growth zones

Meth and Carlson (2005) showed that the garnet growth zones in one sample of Orange Gneiss, AG-4, grew contemporaneously. They posited that formation of the intricate Ca zones, repeated identically in garnet crystals of various sizes throughout AG-4, is conceivable only if each zone in all crystals grew simultaneously. They supported this interpretation with two other lines of evidence that are based mostly on observations of a dominant high-Ca zone observed in all crystals (bright white in Fig. 6).

First, they observed that inclusion trails intersect chemical zones at a particular point in all crystals. In every crystal in AG-4, inclusion trails are straight in central



Figure 6: Calcium X-ray maps of centrally sectioned garnet crystals from Orange Gneiss Sample AG-4 from Passo del Sole, showing that all crystals in AG-4 contain the same unique Ca oscillations (from Meth and Carlson, 2005). Lighter colors correlate with higher Ca concentrations. Green arrows point to intersections of high-Ca annuli (bright white) and inclusion trails. High-Ca annuli intersect inclusion trails at the same point, just after inclusion trails bend, in every crystal throughout AG-4. Similar phenomena that demonstrate contemporaneity of garnet growth zones are observed in all samples from Passo del Sole.

portions, preserving a planar foliation and no rotation during early stages of garnet growth. Inclusion trails are curved in outer portions of every crystal, recording rotation during later stages of garnet growth. The inflection point between the straight and curved sections of each inclusion trail, which represents the point in time when the garnet crystal began to rotate, occurs just inside the high-Ca zone in each crystal (Fig. 6). Assuming that all of the garnet crystals in a single hand sample experienced the same rotation history, the inflection point in all crystals represents a single point in time. Therefore, the intersection of chemical growth zones at the same point near the onset of curvature in inclusion trails in every crystal throughout AG-4 implies that growth of chemical zones was also contemporaneous throughout the sample.

The second piece of evidence found by Meth and Carlson that supports the contemporaneity of chemical zones in AG-4 is the similarity of compositions of unique zones. If, as suggested by textural features, unique zones in every crystal grew at the same time, and if chemical equilibrium was established at that time, each distinct zone should have the same composition in all crystals. Meth and Carlson (2005) found this to be true for the dominant Ca spike in garnet crystals in AG-4.

Subsequent studies that have examined other samples from the Orange Gneiss (Berg, 2007, this study) have found that not only do unique Ca zones have the same composition in all crystals throughout AG-4, but also *every* annulus that is a certain fractional distance from the core of its host crystal, regardless of uniqueness in chemical composition or crystal size, has the same composition in every crystal throughout *each* sample studied to date (cf. Fig. 7). Coupled with the inferences of nearly simultaneous

Figure 7 (next 2 pages): Weight-percent-oxide results of quantitative EPMA traverses between cores and rims of four centrally sectioned garnet crystals of varying sizes from Sample PDS 03-30, a sample from the Passo del Sole locality, Central Swiss Alps, plotted with (a) millimeters from core on the x-axis, and (b) normalized fractional distances on the x-axis. Notice that central MnO concentrations for all crystals are similar. Also note the similarity of the normalized profiles for each crystal in part (b), indicating that compositions at a given fractional distance are the same in every crystal, regardless of size, throughout the sample. This phenomenon is observed in every sample studied to date from Passo del Sole, with the exception of some portions of Mn profiles in Sample AG-4, in which Mn was not in equilibrium at the time of nucleation. Small variations amongst traverses in (b) may be due to slightly misoriented central sections, small differences in nucleation time, or the effects of diffusional competition in the final stages of garnet growth. See text for a more detailed description.



2.0

1.6

0.0 0 🟚

0.8 1.2 mm from core



nucleation of all crystals and size-proportional growth developed below, this suggests that every annulus represents a single point in time and implies that major elements were in equilibrium throughout the garnet growth period. This allows for separation of garnet growth in the Orange Gneiss into discrete time intervals, permitting calculation of strain rates over small increments of time throughout garnet growth.

Near-simultaneous nucleation of garnet crystals

With the interpretation that unique chemical zones in all crystals throughout each sample grew contemporaneously, it is apparent from the geometry of Ca oscillations in garnet from the Orange Gneiss that crystals nucleated nearly simultaneously as well. Repetition of the *complete* set of intricate zones (time markers) in every crystal throughout each sample, regardless of size, indicates that each crystal must have been growing during roughly the same period of time. However, garnet crystals generally lack unique oscillations in their cores, making timing of nucleation slightly ambiguous; although each crystal preserves the entire set of identical oscillations, it would be unclear without further measurement how long before formation of the first oscillation each garnet nucleated. Measurements of AG-4 made by Meth and Carlson (2005) show that in all crystals, the volume of the inner zone (the zone inside the first unique Ca oscillation) makes up no more than 15% of the entire volume of the host crystal. Thus, no more than 15% of garnet growth in the sample had taken place before all crystals had nucleated, implying that if nucleation of all crystals was not simultaneous, it was nearly so.

The central Mn concentration in garnet is commonly used as a proxy for nucleation time in rocks where Mn has equilibrated rock-wide (Meth and Carlson, 2005).

In most samples from the Orange Gneiss, including those examined in this study, central Mn concentrations of garnet porphyroblasts are nearly identical (e.g., Fig. 7), strengthening the argument that all crystals in each sample nucleated nearly simultaneously, and implying that Mn had achieved rock-wide equilibrium at the time of nucleation.

In one Orange Gneiss sample from Passo del Sole (AG-4), central Mn concentrations are not similar, but vary from 4.6 to 8.3 wt.% (Meth and Carlson, 2005). However, the low central-Mn concentrations are limited to crystals in unusual microstructural settings; they are either asymmetrically zoned crystals growing adjacent to quartz veins or mica-free layers, or clusters in which multiple crystals in very close proximity coalesced early in the crystallization interval. In all these cases, Mn concentrations rise outward, so that the mantles and rims of these crystals have Mn compositions that match normal crystals, establishing the same congruence of compositions seen in other samples shortly after the initiation of garnet growth (Meth and Carlson, 2005). Ca zones in AG-4 also show evidence of simultaneous nucleation, as described above.

Size-proportional zones

Meth and Carlson (2005) observed a near-linear positive correlation between crystal radii and thickness of Ca and Mn zones in crystals of various sizes throughout AG-4, indicating that the radial rates of crystal growth are approximately proportional to the radii of the garnet crystals at the time of growth. They determined that each individual crystal obeyed a diffusion-controlled growth rate law. Thus, they inferred that the correlation between crystal radius and radial growth rate represents crystals that grew in compliance with a diffusion-controlled rate law, but in areas with different local matrix compositions; garnet crystals *and* individual zones simply grew faster and larger in regions that were richer in garnet-forming nutrients. Since garnet crystals nucleated simultaneously, this remarkable growth mechanism results in garnet crystals of various sizes, with individual zone thicknesses that are all proportional to crystal size. This phenomenon is observed in all Orange Gneiss samples from Passo del Sole studied to date (Meth and Carlson, 2005; Berg, 2007; this study).

This growth mechanism enables precise calculation of strain rates by allowing for precise calculation of effective bulk composition corresponding to interior growth zones in garnet. As minerals with slow rates of intracrystalline diffusion (including garnet) grow, they effectively sequester the nutrients that constitute them. This isolates these nutrients from the other components of the rock, thereby preventing them from participating in further reaction. This has the effect of decreasing the fraction of these nutrients in the remaining *effective* bulk composition, an input necessary for strain-rate calculations for interior zones in garnet.

Because the width of each individual garnet growth zone—including central zones—is approximately proportional to the size of its host crystal in all crystals throughout each sample at Passo del Sole, the volume fraction of each crystal found inside any arbitrary zone (time marker) is equal to the *total* modal amount of garnet in the sample that crystallized before the time represented by that zone. This allows for more precise calculation of effective bulk composition than is typically possible because the

material sequestered in garnet (removed from the reactive matrix) in an entire sample at any given time during the garnet growth period can be quantified by analyzing a single crystal. Without this remarkable capability, imprecise estimations of effective bulk composition that must rely on unverifiable and potentially unrealistic assumptions (e.g., Biermeier and Stüwe, 2003) would be required. Avoidance of these less-reliable techniques allows for unprecedented precision in the strain rate calculations presented in this study.

Chemical equilibrium

It should be pointed out that rock-wide chemical equilibrium of major elements throughout garnet growth is implicit in the arguments above for contemporaneous growth of zones and simultaneous nucleation of garnet crystals, and is indeed observed in Orange Gneiss samples (with the exception of crystals in unusual microstructural environments, as noted above). Rock-wide chemical equilibrium of Mn at the time of nucleation is implied by nearly identical core Mn compositions; the Mn concentration in the matrix must have been the same throughout each sample at the time of nucleation to yield such similar central Mn concentrations. Compositional similarity of individual annuli in crystals throughout each sample indicates that rock-wide equilibrium was achieved throughout the garnet growth period; at the time when each garnet growth zone formed, the concentration of major elements in the matrix was the same throughout the entire sample.

Rock-wide chemical equilibrium throughout garnet growth allows for use of equilibrium thermodynamic models to calculate temperatures corresponding to garnet growth zone boundaries, which are used to calculate strain rates for several time increments throughout garnet growth.

Implications for strain-rate calculations

Taken together, the contemporaneity of growth zones, the nearly simultaneous nucleation of garnet throughout each sample, the size-proportional growth of garnet, and the chemical equilibrium implied by these features, make the rocks at Passo del Sole incomparably well-suited for extraction of strain rates at high temporal resolution. These features allow for: (1) separation of garnet crystallization in the Orange Gneiss into discrete zones that correspond to time intervals during garnet growth; (2) precise calculation of effective bulk compositions that correspond to each zone boundary; and (3) equilibrium thermodynamic modeling of temperatures for each zone boundary. Combining these temperatures with a heating rate and measured deflections of inclusion trails forms the basis for the approach taken by Berg (2007) and in this study.

PREVIOUS WORK: BERG (2007)

Berg (2007) used the method he developed to calculate strain rates from garnet in the Orange Gneiss unit from the Passo del Sole region in the central Swiss Alps, which is also the focus of the current study. The unique high-temporal-resolution strain rates calculated in his study exhibit twofold to threefold variations over small time increments (~0.25 to 1.5 Myr). Taken together with evidence that unique oscillations in garnet composition result from episodic channelized external fluid flow, Berg's strain-rate results led him to conclude that rapid increases in strain rates were the result of strain softening due to episodic influx of external fluids.

Unique garnet zoning: A result of episodic channelized external fluid flow

Berg's (2007) conclusions are based in part on the interpretation that the unusual zoning observed in garnet at Passo del Sole is due to episodic, open-system fluid flow. There is reason to believe this because episodic, externally controlled fluid flow is common in shear zones. For example, Floyd and Winchester (1983), observing channels of varied mineralogy, found that K-, Rb-, and Ba-rich fluids derived from nearby sediments traveled in well-defined channels in garnet schist within a shear zone in the Ben Hope sill suite in northern Scotland. Marquer et al. (1994) used oxygen isotopes to determine that a Ca-rich fluid moved through channels in mylonites in a shear zone in the Aiguilles Rouges Massif in the Western Alps.

Berg argues that the unique oscillations in garnet composition could not have been caused by progression of reactions due only to changes in pressure and temperature. Pressure and temperature in a regionally metamorphosed setting have regional-scale effects, but the oscillations observed at Passo del Sole, while identical in every crystal throughout a single hand sample, vary for hand samples that are only meters apart, even along strike. This indicates that the oscillations are a result of an agent whose effects are limited to a more local scale.

Berg (2007) also makes the case that oscillations are not a result of mid-growth resorption. It is imaginable that garnet began to grow, and then stopped growing due to changes in pressure, temperature, or both. It may have been resorbed at this point, elevating concentrations of certain elements in its rim, and then begun to grow again. This process would produce an annulus of elevated concentration of certain elements, as seen in samples at Passo del Sole. However, the annulus would be more ragged and discontinuous than the idiomorphic zones in Passo del Sole garnet. Additionally, continuously curved inclusion trails show no evidence for growth hiatuses in Passo del Sole Sole garnet crystals.

Striking evidence of infiltration of externally-derived fluids was observed by Berg (2007) in some uncommon garnet porphyroblasts from Passo del Sole that show almost complete replacement of original prograde-composition garnet by high Mn, low Mg, \pm high Ca garnet (Fig. 8). In these porphyroblasts, material of distinctly different compositions from the original garnet penetrated crystals from rims and edges along interior fractures. This texture is indicative of replacement by fluid mechanisms (Berg, 2007). Also, small garnet porphyroblasts that maintain their original composition are



Figure 8: X-Ray maps (from Berg, 2007) of a portion of a single garnet crystal (crystal edges are most apparent in Ca and Mn maps). Warmer colors represent higher concentrations of each element. Because each map is scaled independently, the same color in different maps correlates to different concentrations. Beam drift during map acquisition gives the appearance of higher concentrations on lower portions of maps, especially apparent in the Ca map. Maps show that almost 80% of original composition has been modified after growth. Notice that islands of protected garnet still preserve original concentric zoning.

included in feldspar, which presumably shielded the small original garnets from outside fluids which otherwise would have altered their compositions.

Finally, an oxygen-isotope study performed by Berg (2007) indicates that fluid present during deformation of the porphyroblasts from the Passo del Sole region was not derived from the Orange Gneiss, but came from either a magmatic or metamorphic source deeper in the section. Berg (2007) also found that samples only meters apart along strike showed opposite trends in the evolution of their stable isotopes. Even more remarkably, isotopic signatures were found to vary across zones within a single garnet. Based on these results and geologic relationships in the area, Berg inferred that metamorphic fluids, derived from devolatilization reactions deep in the Mesozoic cover of the Gotthard Massif (Fig. 4), traveled from depth using the shear zone parallel to the Piora syncline as a conduit, to produce the unique oscillatory zoning in garnets of the Orange Gneiss.

Strain rates and interpretation of variations

Berg calculated strain rates for several garnet growth zones in two samples. One sample includes garnet crystals characterized by a high-Ca annulus, and the other features garnet crystals with a prominent Mn annulus. He found that strain rates increased twofold to threefold in zones of anomalous composition, compared to strain rates in zones of normal composition (Fig. 9). The correlation between elevated strain rates and high-Ca or high-Mn zones, along with evidence that zones of anomalous concentration





Figure 9: Strain-rate results of Berg (2007), for (a) Sample AG-4 and (b) Sample PDS 03-1; from Berg (2007). The translucent blue box in frame (a) highlights high strain rates that correlate with a high-Ca zone. The translucent magenta box in frame (b) highlights elevated strain rates that correlate with a high-Mn zone.

result from episodic channelized flow of external fluids, led Berg to conclude that fluctuations in strain rate are caused by strain softening as a result of fluid flow.

