Microdiamond in high-grade metamorphic rocks of the Western Gneiss region, Norway

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ABSTRACT

Three grains of microdiamond were recovered from high-grade gneiss exposed in the Western Gneiss region, Norway. Identification and characterization of the diamond grains by Raman and infrared spectroscopy indicate the presence of substitutional impurities of H and N. Primary fluid inclusions in garnet and quartz in the diamond-bearing rock demonstrate the evolution of metamorphic volatile fluids from reduced N_2-CO_2 compositions during the peak phase of metamorphism, to N_2-CH_4 ± H_2O–bearing compositions during retrograde metamorphism. Compatible geologic, petrologic, and fluid composition data imply a metamorphic origin for the microdiamonds; if so, the metamorphic and fluid conditions recorded by the microdiamonds and gneissic host may be applicable to microdiamond investigations in other high-pressure, regionally metamorphosed orogens.

INTRODUCTION

Discoveries of coesite (e.g., Chopin, 1984; Smith, 1984; Okay et al., 1989; Wang et al., 1989) and microdiamond (e.g., Rozen et al., 1972; Sobolev and Shatsky, 1990; Xu et al., 1992) in regional metamorphic terrains have generated provocative research regarding continental collisions, the tectonic context of high- and ultrahigh-pressure metamorphism, and orogenic exhumation (see Platt, 1993, for review). Our study documents the morphology, Raman spectral characteristics, and H and N contents of newly discovered microdiamond (Dobrzhinetskaya et al., 1993) from high-grade gneiss on the island of Fjørtoft (Fig. 1), in the Western Gneiss region, Norway. The occurrence of microdiamonds in three regional metamorphic provinces in China, Kazakhstan (see above references), and now Norway, is a geodynamic challenge similar to that propagated by discoveries of coesite in regional collision zones during the last decade.

BACKGROUND

In 1992, the Geological Survey of Norway began an investigation for possible microdiamond in the Western Gneiss region; the first microdiamonds were retrieved from a garnet-kyanite-phlogopite gneiss and a garnet-pyroxene-amphibole-biotite gneiss from Fjørtoft island (Fig. 1). These crystals were recovered at TSNIGRI (Central Research Institute of Geological Prospecting for Base and Precious Metals), Moscow, and were identified positively by optical methods, X-ray diffraction, and Raman spectroscopy at Moscow State University by Posukhova and Orlov (Dobrzhinetskaya et al., 1993).

As part of the current study, laboratory recovery procedures for microdiamond separation were repeated at the Geological Survey of Norway to address potential uncertainties with laboratory contamination at TSNIGRI. Subsequent recovery and characterization of a new set of microdiamonds from the Fjørtoft garnet-kyanite-phlogopite gneiss at the Geological Survey of Norway laboratories have generated data from which we can begin to assess their potential conditions of formation.

REGIONAL SETTING

The Western Gneiss region (Fig. 1) comprises Precambrian gneissic basement and interfolded supracrustal rocks metamorphosed and deformed ~400 to 450 Ma during collision between Baltica and Laurentia (Cuthbert and Carswell, 1990). The region represents the deepest structural level of the Scandinavian Caledonides, and the metamorphic grade increases broadly from southeast to northwest (Griffin et al., 1985). The microdiamond-bearing gneisses crop out on the island of Fjørtoft within the

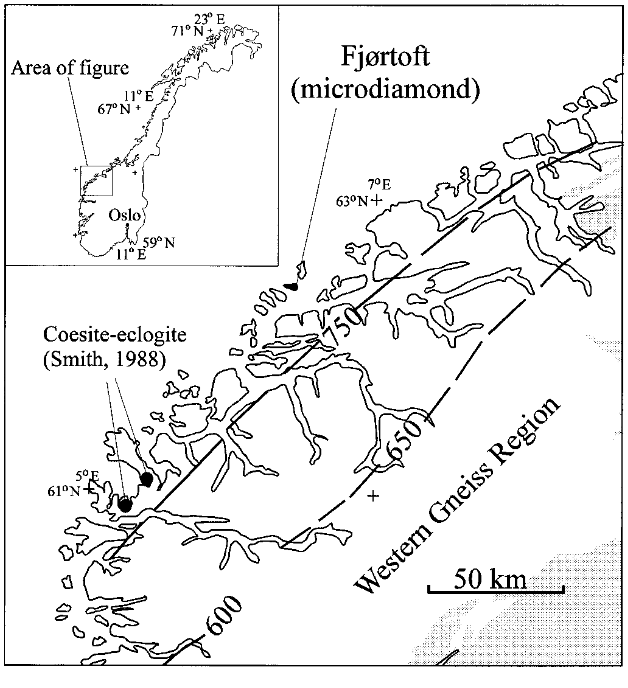

Figure 1. Map of Western Gneiss region (WGR) and location of Fjørtoft island; microdiamond-bearing rocks are from northeasternmost corner of island. Pattern of temperature values (in °C) for Scandian metamorphism are shown as dashed lines and increase toward northwest (after Griffin et al., 1985). Area northwest of 750 °C also contains highest calculated metamorphic pressures; two coesite localities of Smith (1988) are within high-temperature and high-pressure zone of WGR.

