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STABILITY OF DETRITAL HEAVY MINERALS ON THE NORWEGIAN CONTINENTAL SHELF AS A FUNCTION OF DEPTH AND TEMPERATURE

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ABSTRACT: **Petrographic analysis of 1931 thin sections from sandstones of Pliocene to Devonian age on the Norwegian continental shelf indicate that the heavy minerals zircon, tourmaline, rutile, apatite, and spinel survive to depths exceeding 5000 m and to temperatures of around 200°C without showing signs of intrastratal dissolution. On the other hand, the maximum depth and temperature of occurrence for amphibole are 841 m and 40°C, around 1500 m and 55°C for sphene when 0.5 km of probable uplift is taken into account, 2231 m and 92°C for kyanite, 2559 m and 95°C for epidote, 2810 m and 109°C for staurolite, and 4589 m and 175°C for garnet. Initial signs of garnet dissolution occur at around 2000 m depth, and all garnets are partially dissolved at depths greater than 3500 m. Monazite is present down to 4858 m and 182°C and chloritoid to 3811 m and 149°C. It is, however, uncertain whether this is due to the low number of samples deeper than 4858 m and to the rare occurrence of chloritoid, or to intrastratal dissolution. The same sequence of heavy-mineral stability is found when volume of quartz cement is used as a proxy for time-temperature exposure. Quartz cement is not found in samples containing amphibole or detrital sphene. A maximum of a fraction of a percent quartz cement is found in samples containing kyanite, up to 1% together with epidote, up to 6% with staurolite, up to 24% with chloritoid, up to 25% with garnet, whereas maximum values of 25–35% are present together with zircon, tourmaline, rutile, apatite, spinel, and monazite. The sequence of persistence of heavy minerals versus depth found in this study is very similar to results from several previous studies, although unstable heavy minerals survive to greater depths in very young and rapidly buried sandstones, and there are some differences regarding the stability of sphene and epidote.**

Heavy mineral dissolution has created secondary pores and possibly has contributed to precipitation of kaolinite, illite, quartz, and carbonates in the studied sandstones, but these reactions are of very limited volumetric importance.

INTRODUCTION

Detrital heavy minerals are frequently used for investigating sandstone provenance, but numerous previous studies have shown that a number of heavy minerals are dissolved during burial (e.g., Pettijohn 1941; Wiesender and Maurer 1959; Morton 1979; 1984; Milliken and Mack 1990), and also as a result of weathering at or close to the sediment surface (e.g., Goldich 1938; Sindowski 1949; Nickel 1973; Friis 1974; Morton 1986). Knowledge of which heavy minerals dissolve during burial, and at what depths and temperatures, is therefore essential for correctly interpreting data on heavy mineral provenance. Although dissolution of heavy minerals during burial may complicate provenance studies, the process may, on the other hand, provide valuable information about paleotemperatures. For instance, absence of various common heavy minerals at unusually shallow depth may suggest uplift of the sandstone, and could also provide an indication of the probable magnitude of uplift. The stability range of detrital heavy minerals with regard to depth, temperature, and time-temperature exposure is therefore of major interest for both provenance studies and for studies of large-scale tectonic history.

In this study, the distribution of detrital heavy minerals on the Norwegian continental shelf as a function of burial depth has been investigated through petrographic analysis of nearly two thousand samples, and results compared with data from previous studies from other areas. Using temperature measurements from production tests and corrected bottom-hole log temperatures the distribution of heavy minerals versus temperature was also mapped. However, because intrastratal dissolution of heavy minerals is probably dependent upon the combined effect of time and temperature rather than present depth or temperature alone (Morton 1984, 1985a), it is also desirable to map heavy-mineral distribution versus a parameter representing the time-integrated thermal exposure of each sample. Previous studies have shown a clear correlation between time-temperature exposure and volumes of quartz cement in sandstones from the Norwegian shelf (Ehrenberg 1990), and observed volumes of quartz cement in sandstones from this area have been modeled successfully by assuming a time-temperature control on the quartz cementation process (Lander and Walderhaug 1999; Walderhaug 2000; Walderhaug et al. 2000). We have therefore also attempted to investigate the relationship between intrastratal dissolution of heavy minerals and the combined effect of time and temperature by using content of quartz cement as a proxy for time-temperature exposure, i.e., plotting the presence of different heavy minerals against volume of quartz cement.

