Chemical (U–Th–Pb) dating of monazite: Analytical protocol for a LEO 1450VP scanning electron microscope and examples from Rogaland and Finnmark, Norway

TROND SLAGSTAD

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Monazite is a common accessory mineral and is a valuable mineral chronometer on account of its relatively high U and Th contents, negligible common Pb, and a high closure temperature. Because all the Pb present in monazite is derived from decay of U and Th, an age can be calculated based on the concentrations of U, Th and Pb. This contribution presents the analytical protocol for U–Th–Pb chemical dating of monazite using a LEO 1450VP scanning electron microscope. Using the analytical protocol described here, approximately 15 spots can be analysed in 24 hours. Instrumental drift during analytical sessions is monitored by repeated measurements of internal standards. Monazites of known age, ranging from Palaeoproterozoic, through Mesoproterozoic to Palaeozoic, yield chemical ages that are well within error of the isotopic ages. One pelite sample from the contact aureole to the Egersund anorthosite complex in the Sveconorwegian province, Rogaland contains monazite inclusions in garnet that yield a mean age of 1002 ± 17 Ma, interpreted to represent regional high-grade Sveconorwegian metamorphism, whereas matrix monazites yield a mean age of 923 ± 19 Ma, corresponding to anorthosite magmatism and thermal overprinting. A kyanite-biotite schist from Sørøya in the West Finnmark Caledonides, the type area of the elusive Late Cambrian Finnmarkian event, contains monazites with a mean age of 416 ± 10 Ma. This observation suggests that the high-grade metamorphism in the West Finnmark Caledonides was related to the Scandian event, and does not lend support to the existence of a Finnmarkian event in this area.

Trond Slagstad, Geological Survey of Norway, 7491 Trondheim, Norway
E-mail: Trond.Slagstad@ngu.no

Introduction

Monazite is a light rare earth element (LREE) phosphate that is found as an accessory phase in a variety of rock types. In addition to LREEs, monazite can contain up to several thousand ppm of U and several wt.% Th; in contrast, Pb is typically excluded from the monoclinic structure, which means that nonradiogenic Pb can be neglected for most practical purposes. Diffusion of major and trace components in monazite appears to be slow (Parrish 1990, Cherniak et al. 2004) and monazite is commonly zoned with respect to composition and age, preserving multiple age and/or compositional domains within a single thin section, and in many cases within a single grain. These factors combine to make monazite well suited for in situ spot analysis which, combined with microstructural and microchemical analysis, can yield information about the timing and nature of polymetamorphic events in a sample (e.g., Williams et al. 1999, Pyle & Spear 2003, Foster et al. 2004).

Isotopic dating of monazite is possible using a number of techniques, most commonly TIMS (single grain analysis) (e.g., Schärer 1984, Parrish 1990), SIMS and SHRIMP (spot analysis) (e.g., Stern & Berman 2000), and more recently LA–ICP-MS (e.g., Foster et al. 2002). In the last decade or so, however, electron microprobe analysis has proved an efficient, accurate and precise alternative to more expensive and less accessible isotopic dating techniques (Parrish 1990, Suzuki & Adachi 1991, Montel et al. 1996, Cocherie et al. 1998). In the latter method, the age is determined from the U, Th and Pb concentrations of the monazite by iteratively solving the age equation of Montel et al. (1996). The age calculation assumes negligible common Pb, that the isotopes of U are present in their crustal abundances, and that the elemental concentrations have not been significantly modified by diffusion.

The purpose of this contribution is to describe the analytical protocol for chemical dating of monazite using the LEO 1450VP scanning electron microscope (SEM) at the Geological Survey of Norway (NGU). The benefits of this method compared with the LA–ICP–MS analyses, also performed at NGU, is the ability to analyse smaller grains or individual domains within single grains, and to perform routine analysis directly on standard polished thin sections. The method has been developed and tested by analysing monazites of known age (Palaeoproterozoic, Mesoproterozoic and Early Devonian), determined by isotopic SHRIMP and TIMS dating (Fig. 1). The method was then employed to two

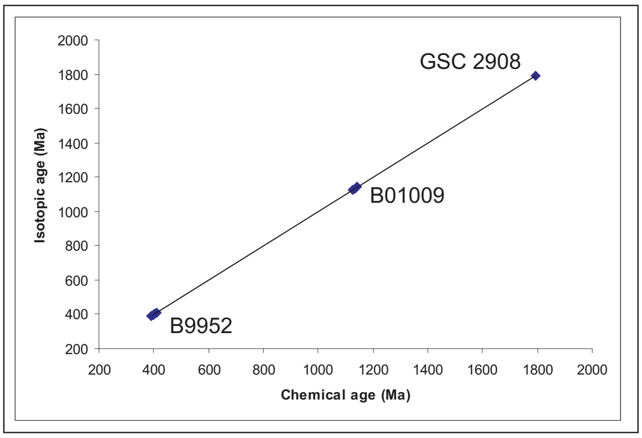

Fig. 1. Comparison of U–Th–Pb chemical ages, determined using NGU's LEO 1450VP scanning electron microscope with ages determined using isotopic methods (SHRIMP and TIMS) for samples IP165, IP249 and GSC 2908.

pelite samples; one from the contact aureole of the c. 930 Ma Egersund anorthosite complex in Rogaland, Southwest Norway, and another from Sørøya in West Finnmark, North Norway, the type area of the elusive c. 500 Ma Finnmarkian orogeny (Fig. 2).

The LEO 1450VP scanning electron microscope

The scanning electron microscope facility at NGU consists of a 1450VP electron microscope from LEO Electron Microscopy Ltd. (now Carl Zeiss) equipped with X-ray detection systems Energy 400 and Wave 500 from Oxford Instruments. The X-ray detection system includes an energy dispersive spectrometer (EDS) and a single wavelength dispersive spectrometer (WDS) for trace and critical element analysis. During monazite analysis, the EDS is used for quantitative determination of P, Ca, La, Ce, Pr, Nd and Sm, and the WDS is used for determination of Y, Th, U and Pb concentrations.