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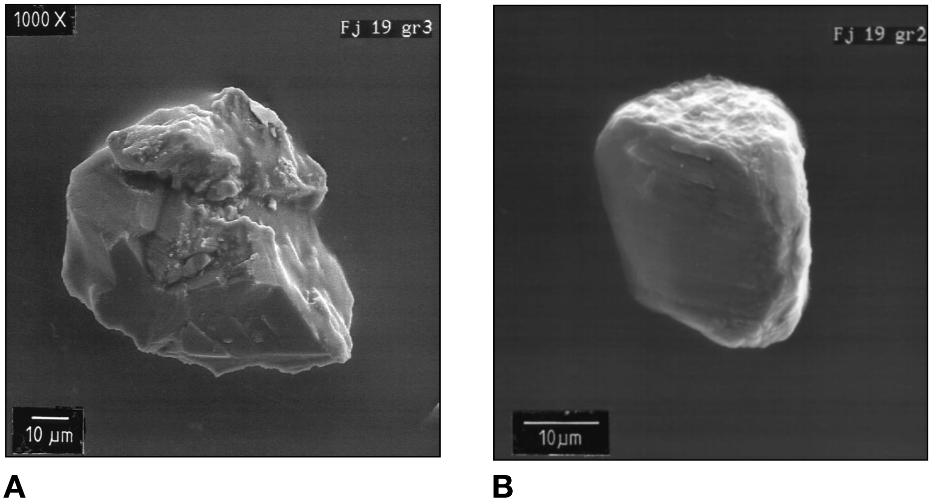

Figure 2. Scanning electron microprobe images (secondary electron intensity) of microdiamond grains from Fjørtoft taken after coating with Au at Continental Shelf Institute, Trondheim (by T. Boassen). Scale bars are in micrometres. A: Larger crystal (Fj-19 gr.3) has intense green color and complicated morphology, very similar to several Fjørtoft microdiamonds recovered at Central Research Institute of Geological Prospecting for Base and Precious Metals in 1993. This morphology is not comparable to typical Kokchetav microdiamonds. Largest dimension is ~45 µm. B: This small yellow-green diamond (Fj-19 gr.2) is round with even surfaces and distinct striations visible on largest face. This morphology is not similar to any from first set of Fjørtoft microdiamonds recovered at TSNIGRI, nor to any from Kokchetav diamond collections (see Nadezhdina and Posukhova, 1990, for Kokchetav diamond descriptions). Largest dimension is ~20 µm.

northwestern high-grade zone of the Western Gneiss region (Fig. 1).

METHODS

Sampling of Materials

The rock units on Fjørtoft include garnet-kyanite-phlogopite gneiss, migmatitic garnet-amphibole-biotite-feldspar gneiss, calc-silicate rock, eclogite lenses in garnet-amphibole-biotite-plagioclase ± clinopyroxene gneiss, and augen-orthogneiss. The microdiamond-bearing rock in this study includes a mineral assemblage of garnet ($Alm_{65}Prp_{28}Grs_6Sps_1$), kyanite, phlogopite, quartz, plagioclase, K-feldspar, rutile, graphite, sulfide minerals, iron oxides, monazite, and zircon.

We crushed and sieved ~50 kg of the Fjørtoft garnet-kyanite-phlogopite gneiss to ≤1 mm size fractions. Ten sets of homogeneous material (~100 g each) were then subjected to thermochemical dissolution in highly concentrated HCl and H_2SO_4 after preliminary heating of the material in NaOH at temperatures from 400 to 500 °C. Residual mixtures consisted of kyanite, garnet, zircon, monazite, quartz, and graphite; these residua were dissolved in HF to reduce sample sizes to a few milligrams. Several diamondlike crystals were recovered, but only three (two 10–20 µm, and the other 45 µm, in diameter) were confirmed as diamond (Fig. 2). These yellow-green diamond grains were identified by Raman microprobe (RMP) and infrared (IR) spectroscopy.