This study seeks to further test this interpretation by using methods similar to those used by Berg (2007) to calculate strain rates from Passo del Sole garnet crystals for two additional samples: one that did not experience significant influx of external fluids and another that did.

METHODS

Strain rate equation

Before deriving the equation used to calculate strain rates, it should be noted that determinations in this study are made under the assumption that porphyroblasts rotate within a matrix, resulting in deflections of inclusion trails within the porphyroblasts, as was proposed by Rosenfeld (1968, 1970). Bell and his colleagues (Bell, 1985; Bell et al., 1992a; Bell et al., 1992b; Hayward, 1992) proposed an alternative case in which the matrix in a rock rotates around porphyroblasts to produce deflections in inclusion trails. The theory of Bell has fallen into disfavor (Johnson et al., 2006), and most workers in the field agree that porphyroblasts. Thus, the methodology implemented in this study regards the garnet crystals as having rotated as isolated rigid spheres in a matrix undergoing pure shear.

Rotation rate is calculated using parameters determinable from rotated garnet porphyroblasts with the equation (Biermeier and Stüwe, 2003):

$$\dot{\omega} = \frac{\omega}{\Delta t} = \frac{\Delta T}{\Delta t} \frac{\omega}{\Delta T},$$
 Eq. 1

For a given growth zone, $\dot{\omega}$ is rotation rate (radians \cdot s⁻¹), ω is the rotation preserved by deflections in inclusion trails in the zone (radians), Δt is the length of time during which

the growth zone grew (s), and ΔT is the change in temperature during the growth of the zone (°C).

The fundamental relationship between rotation rate of rigid objects ($\dot{\omega}$), and instantaneous shear strain rate ($\dot{\gamma}$) in a matrix undergoing simple shear is

$$\dot{\omega} = 0.5 \cdot \dot{\gamma}.$$
 Eq. 2

The relationship defined by Eq. 2 holds because half of the angular shear experienced by a rotating sphere results from rigid-body rotation and the other half is a result of pure shear at 45 degrees to the rotation axis (Simpson and De Paor, 1993). In progressive pure shear, the matrix flows symmetrically around the rigid body and applies equal fiber loading stress to each side, so that the body does not rotate (Simpson and De Paor, 1993). Calculations in this study are carried out under the assumption that the same arguments apply to general shear. That is, both pure shear and rigid-body rotation act on a spherical body (garnet porphyroblast) in equal parts, but the crystal only rotates as a result of the rigid-body rotation component; the pure shear component does not produce any rotation. Therefore, the rotation preserved by the crystal is half of the total shear strain acting on it. This assumption holds only if the crystals studied are allowed to rotate freely in an infinite matrix. The main impediment to the ability of a spherical crystal to rotate freely is the presence of other crystals nearby. In fact, calculations performed by Biermeier and Stüwe (2003) indicate that the rate of rotation can vary from $\dot{\omega} = 0.25 \cdot \dot{\gamma}$ to $\dot{\omega} = 0.75 \cdot \dot{\gamma}$, depending on the number and geometry of other crystals around a porphyroblast. However, additional calculations by Biermeier and Stüwe (2003) indicate that when a distance of at least half of the porphyroblasts' diameters separates surfaces of the crystals, the variability in the cofactor in Eq. 2 is small enough to be ignored. Garnet crystals analyzed in this study are separated by at least this distance from other porphyroblasts. Therefore, Eq. 2 should adequately approximate the relationship between rotation rates and shear-strain rates for garnet crystals in this study.

Eqs. 1 and 2 are combined to form

$$\dot{\gamma} = 2\left(\frac{\omega}{\Delta T} \cdot h\right),$$
 Eq. 3

in which *h* is heating rate (°C/Myr), and is equivalent to the $\Delta T/\Delta t$ term in Eq. 1, presumed constant. Eq. 3 is used in this study to calculate hand-sample-scale strain rates for increments of time corresponding to zones defined by chemical features or by arbitrary volumetric boundaries.

Samples

Two samples from a suite collected from the Orange Gneiss unit at Passo del Sole by Berg in 2002 and 2003 were chosen for strain-rate analyses in this study. These choices were based on reconnaissance analyses (X-ray maps of major elements and EPMA quantitative traverses of non-centrally-sectioned garnet crystals) collected by Berg (2007).

The first sample, PDS 03-30, was chosen because reconnaissance analyses show that garnet crystals in this sample have composition profiles typical of prograde garnet zoning in pelites (e.g., bell-shaped profiles for Mn) and thus appear to have been unaffected by open-system fluid flow. This makes PDS 03-30 useful as a control to test whether or not elevated strain rates are indeed limited to samples that have been affected by fluids—a test not conducted in Berg's (2007) study. The second sample, PDS 03-2, was chosen because garnet crystals in this sample each feature an annulus of anomalously high Ca concentration, a feature that in other samples was regarded by Berg as a result of a transitory influx of Ca-rich fluid. This sample is used to test the robustness of Berg's interpretation by determining if strain rates are elevated in the zone of increased Ca concentration, as is the case in sample AG-4 analyzed by Berg (2007) (Fig. 9).

The locations of the samples studied here were also chosen so that, when examined as a suite with samples studied by Berg, they would allow for comparison of strain rates for samples at different positions with respect to the prominent shear zone, and for comparison of strain rates for samples in close proximity to one another (Fig. 10).

Four garnet crystals from each sample were used to calculate strain rates in this study. Central sectioning and EPMA for one of the crystals from PDS 03-2 were performed by Berg (2007).

Detailed descriptions of each sample can be found in Appendix A.

Sample preparation: Making central sections

Much care was taken to cut and grind garnet crystals through their morphological centers, perpendicular to their axes of rotation. This is crucial to this study for two reasons. First, in order to obtain true compositions of the core and compositions along a core-to-rim traverse of a crystal, the section analyzed must expose the nucleation site for the porphyroblast, which is likely to lie near the morphological center of the crystal. Second, the section perpendicular to the axis about which the crystal has rotated must be



Figure 10: Outcrop sketch map after Berg (2007) showing locations of samples he collected at Passo del Sole. Map area roughly correlates to the area enclosed by the black rectangle in Figure 4. Samples marked by blue circles are examined in this study. Berg (2007) calculated strain rates for samples marked by red circles.

exposed in order to capture the maximum amount of rotation preserved by trails of elongate inclusions.

In order to accomplish this specialized sectioning, first a billet was cut in the shape of a rectangular prism from each oriented hand sample. One surface of the prism was cut perpendicular to foliation and axes of garnet rotation, using the known sense of shear and structural features such as delta clasts as guides. Next, the billet was scanned using high resolution X-ray computed tomography (HRXCT) at the UTCT facility at the University of Texas at Austin Department of Geological Sciences (Appendix S1– supplementary disc). HRXCT analysis yielded a 3-dimensional rendering of the billet, revealing the location of garnet porphyroblasts in the rock and the orientation of inclusion trails within each garnet crystal.

Individual crystals were chosen for further analysis using HRXCT data. Porphyroblasts with inclusion trails visible in HRXCT data and at least half their diameter separating them from other porphyroblasts (to eliminate interference effects) were chosen.

In addition to determining the size and locations of garnet in the billet, HRXCT data were used to confirm that the billet was cut in an orientation such that one face was orthogonal to the axis about which porphyroblasts rotated. This was done by examining 2-D slices of the 3-D HRXCT data through garnet crytals. Slices with the same orientation as the face of the billet were compared to slices whose orientations differed slightly from the orientation of the face of the billet, to verify that the visible rotation of garnet crystals, preserved by inclusion trails, is maximized at the orientation parallel to

the cut face of the billet for both samples. Because the maximum rotation can only be seen when looking at a section through the morphological center of a garnet perpendicular to the axis about which the crystal rotated, it was concluded that the face of each billet was in fact orthogonal to the axis of rotation of garnets within it.

Billets were then carefully ground with a Hilquist thin section machine to the central sections of each crystal, using HRXCT data as a guide. Sections produced are between 0.5 and 2.5 mm in thickness. When the central section was reached, it was polished with diamond paste on a polishing wheel until suitable for electron probe microanalysis.

Electron probe microanalysis

Electron probe microanalysis was performed using the JEOL JXA 8200 microprobe at The University of Texas at Austin. Backscattered electron (BSE) images; wavelength dispersive spectroscopy (WDS) X-ray maps of Mg, Ca, Fe, Mn, Y, and Sc; and quantitative traverses of each crystal were collected. Energy dispersive spectroscopy (EDS) analysis was performed to identify inclusions and matrix phases. BSE images and WDS X-ray maps of Mg, Al, Si, Na, Ca, Ti, K, and Fe were also collected for one representative thin section for each sample. Conditions for and results of EPMA analyses can be found in appendices B, C, and D.

Definition of growth zones

To calculate strain rates for increments of time shorter than the growth period of a whole garnet, each crystal was divided into zones based on chemical zonation and/or simple volumetric subdivision. Since chemical zones are size-proportional and geometrically identical in every crystal throughout each sample (as described in the Geological Background section), a single set of zones characterizes every garnet crystal throughout a sample. Depending on which property was more prominent, the zones for PDS 03-30 and PDS 03-2 were defined using chemical zones, volumetric subdivisions, or a combination of both.

Because PDS 03-30 lacks distinctive chemical zoning patterns, only one chemical zone was used. The most central zone, Zone 1, includes the volume within the annulus defined by the base of the central yttrium peak. The remaining zone boundaries divide crystals into four approximately equal parts by volume, based on radii corresponding to quantitative traverses. That is, Zones 1 and 2 together, Zone 3, Zone 4, and Zone 5 each make up about 25% (an arbitrary percentage) of the volume of each garnet (Figs. 11, 12). Note that the distance between the nucleation site and rim (radius) is not the same for every radial direction outward from the nucleation site of an individual crystal, due to inequant sides and discontinuous rims. Because the volumetric zones are based on the radius of each crystal measured along one radial direction (where the quantitative traverse was collected), and drawn for the remaining sides of the crystal following the shapes of chemical zones, each volumetric zone may make up slightly more or less than 25% of the volume of each garnet. This is especially noticable in Zone 5, where the effect of dicontinuous rims on zone volume percent is greatest.

Nucleation sites were defined by central peaks in Mn concentration (see X-ray maps in Appendix C). The central Mn peak in Garnet Ga does not coincide with the



Figure 11: Volumetric and compositional zone boundaries for four centrally sectioned garnet crystals in sample PDS 03-30, overlain on Ca X-ray maps. Warmer colors indicate higher Ca concentrations. Note that colors in each map are scaled independently, so the same color correlates to different concentrations in different maps. Dashed lines mark inferred zone boundaries. See text for description of each zone.



Figure 12: Quantitative EPMA core-rim traverses of garnet 7 from PDS 03-30. Zones are marked with alternating light gray and white shaded areas and labeled with zone numbers.

morphological center of the crystal or with the maximum Ca concentration. This suggests that Garnet Ga may have grown in anomalous way; it may be the product of early coalescence of two crystals, or its growth may have been impeded by a mineralogical feature such as a quartz vein. For this reason, the zones for Garnet Ga appear to be off-center when overlain on the Ca map, but are consistent with Mn zoning patterns.

Zones for PDS 03-30:

Zone 1: core to base of Y peak

Zone 2: base of Y peak to 25% volume annulus

Zone 3: 25% volume annulus to 50% volume annulus

Zone 4: 50% volume annulus to 75% volume annulus

Zone 5: 75% volume annulus to rim

Zones in garnet crystals in PDS 03-2 were defined based on the sample's remarkable Ca zoning in order to investigate the differences in strain rates between high-Ca and low-Ca zones (Figs. 13, 14). Zone 1 spans the volume from the cores of garnet crystals to the gradual increase in Ca concentration that marks the inner boundary of the high-Ca zone. Zone 2 starts at this inner boundary, encompasses the Ca peak, and ends at the gradual decrease in Ca concentration that designates the outer boundary of the high-Ca zone. Zone 3 is the portion between the high Ca zone and the rim of garnet porphyroblasts. The gradual slope on either side of the Ca peak in PDS 03-2 made defining the zone boundaries ambiguous. Zone boundaries were chosen to make Zone 2, the high-Ca zone, relatively narrow to ensure that strain rates for this zone reflect only



Figure 13: Zones defined by calcium peaks in PDS 03-2 (shown by blue lines in 130, 197, and 409 and red lines in Berg) overlain on Ca X-ray maps collected as part of this study (130, 197, and 409) and by Berg (2007). Warmer colors in 130, 197, and 409 and lighter colors in Berg represent higher concentrations of Ca. The same color does not correlate to the same Ca concentration in all maps. Note that the gradual increases and decreases in Ca concentration (rather than sharp transitions) made defining boundaries for the high-Ca zone ambiguous. The high-Ca zone was kept narrow to ensure that strain rates only reflect times when fluid was present. Zone 2 in garnets 130, 197, and 409 corresponds to Zones 2, 3, and 4 of Berg. See text for description of each zone.



Figure 14: Quantitative EPMA core-rim traverses of garnet 409 from PDS 03-2. Zones are marked with alternating light gray and white shaded areas and are labeled with zone numbers.

periods of time when fluids were present in the sample, not an average that may include times when fluids did not affect the sample as greatly or at all.

Zone 3, defined by the calcium peak, occurs at a larger fractional distance from the core in Garnet 197 than in the other crystals. It is safe to assume that the high-Ca zone represents a single event nonetheless, because it has the same characteristics as the high-Ca zones in the other crystals in PDS 03-2. Under this assumption, the position of the high-Ca annulus at a greater fractional distance from the core in Garnet 197 than in the other crystals suggests that more material grew in Garnet 197 than in other crystals before the high-Ca event occurred. This implies that Garnet 197 may have nucleated slightly earlier than the other crystals in PDS 03-2.