Calibration

Calibration for EDS measurements (except Sm) is conducted on the SPI Monazite standard from Kulyk Lake, Saskatchewan, Canada. Sm calibration is done using a synthetic $Sm_3Fe_5O_{12}$ standard. In both cases, a counting time of 100s is used. Calibration of Y, Th, U and Pb is conducted using both synthetic and natural standards, summarised in Table 1.

Besides U, Th and Pb, which are used to calculate the age, Y is analysed for reduction of interference. For typical monazite compositions, the Y L1α and Th Mα lines are free from interference (Pyle et al. 2005). Pb Mα is chosen over Pb Mβ because the analytical precision of Pb Mα, after correction for Th and Y interference, is greater than Pb Mβ, except for very Th-rich monazite (> c. 10 wt.% Th) (Pyle et al. 2005).

U Mβ is chosen over U Mα based on the lesser interference of Th Mγ on U Mβ than Th Mβ on U Mα (Pyle et al. 2005). Pyle et al. (2005) presents a comprehensive discussion on x-ray line interferences and their correction.

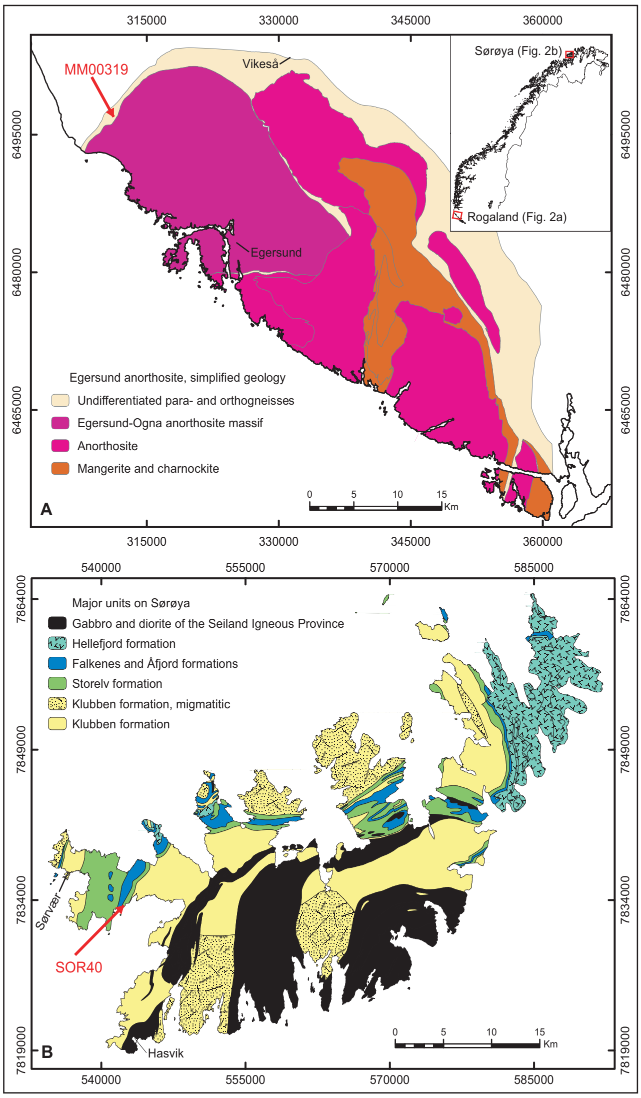

Fig. 2. (A) Simplified geological map of the Egersund anorthosite province and surrounding area, after Marker et al. (2004), showing the location of sample MM00319. UTM coordinates for zone 32, WGS84. (B) Geology of Sørøya, after Roberts (1973), showing the location of sample SOR40. UTM coordinates for zone 34, WGS84.

Analysis

After calibration, the monazite analyses are conducted using the routine protocol for quantitative analysis on the SEM. EDS measurements are conducted using 400s counting time with the collimator adjusted to c. 30% deadtime. Counting times for WDS measurements are summarised in Table 1.

The age calculation is performed by entering the concentrations of Y, Pb, Th and U in an Excel spreadsheet developed by Michael J. Jercinovic of the University of Massachusetts. The spreadsheet can be downloaded from http://geoinfo.nmt.edu/labs/microprobe/monazite/home.html and solves the age equation given in Montel et al. (1996) by iteration until a solution is reached to 0.001 Ma. The spreadsheet corrects for the interference of Y Lα on Pb Mα. The error reported on the age is at the 1σ level.

Table 1. SEM settings for monazite chemical age calibration and analysis.

Element	Crystal	Line	Standard	Accelerating voltage (keV)	Beam current (nA)	Peak* (mm)	Low bkg (mm)	High bkg (mm)	Peak time (s) Calibration	Total bkg time (s) Calibration	Peak time (s) Analysis	Total bkg time (s) Analysis
Y	PET	$L\alpha$	SPI Crocoite	15	100	6.448	6.380	6.499	100	100	150	150
Pb	PET	$M\alpha$	SPI YAG	15	100	5.286	5.217	5.426	100	100	600	600
Th	PET	$M\alpha$	ThO_2	15	100	4.137	4.080	4.200	100	100	300	300
U	PET	$M\beta$	UO_2	15	100	3.716	3.560	4.160	100	100	450	450

Wave dispersive spectrometer settings are specific to the LEO 1450VP scanning electron microscope at the Geological Survey of Norway. A peak search is conducted for each element prior to both calibration and analysis. Elements are analysed by atomic number (Y first, Pb last). YAG = yttrium aluminium garnet. *The peak is determined by doing a peak search before each new analysis, and therefore changes slightly from time to time.

In contrast to electron microprobes that are commonly equipped with several WD spectrometers allowing simultaneous analysis of Y, Pb, Th and U, the single WD spectrometer on the SEM requires consecutive analysis of these elements. This means that each spot analysis takes about 75 minutes. For this reason the SEM's Automate-function is used routinely, allowing users to predefine spots which can be analysed automatically. This way, approximately 15 spots can be analysed in a day. Instrumental drift during analytical sessions lasting up to 24 hours or more is monitored by repeated measurements of internal standards (monazite from samples B9952 and B01009, discussed below).