Raman Spectroscopy

Procedures for Raman spectroscopic analysis at the National Museum of Natural History in Paris (by D. C. Smith) included a DILOR XY RMP operated in multichannel microanalysis mode with 1024 diodes and room temperature of 23 ± 1 °C; the argon laser was operated at 514.53 nm and 100 mW power. Five to ten accumulations were made during 0.2 to 1 s time spans with slits of 300 µm and a spectral range of 200 to 1400 cm^{-1}.

Two crystals analyzed from the Fjørtoft gneiss (Fj-19) provided identical spectra of the diamond structure (Fig. 3). The peak centers at half height are all within ±1.2 cm^{-1} of the ideal value of 1332 cm^{-1} for the characteristic diamond C-C bond vibration. The C-C peaks of the WGR diamond grains (Fig. 3B) are wider on the lower wave number side than that of the standard diamond used at the Paris Museum. This feature is evidence for distortion in the structure, possibly due to the presence of other atoms such as N, B, or H.

Infrared Spectroscopy

Analytical procedures for the IR analyses at University College, London (by W. R. Taylor), included an IR microscope coupled to a Bruker IFS45 FTIR (Fourier transform infrared) spectrometer using acquisition parameters of 200 scans at a resolution of 8 cm^{-1} over the range 4000 to 650 cm^{-1} and a microscope MCT detector with an aperture of 25 µm. Good infrared spectra could not be obtained from the two smaller diamond grains because their sizes approach the diffraction limit for infrared radiation. Two spectra from the largest microdiamond (Fj-19 gr.3) were obtained. One spectrum is presented in Figure 4A; Figure 4B shows a comparative spectrum from a Kokchetav microdiamond.

The IR spectra from the largest microdiamond from Fjørtoft indicate a mixed Ib-IaA type diamond; impurities of N are characterized by absorption peaks in the IR spectrum at 1282 cm^{-1} (type IaA) and at 1134

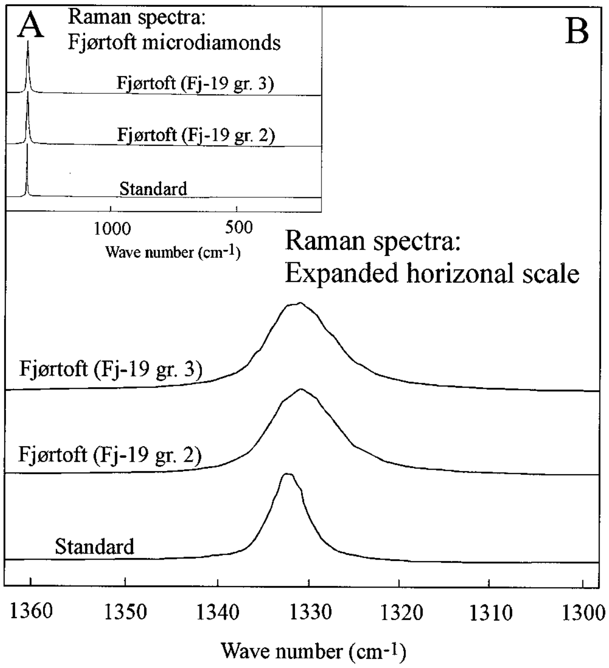

Figure 3. Raman spectra. A: Determined on standard and Norwegian crystals Fj-19/gr.2 and Fj-19/gr.3. B: Same three spectra with greatly expanded horizontal scale to display band widening toward lower wave numbers of two natural crystals (see text for discussion). Peak centers at half height: standard diamond = 1333.2 and 1332.3; crystal Fj-19/gr.2 = 1331.7 and 1331.1; crystal Fj-19-gr.3 = 1332.3 and 1331.1; these constitute duplicate measurements, taken three hours apart; all values were lower second time.

cm^{-1} (type Ib). The diamond has high concentrations of both H and N substitutional impurities, as indicated by strong infrared peaks at 3107 cm^{-1} (H) and between 1300 and 1100 cm^{-1} (N). Different amounts of N are present with different ratios of IaA to Ib N defects and document an inhomogeneous N distribution. Table 1 summarizes the infrared properties of the microdiamond in comparison to type Ib-IaA microdiamond from Kokchetav and a typical synthetic diamond from DeBeers.