Zones for PDS 03-2:

Zone 1: core to inner bound of high-Ca zone

Zone 2: high-Ca zone

Zone 3: outer bound of high-Ca zone to rim

Measurement of deflections: Determining ω

The rotation angle recorded by trails of elongate inclusions (mostly quartz) in garnet porphyroblasts was measured using backscattered electron images (Fig. 15). ADOBE ILLUSTRATOR was used to draw smoothed curved lines through inclusions in crystals where inclusion trails are less well defined. The lines serve as visual averages in order to disregard inclusions that are not representative of the trends of the inclusion trails. To draw them, orientations of smaller inclusions were preferentially used as



Figure 15: BSE image of garnet 2 from PDS 03-30 showing how deflections in inclusion trails were measured. A smoothed line was drawn to visually average deflections, then lines tangent to inclusion trails or the visual averaging line were drawn at each zone boundary. Angles between tangent lines represent rotation, ω , for each zone. See text for further detail on this method.

guides because they more precisely mark the orientation of the foliated matrix relative to the orientation of the garnet crystal at a specific time. Next, lines tangent to inclusion trails were drawn where the inclusion trail intersects each zone boundary. When it was difficult to determine the orientation of inclusion trails where they intersect zone boundaries, visual averaging lines were used in the place of inclusion trails to draw tangent lines. That is, lines tangent to the *visual averaging line* were drawn where the *visual averaging line* intersects each zone boundary. The deflection angle for each zone, ω (Eq. 1 and 3), is the angle between the tangent lines at the intersection of the inner and outer boundary for that zone. The angle was measured using the ruler tool in ADOBE PHOTOSHOP.

Thermodynamic modeling: Determining ΔT

In order to determine the temperature increase during the growth of a particular zone in a garnet crystal (ΔT in Eq. 3), thermodynamic modeling was used to determine growth temperatures for each zone boundary. The difference between temperatures corresponding to the boundaries of a zone is equal to ΔT for that zone.

The method used in this study diverges from the one used by Berg (2007) in the number of crystals from each sample for which temperatures were calculated. Berg calculated temperatures for one crystal from each sample and related those temperatures to deflections of inclusion trails in that and two other porphyroblasts from the sample to determine strain rates for three total crystals in each sample. He did this under the assumption that temperatures for the same zone boundary in each crystal are identical.

This is a reasonable assumption because all crystals throughout each sample from Passo del Sole are composed of size-proportional zones of identical composition (as described in the Geologic Background section). However, this study seeks confirmation of this assumption by calculating temperatures for each zone boundary in four garnet crystals from each sample, rather than only one.

Thermodynamic models

The models employed in this study compute, from internally consistent thermodynamic databases, the lowest Gibbs-free-energy assemblages, modes, and compositions of minerals for a given bulk composition across a range of pressures and temperatures. They were used to produce an isochemical phase diagram (or "pseudosection") in pressure-temperature space (Fig. 16) for the effective bulk composition corresponding to each zone boundary in four garnets from each sample studied; the methods for estimating these effective bulk compositions are detailed below. Isopleths of Ca concentration, Mn concentration, and Mg number (Mg# = Mg/(Mg+Fe)) in garnet were also modeled for a range of pressures and temperatures. The intersection of the isopleths that correspond to measured concentrations for zone boundaries of interest determines the *P-T* conditions of formation for that zone boundary (Fig. 16).

When all three isopleths failed to intersect at a single point (or nearly so), the Mg# isopleth was used as a primary guide to determine temperature. This was done for two reasons. First, anomalies in Mn and Ca concentrations in garnet have been attributed to temporary influxes of external fluids (Berg, 2007), implying that garnet grew in an open-system environment during these periods. This may produce inaccuracy in calculations

Figure 16 (next page): Diagram showing how pressures and temperatures are determined using THERIAK-DOMINO thermodynamic modeling software. Diagrams are for Zone 2 in Garnet 7 in Sample PDS 03-30. From the bulk composition input by the modeler, isopleths for (a) XMn, (b) XCa, and (c) Mg# are calculated, along with (d) an isochemical phase diagram. Light gray lines in (d) and (e) bound assemblages and represent reactions. The garnet-in line is colored red in (d) and (e) and lines bounding the equilibrium assemblage are wider than lines representing other reactions. Isopleths corresponding to XMn (magenta), XCa (blue), and Mg# (green) for the annulus modeled are highlighted in frames (a-c) and overlain on the isochemical phase diagram in frame (e). The intersection of these isopleths corresponds to the pressure and temperature conditions at which the annulus formed, marked by a filled black circle. This intersection gives a pressure estimate of ~6600 bars and a temperature estimate of ~558°C.


of X(Mn) and X(Ca) isopleths because thermodynamic models assume closed-system behavior. However, a lack of anomalous spikes in Fe and Mg in the samples studied suggests that these elements were relatively unaffected by periods of open-system behavior. Thus Mg# isopleths are presumed to be placed more accurately on the pseudosections than isopleths for Mn and Ca concentrations. Second, as shown by its very steep dP/dT slope, the Mg# isopleth is affected minimally by pressure, making it the best thermometer of the three isopleths. Thus the Mg# isopleth yields the most accurate measurement of temperature, which is the important parameter for strain -rate calculations.

The programs most commonly used to perform thermodynamic calculations of this type are THERMOCALC (Holland and Powell, 1990, 1998; Powell et al., 1998), PERPLEX (Connolly, 1990), and THERIAK-DOMINO (de Capitani and Petrakakis, 2010). THERIAK-DOMINO was used in this study because it is intuitive and user-friendly without sacrificing accuracy or utility (de Capitani and Petrakakis, 2010). THERIAK-DOMINO was used with the database created by Holland and Powell (1998) updated to ds5.5 in 2003, with modifications by Tinkham (Pattison, 2011) (Appendix S1—supplementary disc).

Determining bulk compositions

The thermodynamic models used to calculate temperatures for garnet growth zones in this study require bulk composition as the primary input. Initial bulk composition, which is approximated by the current bulk composition of the sample, was used to model core temperatures. Effective bulk compositions, which take into account the sequestration of material in the armored and thus unreactive previously grown portions of garnet crystals, were calculated to model temperatures at points other than the core.

Several techniques are available for determining initial bulk compositions in rocks (e. g., XRF analysis, wet chemical analysis), but most methods yield estimates of bulk compositions for whole rocks. However, determination of bulk composition by estimating mineral modes and compositions allows for estimation of local (thin-section-scale) bulk composition. This scale is more appropriate for use in thermodynamic models of garnet growth because garnet-forming constituents may be drawn from a small volume around each crystal, not from an entire hand sample (Carlson, 1989, 2002). Thus it was used to estimate initial bulk compositions for this study.

To estimate mineral modes, ADOBE ILLUSTRATOR was used to perform image analysis of WDS X-ray maps of one representative thin section from each sample, cut from garnetiferous layers similar to the layers that include analyzed garnet crystals, and from the same billet as central sections, to ensure lithological similarity. To isolate each phase, calculations were performed using one or more element maps of the thin sections. The steps for isolating phases and estimating modes comply with the following general procedure.

First, the phase of interest was ranked amongst the other phases present based on the concentration of a certain element (e.g., biotite has the second highest Fe concentration of any phase in the rock, behind ilmenite). Next, the phases ranked higher than the phase of interest were isolated, starting with the phases that have the highest concentration of any particular element. For these phases that have the highest concentration of a particular element (*a-type* phases), a threshold was set using ADOBE PHOTOSHOP just below the concentration of this element in the phase, creating an image where only pixels representing that *a-type* phase are white. Phases that do not have the highest concentration of any element (*b-type* phases) were isolated by setting a threshold just below their concentration of a particular element, creating an image that assigns white pixels to all phases with concentrations greater than or equal to that of the *b-type* phase and black pixels to phases with concentrations less than that of the *b-type* phase. Then, phases with higher concentrations of that element were subtracted from the image to isolate the *b-type* phase, so that only pixels representing that phase were white. These steps were repeated for phases of subsequently lower ranks in concentration of any element (with subsequently more *a-* and *b-type* phases that must be isolated first) until the phase of interest was isolated. This was done for all phases in each sample and white pixels were counted to estimate modal amounts for each mineral.

A-type minerals in the samples analyzed in this study are quartz (which has the highest Si concentration of all minerals in the sample), chlorite (highest X(Mg)), ilmenite (highest X(Ti)), apatite (highest X(Ca)), and muscovite (highest X(Al)). B-type minerals are biotite, garnet, and plagioclase. The modal abundance of plagioclase can theoretically be determined by considering it as an *a-type* phase, because it has the highest concentration of Na of all the minerals in the sample. However, low contrast on Na maps between pixels representing plagioclase and those representing micas made differentiating between the phases using a Na threshold difficult. Thus, plagioclase was instead considered as a *b-type* phase.

Determination of the modal amounts of *a-type* phases did not require prior estimation of modes of any other phase, so their modal abundances were determined first. Biotite ranks second in Fe concentration behind ilmenite (*a-type*) and garnet ranks second behind apatite (*a-type*) in Ca concentration. Their modal amounts could be determined after the modes of the corresponding *a-type* minerals were estimated. Plagioclase ranks fourth in Al concentration behind muscovite (*a-type*), biotite (*b-type*), and garnet (*b-type*), requiring that the modal amounts of all of these phases be determined before estimating the mode for plagioclase.

As an example, the following procedure was used to isolate biotite. Biotite has the second highest Fe concentration of all phases in the sample, behind ilmenite. Therefore, in order to isolate biotite based on Fe concentration, it was first necessary to estimate the modal amount of ilmenite. Because ilmenite has the highest Ti concentration of any mineral in the sample (it is an *a-type* phase), it could be isolated by simply setting a threshold on the Ti map just beneath the Ti concentration in ilmenite, coloring ilmenite white and all phases with X(Ti) less than that of ilmenite black. Then, biotite (a *b-type* phase) and ilmenite were isolated together by setting a threshold on the Fe map to color all pixels representing minerals with Fe concentrations less than the Fe concentration in biotite [\leq X(Fe in garnet)] black and all phases with Fe concentrations greater than or equal to that of biotite white. Next, the white pixels from the ilmenite map were subtracted from the white pixels in the biotite + ilmenite map, leaving only pixels representing biotite white (Fig. 17). White pixels were counted to estimate the mode of biotite in the sample.



Figure 17: An example of modal estimation by image analysis (Sample PDS 03-2). White pixels were interpreted to represent either ilmenite or biotite in (a), only ilmenite in (b), and biotite in (c), using the procedure outlined in the text. The image in (a) was created by setting a threshold on the Fe X-ray map, (b) was created by setting a threshold on the Ti X-ray map, and (c) was created by subtracting (b) from (a). The modal percent of biotite is estimated by using ADOBE PHOTOSHOP to count the white pixels and used to calculate initial and effective bulk compositions for thermodynamic modeling.

Modal amounts of all minerals were combined with averages of quantitative EPMA spot analyses of each phase (Appendix D) to determine the initial bulk composition.

Although this method works well for estimating the bulk composition that corresponds to initial growth of garnet, estimation of *effective* bulk composition during mineral growth is a significant challenge encountered by thermodynamic modelers.

Several techniques have been proposed for estimating changes in effective bulk composition during crystallization, but each applies only to samples that possess remarkable characteristics. For example, Marmo et al. (2002) took advantage of unique pronounced chemical and inclusion zoning in garnet porphyroblasts in eclogites from New Caledonia to "remove" inner portions of the garnet porphyroblasts from the initial bulk composition to infer estimates for intermediate bulk composition. Evans (2004) developed a procedure for determining effective bulk composition via a Rayleighfractionation model based on measurement of Mn concentration. This method requires that Mn concentration in garnet be controlled by crystal fractionation. It also is limited to rocks in which a simple curvilinear function describes the relationship between Mn in garnet and Mn, Fe, and Ca contents in the rock. Zeh (2006), working with garnets from the Rhula Crystalline Complex in Germany, developed a method to estimate effective bulk compositions, but it is applicable only to rocks that contain Y-rich garnets with Y profiles that feature a flat plateau.

Biermeier and Stüwe (2003), working on garnet crystals that lacked these sorts of distinctive compositional features, were forced to employ a relatively crude estimation of

effective bulk composition. They used the bulk composition of the rock measured by XRF for modeling temperatures of formation at both the core and rim of the porphyroblasts, under the assumption that all porphyroblasts grew at the same rate and terminated growth at the same time. Therefore, temperature differences were only found by using different isopleths for the core and rim. They justify this on the basis of textural features (similar Mn rim concentrations for porphyroblasts of varying sizes, successively lower with decreasing grain size) that suggest this growth mechanism.

Unique features of garnet from Passo del Sole allow for relatively simple and precise calculation of effective bulk composition. The technique described below was developed and used by Berg (2007) and is employed in this study.

As described in the Geologic Background section, every garnet growth zone is approximately size-proportional to its host garnet in every crystal throughout each sample from Passo del Sole. Thus, the volume comprised by a particular compositional zone (z, mm³) relative to the entire volume of its host porphyroblast (g, mm³) can be used to estimate the volume of the sample comprised by the compositional zone (Z, mm³) relative to the entire volume of garnet in the sample (G, mm³):

$$\frac{z}{g} = \frac{Z}{G}$$
. Eq. 4

Three of the variables in Eq. 4 are known: z and g from measurement of a single crystal, and G from estimation of garnet mode by image analysis. Thus the volume of garnet crystallized in the sample (Z) can be determined for any point during garnet growth.

The material that was sequestered by garnet before the growth of each zone in Samples PDS 03-30 and PDS 03-2 was determined by integrating quantitative compositional data (from EPMA core-rim traverses of each crystal) over the volume Z for all zones crystallized before (inside of) the boundary of interest. This material was subtracted from the initial bulk composition to yield effective bulk compositions for each interior zone boundary.

Heating rate: Determining h

Janots et al. (2009) exploited the replacement of allanite by monazite in their samples from the northern Lepontine Dome to determine a heating rate for Alpine metamorphism. They did this by determining temperatures and ages of formation for each mineral. They calculated a temperature of formation of allanite of 430-450 °C using the thermometer of Beyssac et al. (2002). Monazite started replacing allanite after garnet growth had ended at about 560-580 °C. Using *in situ* sensitive high-resolution ion microprobe (SHRIMP) U-Th-Pb dating, they found ages for allanite (31.5 \pm 1.3 and 29.2 \pm 1.0 Ma) and monazite (18.0 \pm 0.3 and 19.1 \pm 0.3 Ma). By combining these ages and temperatures, they calculated a heating rate of 11.5 \pm 3.5 °C/Myr.