Chemical mapping of single grains

A characteristic feature commonly observed in monazite is the presence of compositional domains that, in many cases, coincide with distinct age domains (e.g., Williams et al. 1999, Terry et al. 2000, Dahl et al. 2005). The compositional domains may not be discernible in BSE or CL images but are readily identified in compositional (most commonly Y, Th, U, Pb) maps of the monazite grain (e.g., Figs. 3A, B). Such chemical mapping can be routinely undertaken using the Mapping function on the SEM with a beam current of 3 nA and an accelerating voltage of 20 kV.

Chemical ages from samples of known age

The analytical procedure described above has been employed on 3 samples of known age. The samples are B9952 (Early Devonian), B01009 (Mesoproterozoic) and the Geological Survey of Canada in-house standard 2908 (Palaeoproterozoic). Below, the chemical ages obtained by the SEM are compared with reference isotopic ages determined by SHRIMP and/or TIMS. Fifty spot analyses from 7 grains from sample B9952, 21 spots from 3 grains from sample B01009 and 32 spots from several grains from sample GSC 2908 are used to evaluate the accuracy of the chemical ages obtained using the SEM at NGU. The complete dataset is presented in Slagstad (2005).

Table 2. Chemical ages from single grains obtained using the SEM at NGU, compared with isotopic ages obtained using the SHRIMP.

Sample	Wt. mean chemical age (Ma)	n	Wt. mean SHRIMP age (Ma)	n
B9952-1	410 ± 6	13	408 ± 10	1
B9952-3	403 ± 5	8	396 ± 14	2
B9952-4	392 ± 8	6	397 ±11	3
B9952-5	389 ± 10	2	397 ± 14	2
B9952-6	403 ± 7	11	407 ± 14	2
B9952-7	398 ± 11	5	407 ± 10	1
B9952-8	399 ± 15	5	412 ± 10	1
B01009-02	1132 ± 13	10	1130 ± 14	2
B01009-03	1143 ± 36	6	1123 ±	2
B01009-05	1126 ± 14	5	1132 ± 10	1
GSC 2908	1793 ± 15	32	1795 ± 1	

SHRIMP ages from B9952 and B01009 are reported as $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$, respectively, due to the higher analytical precision of $^{206}Pb/^{238}U$ ratios in relatively young samples, and vice versa for relatively old samples. n = number of spot analyses.

Seventeen SHRIMP analyses of monazite from sample B9952 yield a unimodal age distribution with a weighted mean $^{206}Pb/^{238}U$ age of 402 ± 5 Ma (MSWD = 0.67), corroborated by TIMS analysis yielding an age of 403 ± 5 Ma (Bingen, Davis & Hamilton, unpubl. data). All calculations are made using the Isoplot/Ex (rev. 2.49) program (Ludwig 2001). Fifty-one SEM analyses from the same sample yield a weighted mean age of 401 ± 3 (MSWD = 1.80); averaged data from the 7 grains analysed are presented in Table 2. Twelve SHRIMP analyses of monazite from sample B01009 define a unimodal age distribution with a weighted mean $^{207}Pb/^{206}Pb$ age of 1134 ± 8 Ma (MSWD = 1.60) (Bingen & Hamilton, unpubl. data). Twenty-one SEM analyses from the same sample yield a weighted mean age of 1130 ± 9 Ma (MSWD = 1.17); averaged data from the 3 grains analysed are presented in Table 2. Sample GSC 2908 is a monazite standard from the Geological Survey of Canada, dated at 1795 ± 1 Ma (Stern & Sanborn 1998). Thirty-two SEM analyses from several grains of the standard yield a weighted mean age of 1793 ± 15 (MSWD = 2.40) (Table 2).

The chemical analyses from monazites of known age presented in Table 2 and Fig. 1 show that the accuracy and precision of the SEM analyses are comparable to that obtained by isotopic analysis.

Example 1: Pelite from the contact aureole to the Rogaland anorthosite complex, SW Norway

The Rogaland–Vest Agder sector of the Sveconorwegian Province in southwestern Norway (Fig. 2A) consists of locally migmatitic orthogneisses, megacrystic granitoid orthogneisses, and paragneisses ranging in composition from pelite, quartzite, quartz-diopside gneiss to marble (Hermans et al. 1975). Early geochronological studies of megacrystic granitoid orthogneisses and a pyroxene syenite in Rogaland by Wielens et al. (1980) yielded ages between 1070 and 1030 Ma (U–Pb, zircon), interpreted to reflect the age of high-grade regional Sveconorwegian metamorphism. A more recent study based on zircon SHRIMP U–Pb data yielded an age of c. 1000 Ma for regional Sveconorwegian metamorphism in the area (Möller et al. 2003). Previous isotopic dating of monazite from megacrystic granitoid orthogneisses in Rogaland with a crystallisation age of c. 1050 Ma (Bingen & van Breemen 1998b), yielded ages ranging from 1024 to 997 Ma, interpreted to reflect Sveconorwegian metamorphism (Bingen & van Breemen 1998a, Möller et al. 2003). A spread of monazite ages down to 970 Ma was interpreted by Bingen & van Breemen (1998a) to represent the waning stages of this event, but actually overlaps with a Re–Os age on molybdenite at 973 ± 4 Ma, interpreted by Bingen & Stein (2003) to date granulite-facies metamorphism. Thus, although an age of c. 1000 Ma is generally cited as the age of regional Sveconorwegian high-grade metamorphism in South Norway, the spread in interpreted metamorphic ages spans c. 100 million years. Whether this span in ages represents data collected on material of mixed ages or a prolonged or polystage regional Sveconorwegian metamorphic history is currently unknown.