METAMORPHIC CONDITIONS AND FLUIDS

Calculation of metamorphic pressure-temperature (*P-T*) conditions, combined with textural studies and fluid-inclusion analyses, indicate that high metamorphic *P-T* conditions for Fjørtoft rocks coincided with the presence of N_2-CO_2–rich volatiles. Geothermobarometry indicates minimum conditions for the high-pressure phase of metamorphism on Fjørtoft from 17 to 21 kbar and ~630 to 820 °C. These *P-T* conditions are similar to data reported for other rocks in the area by Krogh (1980), Mørk (1985), and Jamtveit et al. (1991). The rocks presumably reached peak metamorphic conditions during the Scandian phase of Caledonian orogenesis, based on geochronologic data from the area (e.g., Tucker et al., 1991). The high-pressure metamorphic mineral assemblages underwent partial retrograde metamorphism to amphibolite facies during exhumation.

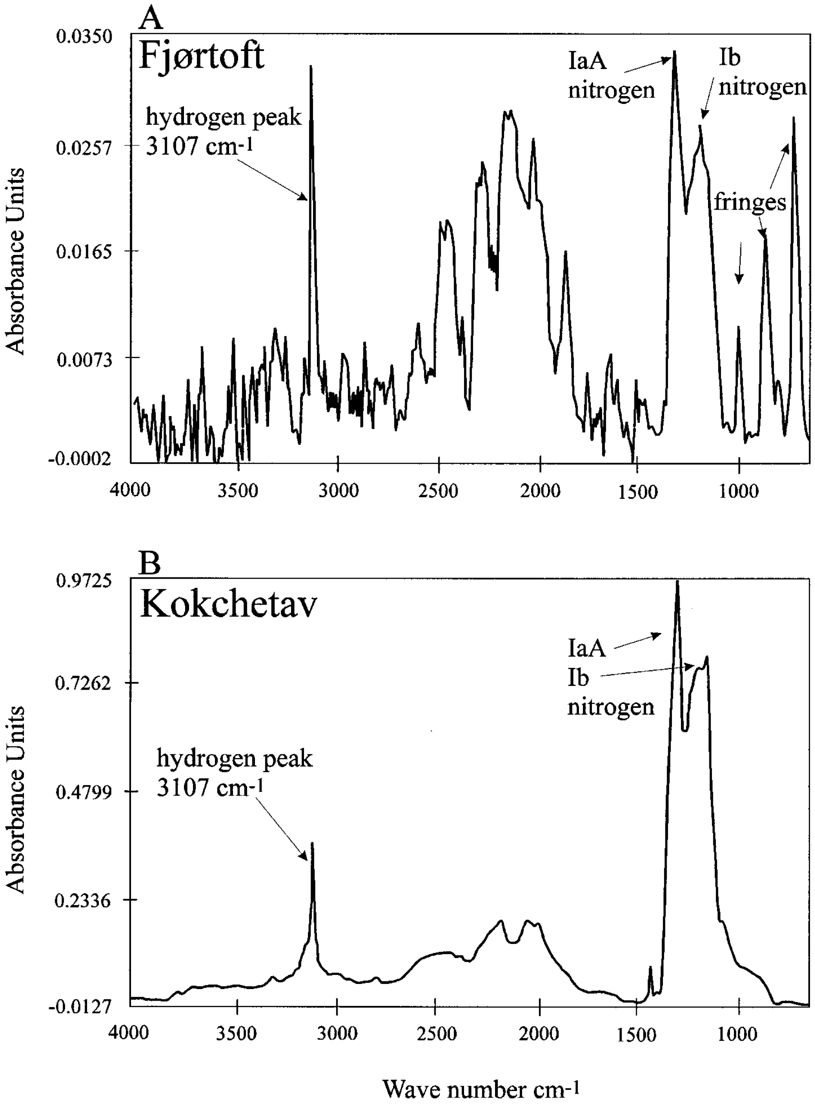

Figure 4. Infrared spectra obtained at University College London on microdiamonds from (A) Fjørtoft and (B) Kokchetav. A: Spectrum from largest Fjørtoft microdiamond (Fj-19-gr.3, ~45 μm) shows high levels of both H and Ib and IaA N impurities (see text for details). Fringes, caused by small size of diamond, obscure characteristic vibrations of carbon lattice at 2500 to 1900 cm^{-1} and prevent quantitative evaluation of diamond thickness. B: Kokchetav microdiamond spectrum (specimen AVK2 provided by A. Verchovsky, Open University, Milton Keynes, and N. Sobolev, Novosibirsk) indicates N and H impurities similar to Fjørtoft but with higher absolute N concentrations and more homogeneous distribution of N impurity (see Table 1).

