Thermal evolution of the Scandian hinterland, Naver nappe, northern Scotland

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SUPPLEMENTARY TEXT

1. SAMPLE DESCRIPTIONS AND STRUCTURAL POSITIONS

Eleven samples containing suitable minerals for geochronology were selected for analysis from a much larger suite of samples collected across the Naver nappe (Fig. 1) and curated at Virginia Tech (Table 1). NT-01 was collected from the leading edge of the Naver nappe near the summit of Ben Kliebrech (see geologic map and review of the area by Strachan 2009), immediately above the Naver thrust. NT-02, 03 and 04 were collected from the leading edge of the nappe exposed on the north side of Loch Naver, while NT-05 was collected immediately above the Naver thrust exposed on the north coast. Samples NT-07, 08 and 09, were collected from the center of the Naver nappe to the east of Loch Naver, while NT- 06 was collected from a similar structural position on the north coast. Samples NT-10 and 11 were collected from the trailing edge of the Naver nappe in the footwall to the Skinsdale thrust.

The Naver nappe, and the Moine Supergroup is, in general, dominated by psammitic lithologies, with minor exposures of pelitic rocks, most of which occur within a few km of the outcrop position of the Naver thrust (Figure 1b). Most of the psammitic samples in this study (Samples NT-06, 07, 08, 09, 10 and 11) are composed of quartz and two feldspars, with 5-15% biotite and accessory phases including monazite, xenotime, zircon, and apatite. The presence of monazite and xenotime in these samples allows us to place robust temperature constraints on rocks that are lacking in more typically useful metamorphic minerals. Muscovite is generally absent from psammitic lithologies, except for rare occurrences of highly resorbed individual grains. One sample (NT-02) is a calc-silicate, containing, quartz, plagioclase, potassium feldspar, biotite, hornblende, titanite, zircon, apatite and magnetite. Evidence for crystallized melt, including symplectites and fine-grained aggregates of quartz and feldspar, is common in many pelitic and psammitic samples (including samples NT-06, NT-09, NT-11, and MT-09-94A – collected adjacent to NT-01 near the summit of Ben Klibreck). Pelite samples (NT-01, 03, 04 and 05) typically consist of quartz, plagioclase, garnet, biotite, muscovite, and ilmenite with accessory monazite, xenotime, apatite, rutile and zircon. Sample NT-03 contains graphite. Only two of our samples (NT-03 and NT-04), both located on the leading edge of the Naver nappe, contain sillimanite which is a typical product of melting reactions (Figure 2a). NT-03 and 04 also contain small amounts potassium feldspar (Figure 2b). Although there is abundant outcrop (pervasive granitic veining) and microscale evidence of crystallized melt, there is very little evidence of *in situ* partial melting. Finally, a sample from the same location as NT-04 contains a single grain of kyanite in a leucocratic vein, in addition to sillimanite in the matrix. The hypothesized *P-T* path for NT-04 passes into the kyanite stability on the retrograde path, which may explain this minor occurrence of kyanite.

2. INFORMATION ON ADDITIONAL ANALYTICAL METHODS

2.1 Electron probe microanalysis

Electron probe microanalysis (EPMA) was carried out at the University of Massachusetts and Virginia Tech. Full thin section compositional mapping of major elements, Ce and Y was performed by Wavelength Dispersive Spectroscopy (WDS) at 200-300 nA current and 15 kV accelerating voltage. Full thin section maps help to identify as many monazite and xenotime grains as possible while placing later geochronology in a larger microtextural context (Williams & Jercinovic 2002; Williams *et al.* 2006). WDS maps of Y Lα, Th Mα, Ca Kα, Nd Lα and U Mα in individual monazite and xenotime grains (Figure 3) was carried out to guide laser ablation spot placement and characterize trace element zoning. Maps of Al Kα, La Lα, Fe Kα, and Zr Lα, were collected for selected titanite grains. Backscatter electron imaging was used to characterize all titanite grains that were dated. All WDS maps within each sample were simultaneously processed to give x-ray count rates for each element the same color value in compositional images (Williams *et al.* 2006). Note that monazites grains in our suite of samples (Figure 3) were not all processed simultaneously, but grains within a given sample were. Monazite and xenotime compositional maps were collected at 100-200 nA current, 50-80 ms pixel dwell time, and pixel step size of 0.5-1 μm.