Berg (2007) used Lu-Hf garnet-rutile isotopic dating to determine the age for garnet growth in the Orange Gneiss at Passo del Sole. This age, namely 25.43 ± 0.44 Ma, is weighted toward the age of the garnet core (where Lu is concentrated), and falls in the range of ages for which the heating rate of Janots et al. (2009) applies. Samples used in the determination of the heating rate by Janots et al. are from essentially the same area as

those used in this study; the sample of Janots et al. that is farthest from the field area of this study is ~ six km away, but most samples of Janots et al. were collected from within one km of those used in this study. There are no intervening younger structures. The coincidence of ages and locations of samples used by Janots et al. and in this study permits the use of the regional heating rate determined by Janots et al. (2009) for calculation of strain rates presented here. Thus, 11.5 °C/Myr is used for the heating rate, h, in Eq. 3.

RESULTS

Results of thermodynamic modeling, measurements of deflections recorded by inclusion trails, and results of strain-rate calculations for Samples PDS 03-30 and PDS 03-2 are presented below, followed by an assessment of uncertainties in derived strain rates.

Sample PDS 03-30

Temperatures

The thermal histories of four garnet crystals from PDS 03-30 are described by isochemical phase diagrams (Appendix E) calculated from estimated bulk compositions (Table 2). Isochemical phase diagrams presented here show assemblage stability fields over a range of pressures and temperatures, given the initial or effective bulk composition at each zone boundary for garnets G2, G5, G7, and Ga from PDS 03-30. Intersections of X(Ca), X(Mn), and Mg# isopleths corresponding to each zone boundary (Table 2) were used to determine pressures and temperatures of formation. Isopleths on most

	Bulk composition (mole fraction)													
Zone boundary	Na	Mg	Al	Si	K	Ca	Ti	Mn	Fe	XCa	XMn	Mg#		
					Ga	rnet 2								
Core	0.0123	0.0290	0.1860	0.5720	0.0490	0.0051	0.0115	0.0024	0.0489	0.218	0.106	0.073		
1	0.0124	0.0291	0.1857	0.5730	0.0493	0.0047	0.0115	0.0017	0.0483	0.218	0.084	0.075		
2	0.0126	0.0294	0.1846	0.5767	0.0502	0.0031	0.0117	0.0005	0.0453	0.212	0.040	0.078		
3	0.0128	0.0296	0.1837	0.5794	0.0509	0.0019	0.0119	0.0001	0.0426	0.193	0.017	0.088		
4	0.0129	0.0297	0.1832	0.5813	0.0513	0.0011	0.0120	0.0000	0.0404	0.147	0.007	0.114		
Rim	0.0131	0.0297	0.1822	0.5842	0.0521	0.0002	0.0122	0.0000	0.0371	0.150	0.031	0.179		
Garnet 5														
Core	0.0123	0.0290	0.1859	0.5721	0.0490	0.0049	0.0115	0.0023	0.0491	0.203	0.103	0.071		
1	0.0124	0.0291	0.1857	0.5732	0.0493	0.0043	0.0115	0.0016	0.0486	0.210	0.077	0.070		
2	0.0126	0.0294	0.1846	0.5768	0.0502	0.0031	0.0117	0.0003	0.0453	0.199	0.023	0.084		
3	0.0128	0.0297	0.1837	0.5795	0.0509	0.0019	0.0119	0.0001	0.0425	0.186	0.011	0.104		
4	0.0129	0.0297	0.1832	0.5812	0.0513	0.0010	0.0120	0.0000	0.0407	0.130	0.005	0.127		
Rim	0.0131	0.0297	0.1822	0.5842	0.0521	0.0002	0.0122	0.0000	0.0371	0.114	0.005	0.172		
					Gai	rnet 7								
Core	0.0123	0.0289	0.1859	0.5722	0.0490	0.0050	0.0115	0.0024	0.0489	0.218	0.109	0.068		
1	0.0124	0.0291	0.1855	0.5732	0.0493	0.0047	0.0115	0.0022	0.0478	0.222	0.082	0.075		
2	0.0126	0.0295	0.1845	0.5767	0.0502	0.0033	0.0117	0.0005	0.0450	0.224	0.036	0.090		
3	0.0017	0.0039	0.0244	0.9441	0.0068	0.0002	0.0016	0.0000	0.0054	0.231	0.019	0.100		
4	0.0129	0.0297	0.1831	0.5812	0.0513	0.0014	0.0120	0.0001	0.0404	0.213	0.011	0.114		
Rim	0.0131	0.0297	0.1822	0.5842	0.0521	0.0002	0.0122	0.0000	0.0371	0.146	0.031	0.179		
					Gai	rnet a								
Core	0.0123	0.0289	0.1867	0.5715	0.0490	0.0049	0.0114	0.0021	0.0494	0.208	0.094	0.066		
1	0.0124	0.0291	0.1862	0.5728	0.0493	0.0047	0.0115	0.0011	0.0486	0.221	0.055	0.075		
2	0.0126	0.0296	0.1849	0.5766	0.0502	0.0030	0.0117	0.0002	0.0452	0.203	0.017	0.105		
3	0.0128	0.0299	0.1840	0.5792	0.0509	0.0013	0.0119	0.0001	0.0430	0.117	0.006	0.128		
4	0.0129	0.0298	0.1833	0.5810	0.0513	0.0009	0.0120	0.0000	0.0407	0.103	0.006	0.142		
Rim	0.0131	0.0297	0.1822	0.5842	0.0521	0.0002	0.0122	0.0000	0.0371	0.099	0.015	0.167		

Table 2: Initial and effective bulk compositions and mole fractions used for isopleths for garnet crystals in PDS 03-30. The system is assumed to be saturated with H_2O .

isochemical phase diagrams for PDS 03-30 intersect tightly, but where they do not, the Mg# isopleth was used as a primary guide for extracting temperatures from these diagrams for reasons described in the Methods section.

Temperatures from thermodynamic modeling for each zone boundary in all crystals studied from PDS 03-30 are included in Table 3. All of the garnet crystals studied nucleated at ~533 °C. Temperatures increase for every zone boundary from core to rim and rim temperatures for crystals converge at ~605 °C. Temperatures at each zone boundary for each crystal are within 4 degrees of each other, with the exception of zones 3 and 4. Temperatures presented here agree well with the range of temperatures that Berg (2007) calculated independently from garnet at Passo del Sole (540-600 °C) and fit within the range of temperatures calculated from exchange thermometry by Todd and Engi (1997) for the Lukmanier area.

Deflections

Deflections were measured for each zone in each of four garnets from Sample PDS 03-30. As described in the Methods section, visual averaging lines were drawn using smaller inclusions preferentially and used in place of inclusions where inclusion orientations were difficult to discern. In most zones, it was possible to measure deflections of inclusion trails on either side of the crystal center and an average of the measurements from both sides was used in strain-rate calculations. In some zones in some crystals, however, inclusions were not sufficient for measurement on both sides of the crystal center. In these instances (zones 2-5 in garnet G7, zones 4 and 5 in garnet Ga)

Garnet 2					-	Garnet 5						Gar	net 7		Garnet a					
	Т	ΔT	Δt	ω	Strain rate	Т	ΔT	Δt	ω	Strain rate	Т	ΔT	Δt	ω	Strain rate	Т	ΔT	Δt	ω	Strain rate
	(°C)	(°C)	Myr	(°)	$(10^{-14} \text{ s}^{-1})$	(°C)	(°C)	Myr	(°)	$(10^{-14} \text{ s}^{-1})$	(°C)	(°C)	Myr	(°)	$(10^{-14} \text{ s}^{-1})$	(°C)	(°C)	Myr	(°)	$(10^{-14} \text{ s}^{-1})$
Core	532	-	-	-	-	533	-	-	-	-	533	-	-	-	-	533	-	-	-	-
Zone 1	-	8	0.7	6.6	1.0	-	8	0.7	5.3	0.84	-	8	0.7	4.4	0.7	-	11	1.0	15.6	1.8
Bnd. 1	540	-	-	-	-	541	-	-	-	-	541	-	-	-	-	544	-	-	-	-
Zone 2	-	19	1.7	36.6	2.5	-	14	1.2	21.3	1.9	-	16	1.4	32.5	2.6	-	16	1.4	27.1	2.2
Bnd. 2	559	-	-	-	-	555	-	-	-	-	557	-	-	-	-	560	-	-	-	-
Zone 3	-	13	1.1	12.1	1.2	-	18	1.6	13.9	1.0	-	20	1.7	7.9	0.5	-	17	1.5	30.6	2.3
Bnd. 3	572	-	-	-	-	573	-	-	-	-	577	-	-	-	-	577	-	-	-	-
Zone 4	-	8	0.7	14.3	2.3	-	6	0.5	2.3	0.2	-	12	1.0	6.0	0.6	-	12	1.0	1.1	0.5
Bnd.4	580	-	-	-	-	579	-	-	-	-	589	-	-	-	-	589	-	-	-	-
Zone 5	-	27	2.3	13.2	0.6	-	26	2.3	2.5	0.2	-	16	1.4	6.7	0.5	-	16	1.4	2.0	0.7
Rim	607	-	-	-	-	605	-	-	-	-	605	-	-	-	-	605	-	-	-	-
Average		15	1.3	16.6	1.5	-	14.4	1.3	9.1	0.8	-	14.4	1.3	11.5	1.0	-	14.4	1.3	15.3	1.5
Total	-	75	6.5	82.8	-	-	72	6.3	45.3	-	-	72	6.3	57.5	-	-	72	6.3	76.4	-

Table 3: Summary of temperatures for each zone boundary with temperature changes (ΔT), measured deflections of inclusion trails (ω), and strain rates for each zone from four crystals from Sample PDS 03-30.

the measurement from only one side of the crystal center was used in strain-rate calculations.

Measurements are shown in Fig. 18 and included in Table 3. Note that deflections are reported in degrees, but were converted to radians for calculation of strain rates via Eq. 3. Central inclusions in each crystal are oriented similarly (within 14 degrees of the mean for all crystals) in PDS 03-30 (Appendix F); no correlation between central inclusion orientation and total rotation is observed.

Strain rates

Table 3 summarizes strain rates for PDS 03-30 calculated using Eq. 3. Strain-rate data for crystals from PDS 03-30 are depicted graphically in Fig. 19. Strain rates for PDS 03-30 average 1.2 x 10^{-14} s⁻¹, and vary only by \pm 0.8 x 10^{-14} s⁻¹ across all garnet compositional zones.



Figure 18: Backscattered electron images of four garnet crystals from PDS 03-30. Shown in each frame are volumetric and compositional zones (zone boundaries defined by blue lines), smooth curves used to visually average deflections (black), and tangent lines used to measure deflections in inclusion trails. Dashed red or white lines represent deflection measurements that are less certain. Dashed blue lines approximate zone boundaries for volumes of garnet that appear to be missing. Measurements are tabulated in Table 3.



Figure 19: Strain rate results for zones 1-5 for garnet crystals G2, G5, G7, and Ga from PDS 03-30. Calculated values are shown by colored horizontal lines, which span the temperatures corresponding to each zone. 30% error in strain rate from uncertainties associated with the heating rate (Janots et al., 2009) is shown by the vertical extent of lighter colored rectangles associated with each line.

PDS 03-2

Temperatures

Isochemical phase diagrams for the core and each zone boundary (defined by the high-Ca annulus) in four crystals (Garnets 130, 197, 409, and Berg) from PDS 03-2 (Appendix E), describe the thermal history of garnet in the sample. Isochemical phase diagrams were calculated from initial or effective bulk compositions (Table 4) and isopleths (Table 4) were used as with PDS 03-30 to determine pressures and temperatures of formation.

Temperatures calculated by thermodynamic modeling are included in Table 5. Nucleation (core) temperatures for garnet in PDS 03-2 are ~572 °C. Temperature increased from core to rim for each crystal at similar increments until garnet growth terminated at ~615 °C. Except at the rim, where the outlying temperature for garnet 409 is ~8 °C from the mean, temperatures for each zone are similar for all crystals. As with Sample PDS 03-30, temperatures for PDS 03-2 fall within the range calculated by previous workers for the area (Todd and Engi, 1997; Berg, 2007).

Deflections

Deflections were measured for each zone of each garnet crystal from PDS 03-2 using the method that was used for PDS 03-30. Less-continuous inclusion trails in PDS 03-2 crystals made measuring deflections more difficult, so fewer crystals yielded

	Mole fo	Mole fractions used for isopleths													
Zone boundary	Na	Mg	Al	Si	К	Са	Ti	Mn	Fe	XCa	XMn	Mg#			
Garnet 130															
Core	0.0121	0.0530	0.1453	0.5817	0.0496	0.0018	0.0112	0.0015	0.0685	0.084	0.091	0.117			
1	0.0123	0.0534	0.1432	0.5857	0.0506	0.0016	0.0114	0.0007	0.0643	0.123	0.068	0.122			
2	0.0124	0.0536	0.1425	0.5870	0.0509	0.0013	0.0115	0.0004	0.0632	0.120	0.046	0.129			
Rim	0.0126	0.0539	0.1403	0.5912	0.0519	0.0005	0.0117	0.0000	0.0590	0.056	0.012	0.161			
	Garnet 197														
Core	0.0121	0.0528	0.1454	0.5807	0.0498	0.0020	0.0112	0.0020	0.0683	0.096	0.076	0.099			
1	0.0124	0.0537	0.1420	0.5875	0.0514	0.0009	0.0116	0.0005	0.0619	0.101	0.060	0.113			
2	0.0125	0.0539	0.1411	0.5893	0.0518	0.0007	0.0117	0.0001	0.0603	0.119	0.022	0.125			
Rim	0.0126	0.0539	0.1403	0.5912	0.0519	0.0005	0.0117	0.0000	0.0590	0.090	0.010	0.166			
					G	arnet 409									
Core	0.0121	0.0530	0.1451	0.5819	0.0496	0.0018	0.0112	0.0017	0.0683	0.086	0.099	0.118			
1	0.0122	0.0532	0.1440	0.5840	0.0502	0.0018	0.0114	0.0009	0.0663	0.105	0.070	0.114			
2	0.0123	0.0534	0.1432	0.5854	0.0505	0.0016	0.0114	0.0004	0.0650	0.115	0.036	0.119			
Rim	0.0126	0.0539	0.1403	0.5912	0.0519	0.0005	0.0117	0.0000	0.0590	0.063	0.010	0.150			
	Garnet Berg														
Core	0.0121	0.0530	0.1451	0.5817	0.0496	0.0023	0.0112	0.0015	0.0681	0.111	0.088	0.123			
1	0.0122	0.0532	0.1441	0.5837	0.0501	0.0019	0.0113	0.0012	0.0662	0.110	0.091	0.125			
2	0.0123	0.0536	0.1430	0.5858	0.0506	0.0015	0.0115	0.0003	0.0647	0.113	0.027	0.754			
Rim	0.0126	0.0539	0.1403	0.5912	0.0519	0.0005	0.0117	0.0000	0.0590	0.090	0.012	0.162			

Table 4: Initial and effective bulk compositions and mole fractions used for isopleths for garnets analyzed in PDS 03-2. The system is assumed to be saturated with H_2O . Note that EPMA data for garnet "Berg" were collected by Berg (2007).