Nondestructive fluid-inclusion analyses at the University of Oslo and the Vrije Universitet, Amsterdam (by R. B. Larsen), from garnet and quartz host minerals in the garnet-kyanite-phlogopite gneiss demonstrate the presence of metamorphic volatiles during high-pressure metamorphism and later retrogression. Raman analytical procedures followed those of Burke and Lustenhouwer (1987). Porphyroblastic garnet is host for two generations of primary fluid inclusions. A third generation of metamorphic volatiles was trapped as primary and secondary fluid inclusions in quartz and secondary inclusions in garnet.

The core of garnet crystallized in coexistence with a N_2-CO_2 fluid, whereas the margin crystallized in an environment characterized by N_2-CO_2-CH_4 fluids. Primary fluid inclusions in matrix quartz document N_2-CH_4 and N_2-CH_4-H_2O fluids during retrograde metamorphism. The fluid-inclusion studies thus demonstrate a continuous evolution of metamorphic volatiles, from N_2-CO_2 near peak metamorphism, to N_2-CO_2-CH_4, and finally to N_2-CH_4 ± H_2O compositions during the retrograde phase (Larsen et al., 1995).

DISCUSSION

We have not yet identified microdiamond in situ in the garnet-kyanite-phlogopite gneiss, and therefore have no indisputable evidence to support either a metamorphic or an alluvial origin for the grains. We argue, however, that a metamorphic origin is most compatible with the available data.

1. Evolution of N_2-CO_2–bearing fluids toward N_2-CH_4 ± H_2O–bearing fluid compositions is compatible with low fO_2 and N-rich fluids appropriate for genesis of type I diamond (Haggerty, 1986). Abundant graphite (up to ~1 vol%) in the matrix of the Fjørtoft gneiss also demonstrates the presence of elemental carbon in the rock.

2. The well-documented continental-collision–related genesis of the WGR is based on a large quantity of compatible geologic data and provides a favorable geodynamic environment for a metamorphic origin of the Fjørtoft microdiamonds. The presence of coesite in eclogite (Smith, 1984; Smith and Lappin, 1989) (Fig. 1) and very high pressures calculated from mineral equilibria in the same northwestern zone of the Western Gneiss region (Jamtveit, 1987; Smith, 1988; Jamtveit et al., 1991) further demonstrates the regional extent of very high pressure metamorphic conditions.

3. Dobrzhinetskaya et al. (1993) reported microdiamond from two different metamorphic rock types on Fjørtoft: a garnet-kyanite-phlogopite gneiss and a garnet-clinopyroxene-amphibole-biotite-feld-

TABLE 1. COMPARISON OF INFRARED PARAMETERS BETWEEN FJØRTOFT AND KOKCHETAV MICRODIAMONDS AND A SYNTHETIC DIAMOND FROM DEBEERS

Sample	Path length (μm)	Hydrogen (mm^{-1})	Nitrogen (ppm)	Ib (%)	Absorption coefficient (μ) at 1282 cm^{-1}
FJ-19SM3A	13.5	12.4	608	50	2.433
FJ-19BC3C	13.8	14.7	832	30	3.961
Kokchetav	144.0	14.8	1754	55	6.747
DeBeers	198.0	0.0	57	95	0.167

Note: Area of 3107 cm^{-1} H peak normalized to a diamond thickness of 1 mm; N concentrations were determined using an absorption coefficient of 550 at.ppm.mm (atomic parts per million for millimeter thickness) for Ib nitrogen and 150 at.ppm.mm for IaA nitrogen (both at 1282 cm^{-1}).

spar gneiss. The presence of two host rocks with fundamentally different bulk-rock compositions implies that the microdiamonds may have similar metamorphic origins.

The stability regime for diamond is associated with pressures exceeding ~35 kbar at temperatures above ~700 °C (Kennedy and Kennedy, 1976), thus indicating a crustal overburden equivalent to depths of >100 km. A tectonic problem exists in elucidating the mechanism(s) by which crustal blocks are first subducted to such a depth and then exhumed to the surface. Various tectonic mechanisms have been suggested to account for the genesis and exhumation of rocks in high-pressure, collisional orogens (e.g., Andersen et al., 1991; Michard et al., 1993; Dobrzhinetskaya et al., 1994; Huw Davies and von Blanckenburg, 1995), but the lack of data on the compositions of fluids and the physical properties of the continental crust at these depths hinders quantitative tectonic characterization of these provinces. This is exacerbated by incomplete geochronologic data for timing of high, ultrahigh, and retrograde metamorphic events in multiply metamorphosed and deformed orogens. It is possible that microdiamond in regionally metamorphosed orogens is more common than heretofore expected, and that further microdiamond discoveries may aid in sampling the fluid, tectonic, and metamorphic characteristics of the deep crust.

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