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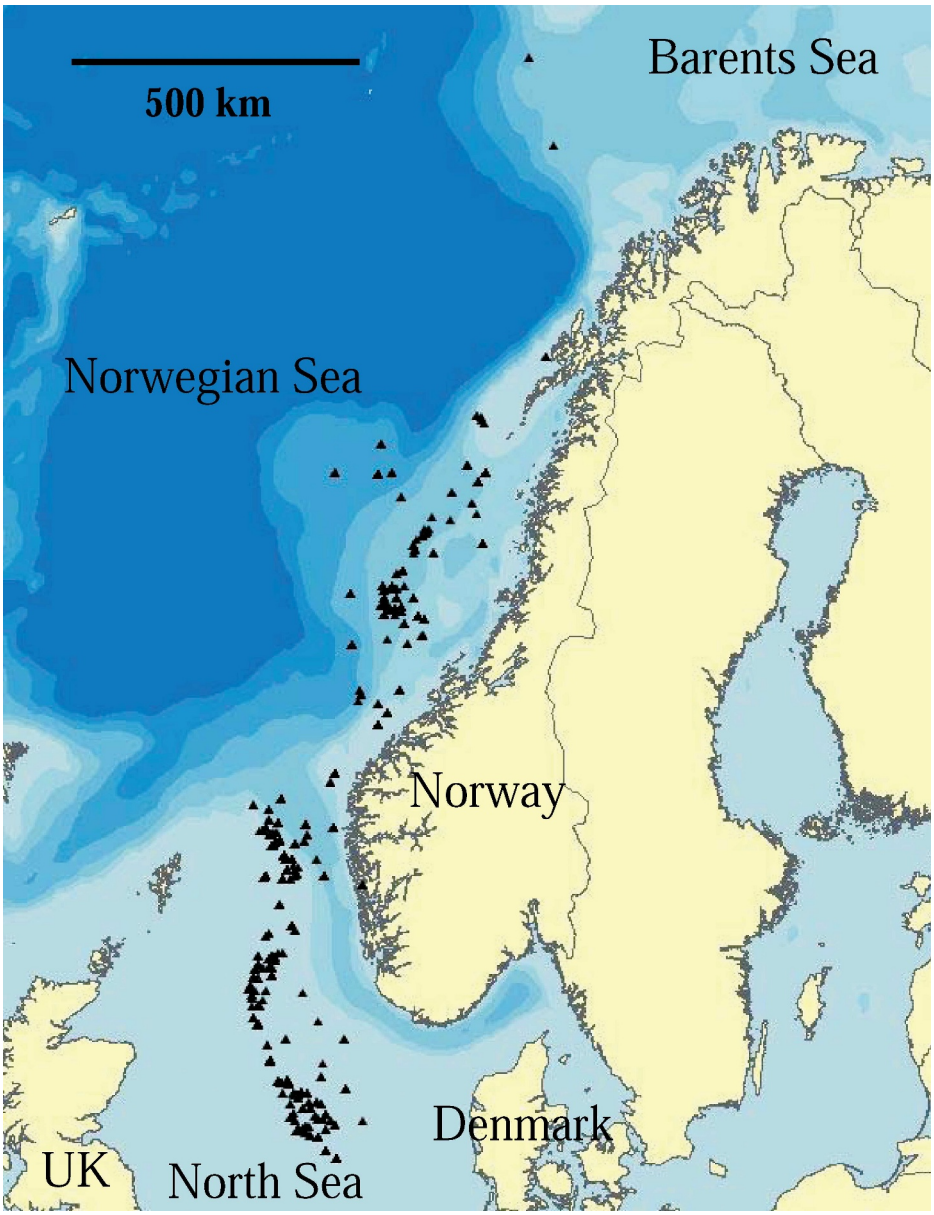

FIG. 1.—Map showing the location of the 229 studied wells and the Bjorøy tunnel (black triangles). The Bjorøy tunnel is the triangle onshore on the southwest coast of Norway.