	Garnet 130					Garnet 197						Garnet 409						Garnet Berg				
	Т	ΔT	Δt	ω	Strain rate	Т	ΔT	Δt	ω	Strain rate	Т	ΔT	Δt	ω	Strain rate	Т	ΔT	Δt	ω	Strain rate		
	(°C)	(°C)	Myr	(°)	$(10^{-14} \text{ s}^{-1})$	(°C)	(°C)	Myr	(°)	(10 ⁻¹⁴ s ⁻¹)	(°C)	(°C)	Myr	(°)	(10 ⁻¹⁴ s ⁻¹)	(°C)	(°C)	Myr	(°)	$(10^{\cdot 14} \text{ s}^{\cdot 1})$		
Core	574	-	-	-	-	572	-	-	-	-	572	-	-	-	-	572	-	-	-	-		
Zone 1	-	2	0.2	4.1	2.6	-	8	0.7	18.1	2.9	-	4	0.3	2.9	0.9	-	5	0.4	16.0	4.1		
Bnd. 1	576	-	-	-	-	580	-	-	-	-	576	-	-	-	-	577	-	-	-	-		
Zone 2	-	6	0.5	45.5	9.6	-	4	0.3	56.4	17.9	-	4	0.3	51.1	16.3	-	8	0.7	57.0	9.1		
Bnd. 2	582	-	-	-	-	584	-	-	-	-	580	-	-	-	-	585	-	-	-	-		
Zone 3	-	36	3.1	15.5	0.5	-	34	3.0	11.0	0.4	-	28	2.4	13.4	0.6	-	33	2.9	16.0	6.2		
Rim	618	-	-	-	-	618	-	-	-	-	608	-	-	-	-	618	-	-	-	-		
Average	-	15	1.3	21.7	4.3	-	15	1.3	28.5	7.1	-	12	1.0	22.5	5.9	-	15	1.3	29.7	6.4		
Total	-	44	3.8	65.1	-	-	46	4.0	85.5	-	-	36	3.1	67.4	-	-	46	4.0	89.0	-		

Table 5: Summary of temperatures for each zone boundary with temperature changes (ΔT), measured deflections of inclusion trails (ω), and strain rates for each zone from four crystals from Sample PDS 03-2.

measurements from both sides of the crystal center. Measurements are shown in Fig. 20 and included in Table 5. Note that deflections are reported in degrees, but were converted to radians for calculation of strain rates via Eq. 3. Orientations for central inclusions in each crystal in PDS 03-2 are within 9 degrees of the mean for all crystals in PDS 03-2 (Appendix F). A tenuous correlation between central-inclusion orientation and total rotation is observed for Garnet 197 in PDS 03-2; this is discussed in Appendix F.

Strain rates

Table 5 summarizes strain rates calculated for PDS 03-2. These data are depicted graphically in Fig. 21. Strain rates for the low-Ca zones in PDS 03-2 (Zones 1 and 3) are low and similar for every crystal. Strain rates for PDS 03-2 are distinguished by a 2-fold to 16-fold increase during the growth of Zone 2, which is defined by the high Ca-annulus.



Figure 20: Backscattered electron images of three garnets from PDS 03-2 and a Ca X-ray map for one crystal from Berg (2007). Shown in each frame are zones defined based on unique Ca zoning in PDS 03-2 (blue in (a-c), red in (d)), smoothed curves used to visually average deflections (black), and tangent lines used to measure deflections in inclusion trails. Zones 2-4 in (d) correspond to Zone 2 in (a), (b), and (c). Dashed white lines represent deflection measurements that are less certain. Dashed blue lines approximate zone boundaries for volumes of garnet that from X-ray maps appear to be missing or where chemical zones were less apparent. Measurements are summarized in Table 5.



Figure 21: Strain-rate results for zones 1-3 for garnet crystals 130, 197, 409, and Berg from PDS 03-2. Calculated values are shown by horizontal colored lines, which span the temperatures corresponding to each zone. Strain rates calculated for the high-Ca zone are marked with bold dashed lines and strain rates for other zones are marked with thin solid lines. 30% error in strain rate from uncertainties associated with the heating rate (Janots et al., 2009) is shown by the vertical extent of lighter colored rectangles associated with each line.

Uncertainties

Three sources of potentially significant error may affect the uncertainties associated with the strain rates presented above: (1) uncertainty of rotation angle measurements; (2) uncertainty in modeled temperatures; and (3) uncertainty associated with the heating rate determined by Janots et al. (2009).

Rotation-angle measurements

Errors in measurement of deflections of inclusion trails may result from imprecision involved with making central sections. If the central section is not perfectly perpendicular to the axis of rotation, the measured deflections will be less than the actual rotation, resulting in a lower calculated strain rate. To quantify the uncertainties associated with this type of error, slices were made through 3-D renderings of HRXCT data of garnet porphyroblasts at orientations 5, 10, and 20 degrees from the correct orientation, which is perpendicular to the axis of rotation. Deflections were measured on the mis-oriented sections (Appendix G) and used to calculate strain rates for each orientation. This analysis shows that, for small misorientations, strain rates vary by ~ 1.2 percent of the correct strain rate per degree offset from the correct orientation. For example, a misorientation error of 10 degrees for a crystal that preserves an actual strain rate of 1.5 x 10^{-14} s⁻¹ would produce a strain rate of 1.3 x 10^{-14} s⁻¹ [1.3 x 10^{-14} s⁻¹ = 1.5 x 10^{-14} s⁻¹ 14 s⁻¹ - (1.5 x 10⁻¹⁴ s⁻¹ · (0.012 x 10))]. This negligible effect, along with close agreement between deflections measured using slices through HRXCT data corresponding to correct central-section orientations and those measured using BSE images of cut central sections (Appendix G, Tables 3 and 5), implies that uncertainties in strain-rate calculations induced by imprecision in the making of central sections are inconsequential.

Thermodynamic modeling

Uncertainty in modeled temperatures results from a combination of the following: (1) uncertainty associated with THERIAK-DOMINO modeling; (2) errors in estimation of bulk composition; and (3) errors resulting from transient open-system behavior.

Uncertainties in the temperatures (and pressures) derived from thermodynamic models are difficult to quantify, due to the unwieldy amount of experimental data included in the internally consistent databases used by thermodynamic modeling software (de Capitani and Petrakakis, 2010). In this application, however, it is the *precision* of the temperature estimates that matters, not their absolute accuracy, because only the relative differences in growth temperatures enter into the strain-rate calculations. The imprecision of such models is significantly less than their inaccuracies (Plunder et al., 2012).

Errors in estimation of initial bulk composition resulting from estimation of mineral modes for *a-type* minerals (phases that have the highest concentration of a particular element) are relatively inconsequential. Their modes are relatively well-determined using image analysis of X-ray maps because there is a small range of chemical thresholds that can be set in ADOBE PHOTOSHOP that produce a reasonable isolation map for these phases. For example, there is about a 1.8 percentage point range of thresholds that produce a reasonable muscovite map from the aluminum map of the representative thin section for PDS 03-2; a threshold that designates 22.3 percent of the pixels in the aluminum map to be muscovite incorrectly identifies some pixels (that

actually represent garnet or biotite) as muscovite, and a threshold that designates 20.5 percent of the pixels to be muscovite incorrectly identifies some muscovite pixels as other phases. For *b-type* phases (those that do not have the highest concentration of any element), however, errors in modal estimation may accumulate because calculations of modes for *b-type* minerals take in to consideration the modes of other minerals. For this reason, the mode for plagioclase—which is dependent on the modal abundances of three other phases, the most of any mineral—is the most uncertain of all the modes estimated here. However, because plagioclase is present in such low abundances, this uncertainty has little effect on the initial bulk composition.

Errors in the calculation of *effective* bulk compositions, however, may be appreciable, and these errors will tend to be cumulative from beginning to end of the growth interval. The procedure used to compute sequestration during growth treats growth increments as complete spherical annuli around previously crystallized material, and it is evident from X-ray mapping that later-stage annuli are commonly discontinuous.

Zones of elevated Ca and Mn concentration have been attributed to short-lived influxes of externally derived fluid (Berg, 2007), implying that garnet grew in an opensystem environment during these influxes. Equilibrium thermodynamic models assume closed-system behavior, so transient open-system behavior may produce uncertainty in temperatures calculated using these models. To minimize this effect, the Mg# (Mg/(Mg+Fe)) isopleth (green in Appendix E) was used preferentially over X(Ca) and X(Mn) isopleths when all three did not intersect tightly to estimate temperatures at zone boundaries. Fe and Mg display growth zoning typical of prograde garnet in pelites in all garnets studied at Passo del Sole, and show no anomalies during intervals of anomalous Ca or Mn concentration, implying that Fe and Mg remained unaffected during periods of open-system behavior.

Despite these potential sources of uncertainty associated with calculation of temperatures, a number of factors contribute to confidence in the temperature differences used to calculate strain rates. First, calculated temperatures are in good agreement with those modeled independently by Berg (2007) using THERMOCALC (Holland and Powell, 1990, 1998; Powell et al., 1998), and with conventional thermobarometric estimates from Todd and Engi (1997). Second, calculated mineral modes and compositions are realistic, and match reasonably well with measured values in the rocks. Additionally, calculated temperatures increase monotonically from core to rim in every garnet crystal studied, as is expected for a prograde crystallization event. Furthermore, in most cases all three isopleth intersections fall within a narrow temperature interval. Even when isopleths fail to intersect—likely the result of an error in effective bulk composition due to improper sequestration or to open-system influx of components—the slope of the Mg# isopleth is so steep, and the range of possible pressures is so small, that temperatures are tightly constrained.

Most importantly, most sources of potential uncertainty associated with calculation of temperatures would affect every temperature calculated in the same way, so temperature differences, which are the inputs for strain-rate calculations, remain robust despite uncertainty in absolute temperatures.

Heating rate

The heating rate of 11.5 °C/Myr calculated by Janots et al. (2009) carries with it a ± 3.5 °C/Myr uncertainty. Because calculated strain rates are directly proportional to the assumed heating rate, this propagates to a 30% uncertainty in strain rates, shown by error boxes in Figs. 19 and 21.

This analysis treats the heating rate as constant over the thermal interval of garnet growth. If instead the heating rate were to vary, calculated strain rates would vary in direct proportion. It is therefore conceivable that the observed relationships between growth and rotation might reflect changes in heating rate rather than changes in strain rate. This possibility will be discussed, but rejected, in the following section.

DISCUSSION

Much insight may be gained by examining the results of this study alongside those from Berg's similar study in 2007.

First, it should be acknowledged that *average* strain rates for whole garnets in samples AG-4, PDS 03-1, PDS 03-30, and PDS 03-2 are similar. Average strain rates over entire garnet growth periods for each of the four samples fall within 2.2 x 10⁻¹⁴ s⁻¹ of the average for all samples, suggesting uniformity in long-term deformation throughout Passo del Sole. However, comparison of *high-temporal-resolution* strain rates calculated using Berg's method reveals that strain rates vary over short time periods and short distances (Fig. 22). Although total rotation is lowest for PDS 03-30, which has not been affected by fluids, total rotation is not further correlated with strain rate, presumed fluid influx, or distance from the shear zone. Results also show no correlation between strain-rate fluctuations and distance from the shear zone, contrary to original conjectures. However, they do suggest that rheology of metamorphic rocks is more complex than previous methods were able to show, leading to the following points of discussion.

Evidence for strain softening caused by channelized, episodic, external fluid flow

Berg (2007) hypothesized, based on strain-rate results for two samples from Passo del Sole, that elevated strain rates are a result of strain softening caused by episodic, externally controlled fluid flow through the system. Results from this study substantiate Berg's interpretation.



Figure 22: Locality map from Figure 10, after Berg (2007), with strain rates from samples studied by Berg (2007) (AG-4 and PDS 03-1) and in this study (PDS 03-30 and PDS 03-2). Horizontal lines in strain-rate plots represent calculated values and span the zones defined in each sample. Uncertainties in strain-rate calculations are shown by the vertical extent of translucent rectangles above and below each line. Low strain rates are marked with gray lines. Elevated strain rates that correlate with high-Ca garnet growth zones are marked with blue lines and elevated strain rates that correlate with high-Mn garnet growth zones are marked with magenta lines.

Taken together with Berg's (2007) strain rate results, the strain rates calculated in this study show that the correlation of increased strain rates with zones of anomalously high Ca or Mn concentrations, is significant (Fig. 22). While strain-rate profiles differ significantly for each sample studied (because fluid flow is highly channelized), elevated strain rates are found only where anomalous concentrations occur. Strain-rate calculations from AG-4 (Berg, 2007) and PDS 03-2 (this study) both yield strain-rate anomalies that correlate with Ca concentration spikes. PDS 03-1 (Berg, 2007), which is only 5 meters along strike from PDS 03-2, in the same lithologic layer, shows a different profile. However, strain-rate increases recorded by PDS 03-2 also correlate with a dramatic positive concentration anomaly, this time in Mn. The robustness of this relationship between increased strain rate and compositional anomalies (in both Ca and Mn concentration at two different temperatures) strongly substantiates the interpretation proposed by Berg (2007).

As an important corollary, strain rates for PDS 03-30 (which shows no evidence of being significantly affected by fluid flow) further affirm Berg's proposal. The lack of significant variation in strain rates during garnet growth in PDS 03-30 (despite inequality in volumetric zones and the anomalous growth mechanism by which Garnet Ga possibly grew, as discussed in the Methods section) implies that where no influx of fluid is observed, strain rates remain unaffected. This suggests that strain rates recorded by garnet at Passo del Sole do not fluctuate as a result of something other than fluid influx.

Strain rate elevations: An artifact of heating rate increases?

One may observe that since strain rates presented here are calculated using a presumed constant heating rate, and because heating rate is directly proportional to strain rate (Eq. 3), the anomalies seen in strain-rate results may actually be artifacts of temporary increases in heating rate. However, this is not a plausible explanation for the fluctuations for several reasons.