The Rogaland anorthosites were emplaced into the high-grade Sveconorwegian gneisses at 931 ± 2 Ma and intrusion of the Egersund–Ogna massif, close to the site where the investigated sample was collected, took place at 929 ± 2 Ma (Schärer et al. 1996). The magmatism created a contact aureole that extends c. 20 km from the intrusive contact, corresponding to the orthopyroxene-in isograd in quartz-bearing metapelites and plagioclase–clinopyroxene-bearing metabasites. An osumulite-in and a pigeonite-in isograd lie c. 10–13 and 5 km from the contact, respectively (Tobi et al. 1985). The temperatures estimated for these isograds are c. 750°C for the appearance of hypersthene, 880°C for osumilite and 900–1000°C for pigeonite (Jansen et al. 1985, Tobi et al. 1985, Westphal et al. 2003). The extensive width of the contact aureole around the Rogaland anorthosite complex relative to comparable anorthosite intrusions elsewhere has been explained by emplacement of two pulses of magma separated by c. 3 million years (Westphal et al. 2003). In addition to the 1024–970 Ma monazite ages discussed above, Bingen & van Breemen (1998a) identified another group of monazites ranging in age from 930 to 925 Ma, attributed to contact metamorphism related to the emplacement of the Egersund massif. Somewhat surprisingly, samples from the granulite-facies domain in the vicinity of the massif contained little evidence of this event. Bingen & van Breemen (1998a) proposed that a lack of a reagent mineral in the investigated orthogneiss, e.g., allanite, could provide an explanation for the lack of regrowth of monazite. This interpretation is corroborated by the new data presented below, where monazites from a pelite adjacent to the Egersund–Ogna massif show clear evidence of growth or resetting between 930 and 920 Ma.

In order to test if the protracted geological history of the Sveconorwegian gneisses in Rogaland is preserved in monazite and can be resolved through chemical monazite dating, monazites from a fine-grained, garnet-rich pelite were analysed. Sample MM00319 was collected within a few tens of metres from the Egersund–Ogna massif (Fig. 2A), i.e., within the pigeonite-in isograd. The analysed monazites can be subdivided petrographically into grains that occur as inclusions in garnet and grains in the matrix (Table 3). Ten analyses from five monazite inclusions in garnet yield ages ranging from 1074 to 975 Ma with a weighted mean age of 1011 ± 21 Ma (MSWD = 1.3). This is similar to the age of regional high-grade Sveconorwegian metamorphism in the Rogaland–Vest Agder sector determined in other studies. However, the data from one of the grains (grain 2, Figs. 3A, B) displays clear compositional and age zonation with a U–Th-poor zone yielding comparatively old ages of 1074 and 1062 Ma, whereas the more U–Th-rich part of the grain yields an age of 999 Ma. Although the data are sparse, this suggests that a hitherto unidentified, early Sveconorwegian event may have affected the gneisses in this area. Excluding the two anomalously old ages, the 8 remaining analyses yield ages ranging from 1036 Ma to 975 Ma with a weighted mean age of 1002 ± 17 Ma (MSWD = 0.61). This age is provi-

Table 3. Chemical data from monazites from samples MM00319 from Rogaland and SOR40 from Sørøya.

Analysis	Y (ppm)	Th (ppm)	U (ppm)	Pb (ppm)	Age (Ma)	1σ error
Sample MM00319						
Matrix monazite						
319-10-1	800	19710	2070	1110	915	43
319-5-2	1310	69150	1860	3500	1018	16
319-6-2	10860	59210	2630	2910	935	17
319-6-3	10460	72810	2940	3440	911	14
319-8-1	2030	34990	3210	1950	935	25
Inclusion along crack in garnet						
319-11-1	2940	50890	3460	2630	924	19
Inclusions in garnet						
319-1-2	9190	36510	2070	2000	1001	32
319-1-3	6780	40080	4680	2570	1004	25
319-1-4	3950	46640	4030	2720	989	23
319-1-5	8790	34140	1640	1890	1036	30
319-2-2	9950	37220	6350	2690	999	20
319-2-3	9460	29280	3790	2060	1062	28
319-2-4	8630	27810	1810	1680	1074	35
319-3-2	8400	35860	2290	2050	1024	27
319-4-1	7970	41640	3530	2390	975	22
319-7-1	9370	28470	3040	1820	1020	30
Sample SOR40						
SOR40-1-1	8150	21300	2290	550	416	23
SOR40-1-2	8710	20670	2720	580	427	22
SOR40-1-3	8730	20490	2630	550	411	23
SOR40-1-4	8790	20450	2420	640	490	23
SOR40-1-5	8800	20350	2420	550	423	23
SOR40-2-1	8270	29280	2740	700	401	17
SOR40-5-1	8380	72970	2450	1500	410	11
SOR40-5-2	8710	95300	2170	1740	376	9
SOR40-3-1	8870	31700	2780	800	429	16
SOR40-3-2	8990	27830	2400	680	416	19
SOR40-4-1	10430	49680	2800	1050	392	15
SOR40-4-2	10160	52090	2570	1200	436	15
SOR40-4-3	10390	53050	2800	1210	428	14
SOR40-6-1	9150	53040	2470	1070	385	14
SOR40-6-2	10440	42140	3920	1000	399	12
SOR40-7-1	9270	79050	2690	1620	408	10
SOR40-7-2	9540	69760	2270	1370	392	11
SOR40-8-1	11530	30090	5930	970	429	13
SOR40-8-2	12040	26590	6290	940	436	14
SOR40-9-1	7700	21470	2170	560	427	23
SOR40-5-4	8520	101960	1880	1900	389	8