Quantitative EPMA data were obtained for garnet, biotite, plagioclase, muscovite and chlorite in sample NT-04 (Table 2). A beam current of 15 nA was used for all quantitative analyses. Total weight percent oxides were typically 98-102% for garnet and plagioclase, 95-97% for muscovite and biotite. Analyses of included phases and those with totals outside these ranges were not used.

X-ray maps of major elements (Si, Al, Fe, Mg, Mn, K, Na, Ca and Ti) were collected in a 10x10 mm area of NT-04 for use in the program XMapTools (Lanari *et al.* 2014). X-ray intensity drift corrections were made for each of these elements (Lanari *et al.* 2014). Individual pixel compositions were calculated based on a calibration of X-ray intensities (De Andrade *et al.* 2006; Lanari *et al.* 2014) that included analyses from all minerals (garnet, biotite, plagioclase, muscovite and chlorite). This functionally assumes that the background X-ray intensities for each element is the same in each mineral (Supplementary Figure 1). This approach was only used for muscovite and greatly improved the apparent meaningfulness of the calculated compositions, relative to the individual standardization method. The Fe, Al and K contents of muscovite calculated by this method were primarily used to estimate the conditions of muscovite equilibration in NT-04 (see below).

2.2 Laser ablation split-stream ICPMS

Laser ablation split-stream (LASS) inductively coupled plasma mass spectrometry was used to collect U-Pb isotopic data and trace element compositions at the University of California at Santa Barbara employing the methods of Kylander-Clark *et al.* (2013) with modifications as outlined in McKinney et al. (2015). U-Pb measurements were made using a Nu Instruments Nu Plasma HR multicollector ICP-MS and trace elements were measured on an Agilent 7700S quadrupole ICP-MS. Counting time for analyses was 20 or 30 seconds. Monazite ‘44069’ (monazite and xenotime; Aleinikoff et al., 2006) and titanite ‘MKED1’ (Spandler *et al.* 2016) were used as the primary U-Pb reference materials. Bananeira (monazite and xenotime; Kylander-Clark *et al.* 2013; Gonçalves *et al.* 2016) and BHVO-2G (titanite; Jochum *et al.* 2005) were used as primary reference materials for trace elements. Iolite (v 2.5) was used to reduce all data (Paton *et al.* 2011). Bananeira and Y17 (Spencer *et al.* 2013) were used as secondary U-Pb standards for monazite and titanite, respectively. The additional uncertainty required to achieve an MSWD of 1 for each isotope ratio in the group of secondary standards in a run was quadratically added to each unknown. Additional uncertainties were 1-3% for monazite and xenotime (Bananeira) and 2-4.5% for titanite (Y17). In nearly all runs the average 206Pb/238U age of Bananeira was within 1% of the accepted value. Analyses of Y17 and the accept isotope ratios fall on a discordia line with a lower intercept of 390±6 Ma (MSWD = 6.4) and the accepted age is 385.5 Ma. Concordia ages and U-Pb weighted averages were calculated in Isoplot (v 4.1, Ludwig, 2008) and plotted in Python (Figure 4). To account for external uncertainty, an additional 1% error was added to the final ages of all our monazite and populations (Table 4, Figure 7-8). Analyses that had greater than ±10% discordance, or an obvious lack of compositional or isotopic fit with a population of analyses, were not included in concordia age calculations. Monazite, xenotime and titanite data are included in Supplementary Tables 1 and 2, respectively. Note that our analyses of the MKED secondary reference titanite have a weighted average of 232±3 ppm Zr (n = 31, MSWD = 1.3) and the accepted value is 236±13 ppm (Spandler *et al.* 2016).

2.3 XRF

The bulk composition of samples NT-03 and NT-04 were measured by X-Ray Fluorescence (XRF) at Franklin and Marshall College on a PANalytical 2404. Fe3+ was measured by titration. The results of these analyses are shown in Supplementary Table 3.

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