First, the mechanisms proposed to have caused regional Lepontine metamorphism are not likely to have produced localized changes in heating rate. All of these mechanisms (Bradbury and Nolen-Hoeksema, 1985; Becker, 1993; Engi et al., 1995; Frey and Ferreiro Mählmann, 1999; Brouwer et al., 2004), including the most robustly supported theory of slab break-off, in which plutons and buoyant pieces of subducted continental crust are thought to have brought heat into the region (Frey and Ferreiro Mählmann, 1999; Brouwer et al., 2004), are tectonic-scale processes. Thus changes in heating rate associated with any of these mechanisms would affect the entire Lepontine region and any anomalies caused by changes in regional heating rate would be pervasive throughout all samples in the area. Core-to-rim strain-rate profiles that differ significantly for samples that are only meters apart imply that the fluctuations seen in these profiles must have been caused by an event with influence at the local scale.

It is conceivable, however, that heat advection by channelized fluids, which *can* have local effects, caused temporary increases in heating rate. This would result in high values for calculated strain rates. However, conditions required for this mechanism to produce the magnitude and duration of anomalies in strain-rate data presented here are

unrealistic. Strain rates calculated in this study show up to 16-fold increases in strain rate that correspond to no more than 8 °C of temperature change. In order for changes in heating rate to produce these results, heating rate must have increased abruptly by up to 16 times and then returned to its original value within less than 32,000 years. Connolly et al. (1996) modeled heating-rate fluctuations of this magnitude and duration in thermal models for fluid circulation. However, these values were found to be possible only when the fluid responsible for advection is derived from a plutonic source. Where fluids are derived from dehydration reactions in metamorphic rocks, as was shown to be the case in the Orange Gneiss at Passo del Sole by Berg's (2007) oxygen isotope study, an unrealistic amount of lateral flow (> 50 km) is required to produce a detectable change in heating rate due to heat advection by fluids (Connolly et al., 1996).

Further supporting the implausibility of this process, to produce the temporal, thermal, and spatial variations observed in anomalies presented here, heating rate increases would have had to occur at different temperatures and different times in rocks less than 5 meters from one another along strike, and would have had to be, purely by coincidence, consistently linked with compositional anomalies in garnet.

For these reasons, the interpretation that strain-rate anomalies are artifacts of temporary fluctuations in heating rate is considered far less plausible than the interpretation of Berg (2007).

Further implications

Settings like Passo del Sole, where metamorphic fluids affect rocks intermittently as they form, are common (e.g., Floyd and Winchester, 1983; Marquer et al., 1994). Such intermittent influxes of metamorphic fluids fostered the high-temporal-frequency fluctuations in strain rates observed in this study. Thus, elevated strain rates over short intervals of time, as a result of strain softening due to episodic fluid influx, may be a common occurrence. This suggests that time-averaged strain rates may mis-represent the rheology of deforming rocks over short time scales.

Application of this method elsewhere, however, poses a significant challenge. Distinctive features of garnet at Passo del Sole made possible highly precise calculation of effective bulk composition at any point throughout garnet growth. In localities where garnet is not characterized by these unique features, high-time-resolution fluctuations in strain rate may be difficult to resolve.

CONCLUSION

New estimates of hand-sample-scale high-temporal-resolution strain rates from rotated garnet at Passo del Sole, taken together with similar estimates presented by Berg (2007), show that strain rates vary with higher temporal and spatial frequency than has been previously observed. These results substantiate the interpretation of Berg (2007), which holds strain softening caused by transitory influx of externally derived fluid responsible for anomalous strain-rate fluctuations.

This study tested this interpretation by calculating strain rates from two samples: one (PDS 03-2) that features a prominent Ca spike, suggesting that it has been affected by ephemeral external fluid influx; and another (PDS 03-30) that shows no unusual zoning patterns, implying that it has remained apparently unaffected by fluids. Results calculated from Sample PDS 03-2 feature a 2-fold to 16-fold increase in strain rate that correlates with the high-Ca zone, presumably caused by temporary influx of high-Ca externally derived fluid. In contrast, Sample PDS 03-30, which has not been affected by fluid influx, features no elevated strain rates. Rather, it is distinct amongst the other samples studied because its strain rates remain relatively low and similar across all zones.

Therefore, this study strongly substantiates Berg's interpretation that elevated strain rates, which coincide with zones of anomalously high concentrations of Ca and Mn in garnet, are a result of strain softening caused by episodic, externally controlled flow of fluids through the system during garnet growth.

APPENDIX A: SAMPLE DESCRIPTIONS

PDS 03-30

PDS 03-30 was collected from Swiss Grid coordinates (702199, 154251), which is very near the shear zone and is one of the easternmost sample locations in Berg's (2007) collection (Fig. 10). The prograde assemblage of PDS 03-30 is qtz + bt + ms + pl + grt + ilm + ap, with small amounts of retrograde chlorite after garnet. High-resolution X-ray computed tomography (HRXCT) data reveal that while garnet is abundant throughout PDS 03-30 (volumetric mode ~ 5.5%), some layers in the sample, which are spaced ~ 5 mm from one another, are more garnetiferous than others.

Quantitative EPMA core-rim traverses and X-ray maps of sections through morphological centers of four garnets from PDS 03-30 (garnets G2, G5, G7, and Ga) (Appendix C) show that garnet crystals from PDS 03-30 have cores that are high in Mn concentration relative to their rims, with a bell-shaped profile between cores and rims. Iron concentration increases gradually from core to rim, as does Mg concentration. A central plateau followed by a gradual decrease toward the rim characterizes Ca concentration. Yttrium concentration is slightly higher near the nucleation site in crystals in PDS 03-30, forming a small central plateau. PDS 03-30 is remarkable amongst other samples at Passo del Sole because it lacks anomalous spikes in concentration of any element. Garnet porphyroblasts in PDS 03-30 include elongate quartz inclusions with rare apatite inclusions. Inclusions in these porphyroblasts form sigmoidal patterns (Appendix C).

PDS 03-2

PDS 03-2 was collected from Swiss Grid coordinates (70224, 154170). This location is about 40 meters south of the shear zone and 45 meters southeast of PDS 03-30 (Fig 10). The prograde assemblage of PDS 03-2 is qtz + bt + ms + grt + pl + ilm + ap. HRXCT data show that garnets are less abundant in 03-2 than in 03-30 (volumetric mode ~ 3.5%). Garnet is concentrated in layers which are spaced about 8 mm from each other.

Quantitative EPMA traverses and WDS element maps (Appendix C) show that Mn concentrations are flat and relatively high in centers of crystals from PDS 03-2, forming a central Mn plateau. The edge of the plateau is marked by a slight peak in Mn concentration, which is followed by a gradual rimward decrease that resembles a normal bell-shaped curve. Calcium profiles feature a zone of elevated Ca concentration with an inner bound at about 2/3 the distance from core to rim of each crystal. This high-Ca zone makes up about 15% of the volume of each garnet. This Ca-rich zone is characterized by three separate peaks, the central one being the highest. Iron and Mg concentrations largely mimick one another qualitatively in PDS 03-2; they are defined by a flat and relatively low central concentration followed by a gradual increase toward the rim. The
transition between the flat portion and the gradual increase of Mg and Fe coincides with the initial increase in Ca concentration.

Garnet porphyroblasts in PDS 03-2 contain sigmoidal inclusion trails which are comprised moslty of elongate quartz inclusions with some apatite inclusions (Appendix C).

APPENDIX B: EPMA ANALYSIS CONDITIONS

EPMA Quantitative Analysis Conditions

Garnet

Accelerating Voltage: 15 kV Cup Current: 200 nA Probe diameter: 0 (focused) Magnification: 1000x Secondary standards: Olivine P-140, Cr Augite, K412 Glass, An50									
Element Spec. # Crystal	Mg 1 TAP	Al 2 TAP	Y 3 PETH	Ca 3 PETH	Fe 5 LiF	Si 2 TAP	Mn 5 LiF		
Peak count time Bkad count	Peak count time 30 30 40 30 30 30 30 30								
time Primary	Bkgd. count time 15 15 20 15 15 15 15 Primary								
Standard	En100	An100	GlassX	An100	Fa100	An100	MnGar		

	Plagioclase							
Accelerating Voltage: 15 kV Cup Current: 20 nA Probe diameter: 10 Magnification: 1000x Secondary standard: An50								
Element	Na	Al	Ca	К	Fe	Si		
Spec. #	1	2	3	4	5	2		
Crystal	TAP	TAP	PETH	PETH	LiF	TAP		
Peak count								
time	30	15	30	30	30	15		
Bkgd. count	Bkgd. count							
time	10	10	15	10	10	10		
Primary	Am							
Standard	Ab	An100	An100	Orth	Fa100	An100		

			Mica ar	nd Chlo	orite				
Accelerating Voltage: 15 kV Cup Current: 20 nA Probe diameter: 10 Magnification: 1000x									
Element	Na	AI	Ti	К	Fe	Mg	Si	Ca	Mn
Spec. #	1	2	3	4	5	1	2	4	5
Crystal	TAP	TAP	PETH	LiFH	LiF	TAP	TAP	PETH	LiF
Peak count time	30	15	40	30	30	30	15	30	20
kgd. count time	10	10	20	10	10	15	10	15	10
-	Am								
rimary Standard	Ab	An100	Di2Ti	Orth	K412	En100	K412	An100	MnGa

EPMA X-Ray Map Conditions

Garnet maps: major elements								
	Acce Prob M	elerating Cup Curr e diamet lagnifical 1000 x 1 5 to 4.5 25 msec	Voltage: rent: 50 rer: 0 (fc tion: 10 .000 pixe µm pixel dwell tir	15 kV nA ocused) 00x els size me				
Element	Mg	Ca	Fe	Mn	Y	Sc		
Spec. #	Spec. # 1 3 5 5 3 4							
Crystal TAP PETH LIF LIF PETH PETH								
Primary								
Standard	En100	An100	Fa100	MnGar	GlassX	An100		

Garnet maps: low-concentration elements

Accelerating Voltage: 15 kV Cup Current: 1 mA Probe diameter: 0 (focused) Magnification: 1000x 1000 x 1000 pixels 1.5 to 4.5 µm pixel size 50 ms dwell time

Element	Y	Sc
Spec. #	3	4
Crystal	PETH	PETH
Primary		
Standard	GlassX	An100

Maps of representative thin sections

Accelerating Voltage: 15 kV Cup Current: 50 nA Probe diameter: 0 (focused) Magnification: 1000x 1000 x 1000 pixels 15 µm pixel size 25 msec dwell time

Element	Mg	Al	Si	Na	Ca	Ti	K	Fe
Spec. #	1	1	2	2	4	3	3	5
Crystal	TAP	TAP	TAP	TAP	PETH	PETH	PETH	LiF
Primary								
Standard	En100	An100	An100	AmAb	An100	DiTi2	Orth	Fa100

APPENDIX C: GARNET EPMA RESULTS

PDS 03-30

PDS 03-30 Garnet 2







PDS 03-30 Garnet 5







PDS 03-30 Garnet 7





PDS 03-30 Garnet a



PDS 03-30 Garnet a



106

PDS 03-2











PDS 03-2 Garnet 197







PDS 03-2 Garnet 409



1 mm

ľ





PDS 03-2 Garnet Berg



From Berg (2007).

PDS 03-2 Garnet Berg



From Berg (2007).

APPENDIX D: EPMA QUANTITATIVE ANALYSES OF MINERALS OTHER

THAN GARNET

PDS 03-30

	Biotite							
		V	/t. % Oxi	de				
	bt 1	bt 2	bt 3	bt 4	bt 5	Average		
Na2O	0.277	0.382	0.461	0.149	0.194	0.293		
K20	9.009	9.123	8.672	8.383	8.690	8.775		
MgO	11.790	12.009	12.084	12.338	11.799	12.004		
CaO	0.000	0.000	0.000	0.005	0.013	0.004		
MnO	0.066	0.000	0.039	0.025	0.000	0.026		
FeO	17.164	16.250	16.473	17.812	17.540	17.048		
TiO2	1.637	1.652	1.819	1.480	1.670	1.652		
Al2O3	19.340	19.008	19.320	18.489	19.016	19.035		
SiO2	37.040	38.061	38.068	35.750	36.764	37.137		
Total	96.323	96.485	96.936	94.431	95.686	95.972		

Cations (Formula basis = 11 O)

	bt 1	bt 2	bt 3	bt 4	bt 5	Average
Na2O	0.040	0.055	0.065	0.022	0.028	0.042
K20	0.850	0.854	0.807	0.810	0.826	0.829
MgO	1.299	1.313	1.313	1.392	1.309	1.325
CaO	0.000	0.000	0.000	0.000	0.001	0.000
MnO	0.004	0.000	0.002	0.002	0.000	0.002
FeO	1.062	0.997	1.005	1.129	1.093	1.057
TiO2	0.091	0.091	0.100	0.084	0.094	0.092
Al2O3	1.686	1.644	1.661	1.651	1.670	1.663
SiO2	2.739	2.793	2.776	2.708	2.739	2.751
Total	7.771	7.748	7.729	7.798	7.760	7.761

		Muse	covite		
		Wt. %	o Oxide		
	ms 1	ms 3	ms 4	ms 5	Average
Na2O	1.161	1.856	1.984	1.369	1.593
K20	9.391	8.387	8.174	6.489	8.110
MgO	1.735	0.681	0.662	1.460	1.135
CaO	0.000	0.003	0.002	0.000	0.001
MnO	0.022	0.008	0.019	0.000	0.012
FeO	2.081	1.200	1.225	1.859	1.591
TiO2	0.269	0.357	0.408	0.000	0.259
Al2O3	32.116	35.445	35.551	34.188	34.325
SiO2	48.411	46.300	46.421	49.787	47.730
Total	95.186	94.237	94.446	95.152	94.755
	Cation	e (Formu	la hacic -	- 11 0)	
	ms 1	ms 3	mc 4	- 11 0) ms 5	Average
	1115 1	113 5	1115 -	113 5	Average
Na2O	0.150	0.241	0.256	0.173	0.205
K20	0.796	0.713	0.693	0.538	0.685
MgO	0.172	0.068	0.066	0.141	0.112
CaO	0.000	0.000	0.000	0.000	0.000
MnO	0.001	0.000	0.001	0.000	0.001
FeO	0.116	0.067	0.068	0.101	0.088
TiO2	0.015	0.018	0.020	0.020	0.018
AI2O3	2.517	2.786	2.786	2.620	2.677
SiO2	3.218	3.087	3.086	3.236	3.157
Total	6.985	6.979	6.976	6.830	6.942