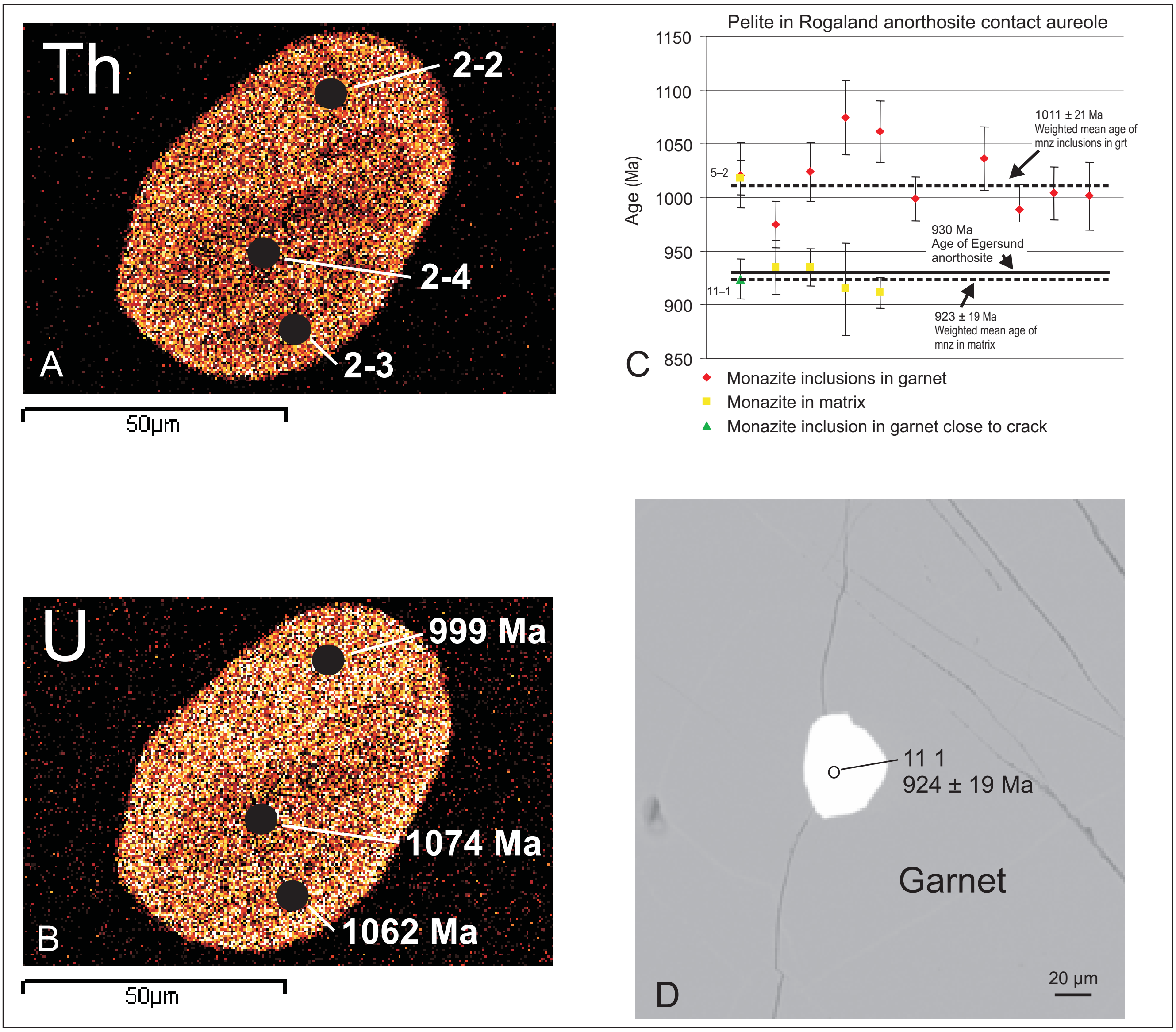

Fig. 3. (A and B) Maps of U and Th concentrations in grain 2 (sample MM00319 from the contact aureole to the Rogaland anorthosite complex). The low U-Th zone yields 'old' Sveconorwegian ages, whereas the relatively U-Th-rich part of the grain yields a 'normal' Sveconorwegian age. (C) Age data from sample MM00319. (D) Grain 11 situated along a crack in garnet and yielding an age of 924 Ma, interpreted to reflect thermal metamorphic overprinting.

sionally taken as the best estimate of the age of high-grade metamorphism in the Rogaland–Vest Agder sector; however, it is important to recognise the possibility that the spread in ages could reflect a prolonged or polystage metamorphic history. The two old ages could represent an early stage in this metamorphic history.

Five analyses were made from four different matrix grains. One of the grains (grain 5) yielded an age of 1018 ± 16 Ma, similar to that found for the monazite inclusions in garnet, whereas the other three grains yield ages ranging from 935 to 911 Ma with a weighted mean age of 923 ± 19 Ma (MSWD = 0.46) (Fig. 3C). This age is interpreted to reflect the age of high-T contact metamorphism related to the emplacement of the Egersund–Ogna massif. One monazite inclusion (grain 11) in garnet, located along a crack in the latter (Fig. 3D), yields an age of 924 ± 19 Ma. The general observation that monazite in the matrix (with the exception of grain 5) and along cracks in garnet yield ages corresponding to the contact metamorphic event, whereas monazite found as inclusions in garnet preserve evidence of the earlier metamorphic history, suggests that resetting or regrowth during contact metamorphism was related to fluid availability. The observation also suggests that garnet growth was related to regional Sveconorwegian metamorphism.

The data presented from this sample show that the chemical ages are comparable to previously published isotopic ages from zircon and monazite in Rogaland. The data also hold some promise that the method may help define the geological evolution of the Rogaland–Vest Agder sector in greater detail than is presently possible from the existing geochronological database. Another significant implication of this work is that monazite appears capable of retaining geochronological information despite being heated to >1000°C for up to several million years (Westphal et al. 2003) provided that the mineral is isolated with respect to metamorphic fluids.