	Chlorite							
		Wt. d	% Oxide					
	chl1	chl 2	chl 3	chl 4	Average			
Na2O	0.006	0.030	0.030	0.035	0.025			
SiO2	25.656	25.870	25.838	25.711	25.769			
FeO	21.312	21.558	21.839	21.579	21.572			
CaO	0.000	0.017	0.003	0.016	0.009			
MnO	0.054	0.042	0.040	0.054	0.048			
MgO	14.850	14.674	14.740	14.965	14.807			
K20	0.008	0.006	0.011	0.025	0.013			
Al2O3	23.347	22.866	22.720	22.635	22.892			
Total	85.233	85.063	85.221	85.020	85.134			

Cations (Formula basis = 18 O)							
	chl1	chl 2	chl 3	chl 4	Average		
Na2O	0.002	0.008	0.008	0.004	0.005		
SiO2	3.483	3.524	3.519	1.967	3.123		
FeO	2.420	2.456	2.488	1.169	2.133		
CaO	0.000	0.002	0.000	0.001	0.001		
MnO	0.006	0.005	0.005	0.003	0.005		
MgO	3.003	2.977	2.990	1.444	2.603		
K20	0.001	0.001	0.002	0.002	0.002		
AI2O3	3.736	3.672	3.648	5.877	4.233		
Total	12.651	12.645	12.661	10.468	12.106		

	Plagioclase								
	Wt. % Oxide								
	pl 1	pl 2	pl 3	Average					
Na2O	7.569	7.350	8.379	7.766					
SiO2	78.338	78.370	77.839	78.182					
FeO	0.169	0.152	0.325	0.215					
CaO	6.344	6.399	6.346	6.363					
MnO	0.000	0.000	0.002	0.001					
MgO	4.767	4.936	4.910	4.871					
K20	0.860	0.848	0.874	0.861					
AI2O3	1.421	1.451	1.452	1.441					
Total	99.468	99.506	100.127	99.700					

Cations (Formula basis = 8 O)

	pl 1	pl 2	pl 3	Average
Na2O	0.650	0.631	0.719	0.666
SiO2	3.460	3.458	3.434	3.450
FeO	0.006	0.006	0.012	0.008
CaO	0.300	0.303	0.300	0.301
MnO	0.000	0.000	0.000	0.000
MgO	0.314	0.324	0.323	0.320
K20	0.048	0.048	0.049	0.048
Al2O3	0.074	0.075	0.076	0.075
Total	4.852	4.844	4.912	4.869
FeO CaO MnO MgO K2O Al2O3 Total	0.006 0.300 0.000 0.314 0.048 0.074 4.852	0.006 0.303 0.000 0.324 0.048 0.075 4.844	0.012 0.300 0.000 0.323 0.049 0.076 4.912	0.008 0.301 0.000 0.320 0.048 0.075 4.869

PDS 03-2

Biotite and muscovite data are from Berg (2007).

	Biotite								
		١	Nt. % Ox	ide					
	bt 1	bt 2	bt 3	bt 4	bt 5	Average			
Na2O	0.350	0.311	0.310	0.317	0.158	0.289			
K20	9.050	8.515	8.688	8.848	9.277	8.876			
MgO	0.000	11.612	11.419	11.288	11.008	9.065			
CaO	0.000	0.000	0.007	0.000	0.000	0.001			
MnO	11.252	0.000	0.018	0.020	0.003	2.259			
FeO	17.905	18.376	17.601	17.940	19.419	18.248			
TiO2	1.431	1.541	1.601	1.591	1.462	1.525			
Al2O3	18.737	18.761	19.024	18.887	18.793	18.840			
SiO2	37.179	36.979	37.502	37.632	36.278	37.114			
Total	95.904	96.095	96.170	96.523	96.398	96.218			

Cations (Formula basis = 11 O)

	bt 1	bt 2	bt 3	bt 4	bt 5	Average
Na2O	0.053	0.045	0.045	0.046	0.023	0.042
K20	0.905	0.808	0.820	0.834	0.887	0.851
MgO	0.000	1.287	1.259	1.243	1.229	1.003
CaO	0.000	0.000	0.001	0.000	0.000	0.000
MnO	0.747	0.000	0.001	0.001	0.000	0.150
FeO	1.174	1.144	1.089	1.109	1.218	1.147
TiO2	0.084	0.086	0.089	0.094	0.082	0.087
AI2O3	1.732	1.645	1.660	1.645	1.661	1.669
SiO2	2.916	2.751	2.775	2.781	2.720	2.789
Total	7.613	7.766	7.738	7.753	7.822	7.739

Muscovite										
	Wt. % Oxide									
	ms 1	ms 3	ms 4	ms 5	Average					
Na2O	1.804	1.637	1.605	1.201	1.562					
K20	8.286	8.328	8.297	8.890	8.450					
MgO	0.704	0.612	0.805	1.658	0.945					
CaO	0.000	0.000	0.000	0.000	0.000					
MnO	0.008	0.020	0.017	0.000	0.011					
FeO	1.469	1.942	1.706	1.944	1.765					
TiO2	0.357	0.200	0.314	0.234	0.276					
Al2O3	35.577	34.445	34.424	31.951	34.099					
SiO2	46.396	44.865	46.159	47.756	46.294					
Total	94.601	92.049	93.327	93.634	93.403					

	Catior	ns (Formu	ıla basis	= 11 0)	
	ms 1	ms 3	ms 4	ms 5	Average
Na2O	0.233	0.218	0.210	0.079	0.185
K20	0.702	0.729	0.714	0.382	0.632
MgO	0.070	0.063	0.081	0.166	0.095
CaO	0.000	0.000	0.000	0.000	0.000
MnO	0.000	0.001	0.001	0.000	0.001
FeO	0.082	0.111	0.096	0.110	0.100
TiO2	0.018	0.010	0.016	0.012	0.014
Al2O3	2.787	2.785	2.736	3.806	3.028
SiO2	3.083	3.077	3.112	6.434	3.926
Total	6.974	6.994	6.966	10.988	7.981

	Plagioclase						
			Wt.	% Oxide			
	pl 1	pl 2	pl 3	pl 4	pl 5	pl 6	Average
Na2O	12.710	11.520	12.845	12.315	12.713	12.448	12.425
K20	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MgO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CaO	0.956	3.108	0.717	1.674	0.956	1.434	1.474
MnO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
FeO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al2O3	22.656	24.617	22.438	23.310	22.656	23.092	23.128
SiO2	63.675	62.519	63.803	63.289	63.675	63.418	63.397
Total	99.997	101.764	99.803	100.588	100.000	100.392	100.424

Cations	(Formula	basis =	8 0)

			•				
	pl 1	pl 2	pl 3	pl 4	pl 5	pl 6	Average
Na2O	1.094	0.979	1.107	1.055	1.094	1.068	1.066
K2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MgO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CaO	0.045	0.146	0.034	0.079	0.045	0.068	0.070
MnO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
FeO	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al2O3	1.182	1.268	1.172	1.211	1.182	1.201	1.203
SiO2	2.818	2.732	2.827	2.789	2.818	2.798	2.797
Total	5.138	5.124	5.140	5.134	5.138	5.135	5.135

APPENDIX E: ISOCHEMICAL PHASE DIAGRAMS

Following are isochemical phase diagrams representing cores, rims, and each zone boundary for four crystals from Samples PDS 03-30 and PDS 03-2. Light gray and black curves separate assemblage fields and represent reactions. Assemblages are labeled for major fields surrounding the equilibrium assemblage (Pl = plagioclase, Grt = garnet, Bt = biotite, Ms = muscovite, Ilm = ilmenite, And = andalusite, St = staurolite, Qtz = quartz, Chl = chlorite, Zo = zoisite). The garnet-in line is marked in red. Reactions bounding equilibrium-assemblage fields are marked with bold lines. Intersections of Mg# (green), X(Ca) (blue), and X(Mn) (magenta) isopleths represent pressure and temperature conditions under which the zone of interest formed. Filled black circles show equilibrium positions from which temperature and pressure were estimated. The Mg# isopleth was used as the strongest guide where intersections are not tight. Where isopleths are not shown (usually in outer zones), concentrations of the element are very low and not in the field of view. In garnet 197, the X(Mn) isopleth does not cross the equilibrium assemblage field; it is marked with a lighter color than other X(Mn) isopleths. Temperatures are summarized in Tables 4 and 6 in the text.
















































































APPENDIX F: CENTRAL INCLUSION ORIENTATIONS

Assuming near-simultaneous nucleation and garnet rotation in a stationary matrix, the central inclusions in each garnet crystal throughout samples PDS 03-30 and PDS 03-2 should have orientations that are somewhat similar, varying only to the degree that the original foliation departed from being rigorously planar. To test if this expectation is upheld, relative orientations of central inclusions in four garnets from PDS 03-30 and six garnets from PDS 03-2 were estimated. ADOBE PHOTOSHOP was used with HRXCT slices, which are parallel to each other and perpendicular to the axis of rotation, through the morphological center of each crystal. The angle between central inclusions in each crystal and the edge of the PHOTOSHOP window (an arbitrary stationary line) was measured. Results are summarized in the following table.

There is no significant correlation between total rotation (Table 3) and central inclusion orientation in PDS 03-30. In Garnet 197 from PDS 03-2, an anomalous central inclusion orientation may be related to an increased amount of total rotation. The central inclusion orientation in garnet 197 differs by about 15 degrees from the inclusion orientations in crystals 130 and 409 (see table below). A total rotation of 85.5 degrees is recorded in garnet 197, as opposed to 65.1 degrees and 67.4 degrees in crystals 130 and 409 (Table 5). Rotation in the central zone of 197 is 18.1 degrees, compared to 4.1 degrees and 2.9 degrees in garnets 130 and 409. These observations—together with the more rimward position of the high-Ca annuli in crystal 197, compared to crystals 130 and 409—may suggest that garnet 197 nucleated slightly earlier than the other crystals in the

sample. This allows for a longer record of rotation in garnet 197, yielding more total rotation. However, the 14 to 15 degree difference in rotation in Zone 1 amongst crystals in PDS 03-2, which may be related to a difference in central inclusion orientation, propagates to a difference in strain rate for Zone of only 12.4 x 10^{-14} s⁻¹ to 2.2 x 10^{-14} s⁻¹ (Table 5). This does not negate the observation that a sharp increase in strain rate —to 9.1 x 10^{-14} s⁻¹ to 17.9 x 10^{-14} s⁻¹ —correlates with the calcium peak in garnet in PDS 03-2.

Crystal	Angle between central inclusion orientation and edge of screen
PDS 03-30	
G2	70.7
G5	55.7
G7	55.2
Ga	43.7
Gu	-5.7
Average	56.3
St. dev.	11.1
PDS 03-2	
130	31.5
197	16.3
409	33.0
257*	21.8
746**	22.0
-	-
Average	24.9
St. dev.	7.1

* Crystal for which strain rate was not calculated because of mistakes in central sect

** Crystal for which strain rate was not calculated because the crystal was incomplet prohibiting definition of zones.

Note that HRXCT data for garnet Berg was not available, so the central inclusion orie that crystal is not included here.
APPENDIX G: DETERMINATION OF UNCERTAINTY DUE TO CENTRAL-SECTION MISORIENTATION

The following table exemplifies the method for calculating percent error per degree of central-section misorientation from the correct orientation, perpendicular to the axis of rotation, for one garnet crystal. To determine the approximation for error in strain rate resulting from one degree of offset from the correct central section mentioned in the text (1.2 percent of the correct strain rate), an average was calculated from the "percent error per degree offset" averages for six crystals from PDS 03-30, as shown in the subsequent table. Strain rates are calculated using Eq. 3. ΔT is the temperature change over the entire growth of each crystal and is estimated using thermodynamically modeled temperatures of cores and rims for crystals examined in detail in this study. For crystals whose core and rim temperatures were not calculated as part of this study, ΔT was approximated by averaging the temperature differences for crystals whose core and rim temperatures were thermodynamically estimated (which are within 3 °C of one another). The heating rate is that of Janots et al. (2009). The value of ω for each increment of offset in two directions (indicated by positive and negative numbers in the table below) is estimated by measuring rotation displayed by curved inclusion trails in HRXCT slices through morphological centers of garnet crystals oblique to correct central section orientations, as described in the text. Note that values for ω are reported in degrees in the table below, but are converted to radians for use in Eq. 3.

Ga	rn	et	2
----	----	----	---

		Δ <i>T</i> (°C) 75	h (°C/my) 11.5		
Angle misorientation from correct central section (degrees)	Rotation (degrees)	Strain rate (s ⁻¹)	Difference in strain rate from zero misorientation (s ⁻¹)	Difference in strain rate from zero misorientation per degree misorientation (s ⁻¹)	Percent error per degree misorientation
0	81.8	1.4E-14	0	`0	0
5	86.8	1.4E-14	6.8E-16	1.4E-16	0.97
10	87.2	1.4E-14	7.5E-16	7.5E-17	0.53
20	91.6	1.5E-14	1.5E-15	7.5E-17	0.53
-5 -10 -20	76.5 82.5 121	1.3E-14 1.4E-14 2.1E-14	1.1E-15 5.1E-17 6.5E-15	2.1E-16 5.1E-18 3.2E-16	1.52 0.04 2.31
0 5 10 20	81.8 87.7 89.4 88.1	1.4E-14 1.5E-14 1.5E-14 1.5E-14	0 8.3E-16 1.1E-15 9.0E-16	0 1.7E-16 1.1E-16 4.5E-17	0 1.18 0.80 0.32
-5 -10 -20	81.1 90.8 97.7	1.4E-14 1.5E-14 1.7E-14	2.9E-16 1.4E-15 2.5E-15	5.8E-17 1.4E-16 1.3E-16	0.41 0.97 0.90
Average					0.87

Crystal	Average percent error per degree misorientation
Garnet 1	1.22
Garnet 2	0.87
Garnet 4	1.78
Garnet 5	0.37
Garnet 6	1.38
Garnet 7	1.04
Average	1.16

APPENDIX S1: SUPPLEMENTARY DATA

A supplementary disc contains the internally consistent chemical database (Holland and Powell, 1998; Pattison, 2011) used for thermodynamic modeling, and HRXCT data for Passo del Sole Samples PDS 03-30 and PDS 03-2.

REFERENCES

- Baudin, T., Marquer, D. & Persoz, F., 1993. Basement-cover relationships in the Tambo Nappe (Central Alps, Switzerland); geometry, structure and kinematics. *Journal* of Structural Geology, 15, 543-553.
- Baxter, E. F., 2004. Can metamorphic reactions proceed faster than bulk strain? Contributions to Mineralogy and Petrology, 146, 657-670.
- Becker, H., 1993. Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine Dome (Swiss Alps); new evidence for Eocene high-pressure metamorphism in the Central Alps. *Geology*, **21**, 599-602.
- Bell, T. H., 1985. Deformation partitioning and porphyroblast rotation in metamorphic rocks; a radical reinterpretation. *Journal of Metamorphic Geology*, 3, 109-118.
- Bell, T. H., Forde, A. & Hayward, N., 1992a. Do smoothly curved, spiral-shaped inclusion trails signify porphyroblast rotation?: Reply. *Geology*, 20, 1055-1056.
- Bell, T. H., Johnson, S. E., Davis, B., Forde, A., Hayward, N. & Witkins, C., 1992b. Porphyroblast inclusion-trail orientation data; eppure non son girate! *Journal of Metamorphic Geology*, **10**, 295-307.
- Berg, C. A., 2007. Strain rates and constraints on chemical homogeneity and length scales of equilibration during Alpine metamorphism at Passo del Sole, central Swiss Alps. United States.

- Beyssac, O., Goffe, B., Chopin, C. & Rouzaud, J. N., 2002. Raman spectra of carbonaceous material in metasediments; a new geothermometer. *Journal of Metamorphic Geology*, 20, 858-871.
- Biermeier, C. & Stüwe, K., 2003. Strain rates from snowball garnet. Journal of Metamorphic Geology, 21, 253-268.
- Biino, G. G., Marquer, D. & Nussbaum, C., 1997. Alpine and pre-Alpine subduction events in polycyclic basements of the Swiss Alps. *Geology*, 25, 751-754.
- Bradbury, H. J. & Nolen-Hoeksema, R. C., 1985. The Lepontine Alps as an evolving metamorphic core complex during A-type subduction; evidence from heat flow, mineral cooling ages, and tectonic modeling. *Tectonics*, 4, 187-211.
- Braid, J. A., Murphy, J. B. & Quesada, C., 2010. Structural analysis of an accretionary prism in a continental collisional setting, the late Paleozoic Pulo do Lobo Zone, southern Iberia. *Gondwana Research*, **17**, 422-439.
- Brouwer, F. M., van de Zedde, D. M. A., Wortel, M. J. R. & Vissers, R. L. M., 2004. Late-orogenic heating during exhumation; Alpine P-T-t trajectories and thermomechanical models. *Earth and Planetary Science Letters*, 220, 185-199.
- Carlson, W. D., 1989. The significance of intergranular diffusion to the mechanism and kinetics of porphyroblast crystallization. *Contributions to Mineralogy and Petrology*, **103**, 1-24.
- Carlson, W. D., 2002. Scales of disequilibrium and rates of equilibration during metamorphism. *American Mineralogist*, 87, 185-204.

- Chadwick, B., 1968. Deformation and metamorphism in the Lukmanier region, central Switzerland. *Geological Society of America Bulletin*, **79**, 1123-1149.
- Christensen, J. N., 1992. The Sr isotopic measurement of rates of tectonometamorphic processes; case studies in southeastern Vermont, USA and the Tauern Window, Eastern Alps. United States.
- Christensen, J. N., Rosenfeld, J. L. & DePaolo, D. J., 1989. Rates of tectonometamorphic processes from rubidium and strontium isotopes in garnet. *Science*, 244, 1465-1469.
- Christensen, J. N., Selverstone, J., Rosenfeld, J. L. & DePaolo, D. J., 1994. Correlation of Rb-Sr geochronology of garnet growth histories from different structural levels within the Tauern Window, Eastern Alps. *Contributions to Mineralogy and Petrology*, **118**, 1-12.
- Connolly, J. A. D., 1990. Multivariable phase diagrams; an algorithm based on generalized thermodynamics. *American Journal of Science*, **290**, 666-718.
- Connolly, J. A. D., Jamtveit, B. & Yardley, B. W., 1996. Mid-Crustal Focused Fluid Movement: Thermal Consequences and Silica Transport. In: Fluid Flow and Transport in Rocks : Mechanisms and Effects. pp. 235-250, Chapman & Hall, London.
- Coward, M. P. & Dietrich, D., 1989. Alpine tectonics; an overview. *Geological Society Special Publications*, **45**, 1-29.
- de Capitani, C. & Petrakakis, K., 2010. The computation of equilibrium assemblage diagrams with Theriak/Domino software. *American Mineralogist*, **95**, 1006-1016.

- Dickin, A. P., 2005. Radiogenic isotope geology. Cambridge University Press : Cambridge, United Kingdom, United Kingdom.
- Engi, M., Todd, C. S. & Thuering, M., 1995. Exhumation of the Central Alps; metamorphic zoning and the evolution of the paleo P-T-field. *Terra Abstracts*, 7, Suppl. 1, 122-122.
- Evans, T. P., 2004. A method for calculating effective bulk composition modification due to crystal fractionation in garnet-bearing schist; implications for isopleth thermobarometry. *Journal of Metamorphic Geology*, 22, 547-557.
- Floyd, P. A. & Winchester, J. A., 1983. Element mobility associated with meta-shear zones within the Ben Hope amphibolite suite, Scotland. *Chemical Geology*, **39**, 1-15.
- Fox, J. S., 1975. Three-dimensional isograds from the Lukmanier Pass, Switzerland, and their tectonic significance. *Geological Magazine*, **112**, 547-564.
- Frey, M., Bucher, K., Frank, E. & Mullis, J., 1980. Alpine metamorphism along the Geotraverse Basel-Chiasso; a review. *Eclogae Geologicae Helvetiae*, **73**, 527-546.
- Frey, M. & Ferreiro M\u00e4hlmann, R., 1999. Alpine metamorphism of the Central Alps. Schweizerische Mineralogische und Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, 79, 135-154.
- Gebauer, D., 1999. Alpine geochronology of the Central and Western Alps; new constraints for a complex geodynamic evolution. *Schweizerische Mineralogische*

und Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, **79**, 191-208.

- Grujic, D. & Mancktelow, N. S., 1996. Structure of the northern Maggia and Lebendun nappes, Central Alps, Switzerland. *Eclogae Geologicae Helvetiae*, **89**, 461-504.
- Hayward, N., 1992. Microstructural analysis of the classical spiral garnet porphyroblasts of South-east Vermont; evidence for non-rotation. *Journal of Metamorphic Geology*, **10**, 567-587.
- Holland, T. J. B. & Powell, R., 1990. An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations; the system K (sub 2) O-Na (sub 2) O-CaO-MgO-MnO-FeO-Fe (sub 2) O (sub 3) -Al (sub 2) O (sub 3) -TiO (sub 2) -SiO (sub 2) -C-H (sub 2). *Journal of Metamorphic Geology*, 8, 89-124.
- Holland, T. J. B. & Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*, 16, 309-343.
- Huber, M., Ramsay, J. & Simpson, C., 1980. Deformation in the Maggia and Antigorio nappes Lepontine Alps. *Eclogae Geologicae Helvetiae*, **73**, 593-606.
- Janots, E., Engi, M., Rubatto, D., Berger, A., Gregory, C. & Rahn, M., 2009. Metamorphic rates in collisional orogeny from in situ allanite and monazite dating. *Geology*, 37, 11-14.
- Johnson, S. E., Dupee, M. E. & Guidotti, C. V., 2006. Porphyroblast rotation during crenulation cleavage development; an example from the aureole of the

Mooselookmeguntic Pluton, Maine, USA. *Journal of Metamorphic Geology*, **24**, 55-73.

- Kamber, B. S., 1993. Regional metamorphism and uplift along the southern margin of the Gotthard Massif; results from the Nufenenpass area. Schweizerische Mineralogische und Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, 73, 241-257.
- Lambert, P., Marquer, D. & Persoz, F., 1992. Structures sur la bordure sud du socle du Gothard; histoire cinematique tertiaire du Val Rondadura (Alpes centrales suisses). Structures on the southern border of the Gotthard basement; Tertiary kinematic history of Val Rondadura, Central, 72, 325-334.
- Lapen, T. J., Mahlen, N. J., Johnson, C. M. & Beard, B. L., 2004. High precision Lu and Hf isotope analyses of both spiked and unspiked samples; a new approach. *Geochemistry, Geophysics, Geosystems - G [super 3]*, 5,
- Mamtani, M. A., 2010. Strain rate estimation using fractal analysis of quartz grains in naturally deformed rocks. *Journal of the Geological Society of India*, **75**, 202-209.
- Marmo, B. A., Clarke, G. L. & Powell, R., 2002. Fractionation of bulk rock composition due to porphyroblast growth; effects on eclogite facies mineral equilibria, Pam Peninsula, New Caledonia. *Journal of Metamorphic Geology*, 20, 151-165.
- Marquer, D., Petrucci, E. & Iacumin, P., 1994. Fluid advection in shear zones; evidence from geological and geochemical relationships in the Aiguilles Rouges Massif (Western Alps, Switzerland). Schweizerische Mineralogische und

Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, 74, 137-148.

Marthaler, M., 2002. Das Matterhorn aus Afrika. Ott Verlag Thun, Lausanne.

- Mercolli, I., Biino, G. G. & Abrecht, J., 1994. The lithostratigraphy of the pre-Mesozoic basement of the Gotthard Massif; a review. Schweizerische Mineralogische und Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, 74, 29-40.
- Merle, O., Cobbold, P. R. & Schmid, S., 1989. Tertiary kinematics in the Lepontine dome. *Geological Society Special Publications*, 45, 113-134.
- Meth, C. E. & Carlson, W. D., 2005. Diffusion-controlled synkinematic growth of garnet from a heterogeneous precursor at Passo del Sole, Switzerland. *Canadian Mineralogist*, 43, Part 1, 157-182.
- Milnes, A. G., 1974. Post-nappe folding in the western Lepontine Alps. *Eclogae Geologicae Helvetiae*, **67**, 333-348.
- Milnes, A. G., 1976. Note on the modal composition of the Antigorio Gneiss (Lepontine Alps, northern Italy). Schweizerische Mineralogische und Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, 56, 101-103.
- Mueller, W., Aerden, D. & Halliday, A. N., 2000. Isotopic dating of strain fringe increments; duration and rates of deformation in shear zones. *Science*, 288, 2195-2198.

- O'Hara, K., 2007. Reaction weakening and emplacement of crystalline thrusts; diffusion control on reaction rate and strain rate. *Journal of Structural Geology*, **29**, 1301-1314.
- Pattison, D., 2011, Professor.
- Pfiffner, O. A., Raumer, J. F. & Neubauer, F., 1993. The structure of the Alps: an introduction. In: Pre-Mesozoic Geology in the Alps. pp. 3-5, Springer-Verlag, Berlin.
- Plunder, A., Agard, P., Dubacq, B., Chopin, C. & Bellanger, M., 2012. How continuous and precise is the record of P-T paths? Insights from combined thermobarometry and thermodynamic modelling into subduction dynamics (Schistes Lustres, W. Alps). *Journal of Metamorphic Geology*, **30**, 323-346.
- Powell, R., Holland, T. & Worley, B., 1998. Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *Journal of Metamorphic Geology*, 16, 577-588.
- Rey, P. F., Teyssier, C. & Whitney, D. L., 2009a. Extension rates, crustal melting, and core complex dynamics. *Geology [Boulder]*, 37, 391-394.
- Rey, P. F., Teyssier, C. & Whitney, D. L., 2009b. The role of partial melting and extensional strain rates in the development of metamorphic core complexes. *Tectonophysics*, 477, 135-144.
- Richter, C., Ratschbacher, L. & Frisch, W., 1993. Magnetic fabrics, crystallographic preferred orientation, and strain of progressively metamorphosed pelites in the

Helvetic Zone of the Central Alps (Quartenschiefer Formation). Journal of Geophysical Research, **98**, 9557-9570.

- Ridley, J., 1989. Vertical movement in orogenic belts and the timing of metamorphism relative to deformation. *Geological Society Special Publications*, **43**, 103-115.
- Rosenfeld, J. L., 1968. Garnet rotations due to the major Paleozoic deformations in southeast Vermont. Interscience Publishers, New York.
- Rosenfeld, J. L., 1970. Rotated garnets in metamorphic rocks. Geological Society of America (GSA) Boulder, CO, United States.
- Rosenfeld, J. L., 1978. Snowball muscovite in the central Swiss Alps; an internal recorder of tectonometamorphism. *Abstracts with Programs Geological Society of America*, **10**, 481-481.
- Rosenfeld, J. L., 1985. Schistosity. In: pp. 441-461, Acad. Press : Orlando, FL, United States, United States.
- Schaltegger, U., 1994. Unravelling the pre-Mesozoic history of Aar and Gotthard massifs (Central Alps) by isotopic dating; a review. Schweizerische Mineralogische und Petrographische Mitteilungen = Bulletin Suisse de Mineralogie et Petrographie, 74, 41-51.
- Schreurs, G., 1993. Structural analysis of the Schams nappes and adjacent tectonic units; implications for the orogenic evolution of the Penninic Zone in eastern Switzerland. *Bulletin de la Societe Geologique de France*, **164**, 415-435.

- Selverstone, J., Axen, G. J. & Bartley, J. M., 1995. Fluid inclusion constraints on the kinematics of footwall uplift beneath the Brenner Line normal fault, Eastern Alps. *Tectonics*, 14, 264-278.
- Simpson, C. & De Paor, D. G., 1993. Strain and kinematic analysis in general shear zones. *Journal of Structural Geology*, 15, 1-20.
- Stampfli, G. M., Mosar, J., Marquer, D., Marchant, R., Baudin, T. & Borel, G., 1998. Subduction and obduction processes in the Swiss Alps. *Tectonophysics*, 296, 159-204.
- Thakur, V. C., 1973. Events in Alpine Deformation and Metamorphism in the Northern Pennine Zone and Southern Gotthard Massif Regions, Switzerland. *Geologische Rundschau*, 62, 549-563.
- Todd, C. S. & Engi, M., 1997. Metamorphic field gradients in the Central Alps. *Journal of Metamorphic Geology*, 15, 513-530.
- Vance, D. & O'Nions, R. K., 1992. Prograde and retrograde thermal histories from the Central Swiss Alps. *Earth and Planetary Science Letters*, **114**, 113-129.
- Zeh, A., 2006. Calculation of garnet fractionation in metamorphic rocks, with application to a flat-top, Y-rich garnet population from the Ruhla crystalline complex, central Germany. *Journal of Petrology*, **47**, 2335-2356.