Example 2: Kyanite-biotite schist from Sørøya, West Finnmark Caledonides, North Norway

The Kalak Nappe Complex in West Finnmark, northern Norway, forms part of the Upper Allochthon of the northern Scandinavian Caledonides (Andréasson et al. 1998, Siedlecka et al. 2004) and consists of a sedimentary cover unconformably overlying a basement of para- and orthogneisses of unknown age. The cover sequence is informally named the Sørøy succession after its type area on Sørøya in West Finnmark (Ramsay 1971) (Fig. 2B). The Sørøy succession consists of an extensive unit of psammite (meta-arkoses and quartzites) structurally overlain by garnetiferous mica schists, pelites, marbles and turbidites. Ramsay (1971) interpreted the Sørøy succession as a continuous depositional sequence displaying a transition from an alluvial or shallow-marine environment, through shelf deposition to distal turbidites. However, recent work shows that the units comprising the Sørøy succession are of widely different age with different geological histories (Kirkland et al. 2005, Slagstad et al. 2006).

Traditionally, most workers in Finnmark have ascribed the main deformation, metamorphism and tectonic shuffling of the Kalak Nappe Complex (basement + Sørøy succession cover) to an Early Palaeozoic (c. 540–490 Ma) Finnmarkian orogenic event (e.g., Sturt et al. 1978). The concept of a Finnmarkian orogeny was originally based on the interpretation that the Seiland Igneous Province, which at the time was dated by the Rb–Sr method at 540–490 Ma (Sturt et al. 1978), formed synchronously with deformation in the Kalak Nappe Complex. Later work, however, suggests that the Seiland Igneous Province, consisting primarily of plutonic rocks of ultramafic to gabbroic composition, was related to an earlier cycle of continental rifting (Zwaan & van Roermund 1990, Reginiussen et al. 1995, Robins & Often 1996, Roberts et al. 2004) rather than to continental collision, thus invalidating the basis for a Finnmarkian orogeny. A radical (for its time) hypothesis was proposed by Krill & Zwaan (1987), who suggested that the deformation and high-grade metamorphism observed on Sørøya was related to the Scandian orogenic event, dated in other parts of the Caledonian orogenic belt to have taken place between c. 425 and 400 Ma.

In order to determine the age of high-grade metamorphism on Sørøya, sample SOR40 from the Åfjord formation of the Sørøy succession in SW Sørøya was collected for the purpose of chemical monazite dating (Fig. 2B). The sample is a rather spectacular-looking kyanite-biotite schist with randomly oriented bladed kyanite crystals up to 4–5 cm long (Fig. 4A). In addition to kyanite, staurolite is locally abundant in these rocks, but has not been observed in this particular sample. Excluding five analyses with Th contents >7 wt.%, sixteen analyses from seven different grains in sample SOR40 yield a weighted mean age of 416 ± 10 Ma (MSWD = 1.17) (Fig. 4B, Table 3). The high-Th monazites were excluded because high Th contents are known to cause interference resulting in calculated ages that are too young (Pyle et al. 2005). One analysis was excluded by the Isoplot program based on statistical criteria (Fig. 4). The age of 416 ± 10 Ma is interpreted to represent the age of high-grade metamorphism and tectonic stacking in this part of the Kalak Nappe Complex. This result suggests that high-grade metamorphism on Sørøya, and probably in other parts of the West Finnmark Caledonides, was related to the Scandian orogenic event. The result does not lend support to (but does not rule out) the existence of an early Caledonian Finnmarkian event. In conjunction with recent work by Kirkland et al. (2005) and Slagstad et al. (2006), this calls for major revisions to the tectonostratigraphy and geological evolution in the northern Scandinavian Caledonides.

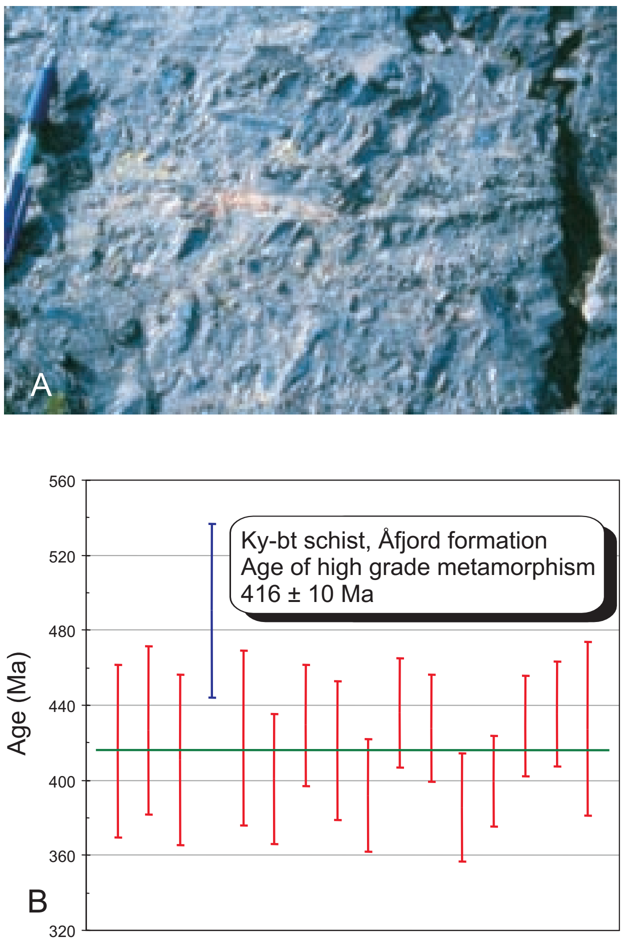

Fig. 4. (A) Field photo of the investigated kyanite-biotite schist from Sørøya. (B) Age data from sample SOR40; analysis 1–4 (in blue) is an outlier recognised by Isoplot by comparing the calculated χ^2 value to critical values predicted in standard statistical tables. The outlier was excluded from the weighted mean calculation.

Conclusions

Using the analytical protocol described herein, U–Th–Pb chemical analysis of monazite for the purpose of chemical dating can be routinely undertaken on NGU's LEO 1450VP scanning electron microscope (SEM). The ages obtained are comparable to the isotopic ages obtained from the same monazites. Approximately 15 analyses can be made in 24 hours. Dating of monazite from a pelite close to the Egersund anorthosite in Rogaland yields an age of 1002 Ma for monazite inclusions in garnet. This age is interpreted as the age of high-grade, regional Sveconorwegian metamorphism, in concordance with previous work in the area. Monazite from the pelite matrix and along cracks in garnet yield an age of 923 Ma, interpreted as the age of contact metamorphic thermal overprinting. This result shows that monazite can retain geochronological information despite being heated to temperatures up to 1000°C for several million years, if they are isolated from the metamorphic fluids in the rock. Dating of monazite from a kyanite-biotite schist from West Finnmark yields an age of 416 Ma, interpreted as the age of high-grade metamorphism in the area. This age supports other, recent work in the area, suggesting that the main metamorphic event in the West Finnmark Caledonides was of Scandian age, as in many other parts of the Scandinavian Caledonides. The result does not lend support to the existence of a Finnmarkian metamorphic event.

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References

Aitcheson, S. J. 1990: Nd isotopic evidence for exotic detritus in the Kalak Nappe Complex, north Norwegian Caledonides. *Journal of the Geological Society of London 147,* 923-926.

Andréasson, P. G., Svenningsen, O. M. & Albrecht, L. 1998: Dawn of Phanerozoic orogeny in the North Atlantic tract; Evidence from the Seve-Kalak Superterrane, Scandinavian Caledonides. *Geologiska Föreningen i Stockholm Förhandlingar 120,* 159-172.

Bingen, B. & van Breemen, O. 1998a: U-Pb monazite ages in amphibolite- to granulite-facies orthogneisses reflect hydrous mineral breakdown reactions: Sveconorwegian Province of SW Norway. *Contributions to Mineralogy and Petrology 132,* 336-353.

Bingen, B. & van Breemen, O. 1998b: Tectonic regimes and terrane boundaries in the high-grade Sveconorwegian belt of SW Norway, inferred from U-Pb zircon geochronology and geochemical signature of augen gneiss suites. *Journal of the Geological Society of London 155,* 143-154.

Bingen, B. & Stein, H. J. 2003: Molybdenite Re-Os dating of biotite dehydration melting in the Rogaland high-temperature granulites, S Norway. *Earth and Planetary Science Letters 208,* 181-195.

Cherniak, D. J., Watson, E. B., Grove, M. & Harrison, T. M. 2004: Pb diffusion in monazite: A combined RBS/SIMS study. *Geochimica et Cosmochimica Acta 68,* 829-840.

Cocherie, A., Legendre, O., Peucat, J. J. & Kouamelan, A. N. 1998: Geochronology of polygenetic monazites constrained by in situ electron microprobe Th-U-total lead determination: Implications for lead behaviour in monazite. *Geochimica et Cosmochimica Acta 62,* 2475-2497.

Dahl, P. S., Hamilton, M. A., Jercinovic, M. J., Terry, M. P., Williams, M. L. & Frei, R. 2005: Comparative isotopic and chemical geochronometry of monazite, with implications for U-Th-Pb dating by electron microprobe: An example from metamorphic rocks of the eastern Wyoming Craton (U.S.A.). *American Mineralogist 90,* 619-638.

Foster, G., Gibson, H. D., Parrish, R. R., Horstwood, M. S. A., Fraser, J. & Tindle, A. G. 2002: Textural, chemical and isotopic insights into the nature and behaviour of metamorphic monazite. *Chemical Geology 191,* 183-207.

Foster, G., Parrish, R. R., Horstwood, M. S. A., Chenery, S., Pyle, J. M. & Gibson, H. D. 2004: The generation of prograde P-T-t points and paths; A textural, compositional, and geochronological study of metamorphic monazite. *Earth and Planetary Science Letters 228,* 125-142.

Hermans, G. A. E. M., Tobi, A. C., Poorter, R. P. E. & Maijer, C. 1975: The high-grade metamorphic Precambrian of the Sirdal-Ørsdal area, Rogaland/Vest-Agder, south-west Norway. *Norges geologiske undersøkelse 318,* 51-74.

Jansen, J. B. H., Blok, R. J. P., Bos, A. & Scheelings, M. 1985: Geothermometry and geobarometry in Rogaland and preliminary results from the Bamble area, S. Norway. *In* Tobi, A. C. & Touret, J. (eds.), The Deep Proterozoic Crust in the North Atlantic Provinces. *Nato Advanced Study Institute Series C158,* 499-516. D. Reidel Publishing Company,

Kirkland, C. L., Daly, J. S. & Whitehouse, M. J. 2005: Early Silurian magmatism and the Scandian evolution of the Kalak Nappe Complex, Finnmark, Arctic Norway. *Journal of the Geological Society of London 162,* 985-1003.

Krill, A. G. & Zwaan, B. K. 1987: Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway. *Norsk Geologisk Tidsskrift 67,* 15-24.

Ludwig, K. R. 2001: Isoplot/Ex version 2.49. A geochronological toolkit for Microsoft Excel. *Berkeley Geochronological Center Special Publication 1a,* 1-55.

Marker, M., Schiellerup, H., Meyer, G. B., Robins, B. & Bolle, O. 2004: Beskrivelse til geologisk kart over Rogaland Anortosittprovins, 1:75 000. *Norges geologiske undersøkelse Rapport 2004.007,* 23 pp.

Möller, A., O'Brien, P. J., Kennedy, A. & Kröner, A. 2003: Linking growth episodes of zircon and metamorphic textures to zircon chemistry: An example from the ultrahigh-temperature granulites of Rogaland (SW Norway). In Vance, D., Müller, W. & Villa, I. M. (eds.), Geochronology: Linking the Isotopic Record with Petrology and Textures. *Geological Society of London, Special Publication,* 220, 65-81.

Montel, J.-M., Foret, S., Veschambre, M., Nicollet, C. & Provost, A. 1996: Electron microprobe dating of monazite. *Chemical Geology 131,* 37-53.

Parrish, R. R. 1990: U-Pb dating of monazite and its applications to geological problems. *Canadian Journal of Earth Sciences 27,* 1431-1450.

Pyle, J. M. & Spear, F. S. 2003: Four generations of accessory-phase growth in low-pressure migmatites from SW New Hampshire. *American Mineralogist 88,* 338-351.

Pyle, J. M., Spear, F. S., Wark, D. A., Daniel, C. G. & Storm, L. C. 2005: Contributions to precision and accuracy of monazite microprobe ages. *American Mineralogist 90,* 547-577.

Ramsay, D. M. 1971: Stratigraphy of Sørøy. *Norges geologiske undersøkelse 269,* 314-317.

Reginiussen, H., Krogh Ravna, E. J. & Berglund, K. 1995: Mafic dykes from Øksfjord, Seiland Igneous Province, northern Norway: geochemistry and palaeotectonic significance. *Geological Magazine 132,* 667-681.

Roberts, D. 1971: A conspectus of Eocambrian - Lower Palæozoic sedimentation on Sørøy. *Norges geologiske undersøkelse 269,* 242-245.

Roberts, D. 1973: Geologisk kart over Norge, berggrunnskart. Hammerfest 1:250 000, *Norges geologiske undersøkelse.*

Roberts, R. J., Corfu, F., Torsvik, T. H., Ramsay, D. M. & Ashwal, L. D. 2004: Redefining the magmatic evolution of the Kalak Nappe Complex. *Geologiska Föreningen i Stockholm, Abstract volume, The 26th Nordic Geological Winter Meeting, Stockholm 126,* 84.

Robins, B. & Often, M. 1996: The Seiland Igneous Province, North Norway. Field Trip Guidebook, IGCP project 336. *Norges geologiske undersøkelse Report 96.127,* 34 pp.

Schärer, U. 1984: The effect of initial 230Th disequilibrium on young U-Pb ages: The Makalu case, Himalaya. *Earth and Planetary Science Letters 67,* 191-204.

Schärer, U., Wilmart, E. & Duchesne, J.-C. 1996: The short duration and anorogenic character of anorthosite magmatism: U-Pb dating of the Rogaland complex, Norway. *Earth and Planetary Science Letters 139,* 335-350.

Siedlecka, A., Roberts, D., Nystuen, J. P. & Olovyanishnikov, V. G. 2004: Northeastern and northwestern margins of Baltica in Neoproterozoic time: evidence from the Timanian and Caledonian Orogens. *In* Gee, D. G. & Pease, V. (eds.), *The Neoproterozoic Timanide Orogen of Eastern Baltica,* Geological Society, London, Memoirs 30, 169-190.

Slagstad, T. 2005: Chemical (U-Th-Pb) dating of monazite using NGU's LEO 1450VP scanning electron microscope: Analytical protocol and examples. *Norges geologiske undersøkelse Report 2005.006,* 126 pp.

Slagstad, T., Melezhik, V. A., Kirkland, C. L., Zwaan, K. B., Roberts, D., Gorokhov, I. M. & Fallick, A. E. 2006: Carbonate isotope chemostratigraphy suggests revisions to the geological history of the West Finnmark Caledonides, North Norway. *Journal of the Geological Society of London 163,* 277-289.

Stern, R. A. & Sanborn, N. 1998: Monazite U-Pb and Th-Pb geochronology by high-resolution secondary ion mass spectrometry. Radiogenic Age and Isotopic Studies: Report 11. *Geological Survey of Canada, Current Research 1998-F,* 1-18.

Stern, R. A. & Berman, R. G. 2000: Monazite U-Pb and Th-Pb geochronology by ion microprobe, with application to in situ dating of an Archean metasedimentary rock. *Chemical Geology 172,* 113-130.

Sturt, B. A., Pringle, I. R. & Ramsay, D. M. 1978: The Finnmarkian phase of the Caledonian Orogeny. *Journal of the Geological Society of London 135,* 597-610.

Suzuki, K. & Adachi, M. 1991: Precambrian provenance and Silurian metamorphism of the Tsunosava paragneiss in South Kitakami terrane, northeast Japan, revealed by the chemical Th-U-total Pb isochron ages of monazite, zircon and xenotime. *Journal of Geochemistry 25,* 357-376.

Terry, M. P., Robinson, P., Hamilton, M. A. & Jercinovic, M. J. 2000: Monazite geochronology of UHP and HP metamorphism, deformation, and exhumation, Nordøyane, Western Gneiss Region, Norway. *American Mineralogist 85,* 1651-1664.

Tobi, A. C., Hermans, G. A. E. M., Maijer, C. & Jansen, J. B. H. 1985: Metamorphic zoning in the high-grade Proterozoic of Rogaland-Vest Agder, SW Norway. *In* Tobi, A. C. & Touret, J. L. R. (eds.), *The Deep Proterozoic Crust in the North Atlantic Provinces,* 477-497. Reidel, Dordrecht.

Westphal, M., Schumacher, J. C. & Boschert, S. 2003: High-temperature metamorphism and the role of magmatic heat sources at the Rogaland Anorthosite Complex in southwestern Norway. *Journal of Petrology 44,* 1145-1162.

Wielens, J. B. W., Andriessen, P. A. M., Boelrijk, N. A. I. M., Hebeda, E. H., Priem, H. N. A., Verdurmen, E. A. T. & Verschure, R. H. 1980: Isotope geochronology in the high-grade metamorphic Precambrian of Southwestern Norway: new data and reinterpretation. *Norges geologiske undersøkelse 359,* 1-30.

Williams, M. L., Jercinovic, M. J. & Terry, M. P. 1999: Age mapping and dating of monazite on the electron microprobe: Deconvoluting multistage tectonic histories. *Geology 27,* 1023-1026.

Zwaan, B. K. & van Roermund, H. L. M. 1990: A rift-related mafic dyke swarm in the Corrovarre Nappe of the Caledonian Middle Allochthon, Troms, North Norway, and its tectonometamorphic evolution. *Norges geologiske undersøkelse Bulletin 419,* 25-44.