SAMPLE MATERIAL AND METHODS

A total of 1931 thin sections impregnated with green or blue epoxy were examined in this study, including 1201 polished thin sections, 88 stained for carbonates with Alizarin Red S. and potassium ferricyanide, 37 stained for K-feldspar with sodium cobaltinitrite, and 501 stained for both K-feldspar and carbonates. The thin sections were made from core samples, and in a few cases from sidewall cores or from cuttings. The examined sandstone samples are from 227 wells on the Norwegian continental shelf, from two wells in the Danish sector of the North Sea close to the boundary against the Norwegian sector, and from Jurassic sandstones encountered within a depression in the Precambrian basement during the drilling of a subsea road tunnel 10 km southwest of the city of Bergen in western Norway (Fig. 1). The studied samples are at their maximum burial depth in approximately 212 wells, whereas samples from the remaining 17 wells, all located close to the Norwegian coast (Fig. 1), have been uplifted from a few hundred metres to around 1.5 km. Wells from the extensive uplifted areas in the Barents Sea were not included in the study. The ages of the studied sandstone samples vary from Devonian to Pliocene; 1 sample is Devonian, 96 samples are Permian, 48 Triassic, 1336 Jurassic, 257 Cretaceous, and 193 Tertiary. The sample depths range from a few meters below the surface to 5463 m below the sea floor.

Present temperatures for the deepest occurrences of the various heavy minerals were estimated from temperatures measured during production tests, and where such data were not available, from corrected bottom-hole log temperatures. The temperature data from production tests is the most reliable, but discrepancies between temperatures from multiple tests in the same well indicate that even these temperatures may deviate from the correct values by as much as 5°C.

All thin sections were examined with a standard polarizing microscope. In addition to identifying the heavy minerals present in all the thin sections, 1843 of the thin sections were point counted with 300 points per thin section. Heavy minerals that occur as inclusions within other grains are not included in the presented data, inasmuch as such inclusions are not in contact with the pore fluid and are therefore protected from intrastratal dissolution. Pervasively calcite-cemented samples were also avoided because heavy-mineral grains surrounded by calcite cement may

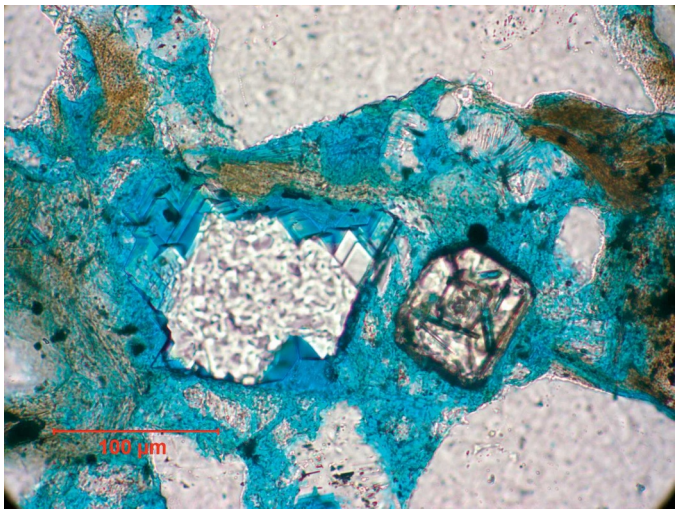

FIG. 2.—An almost euhedral zircon is seen to the right. To the left of the zircon a garnet grain with a faceted surface is present. The garnet is surrounded by porosity (blue) probably formed by garnet dissolution. Upper Jurassic Draupne Formation, well 33/9-18, 3070 m below the sea floor.

survive to greater depth than in samples without calcite cement (Mackie 1923; Bramlette 1941; Hudson 1964; Morton 1979). Grain size was determined by measuring the long axis of thirty to fifty grains per sample and calculating the mean long-axis value for each sample in 659 samples. In the remaining 1272 samples the long axis of a few representative grains was measured, and grain size was estimated from these values. A subset of the polished thin sections was also examined with a cathodoluminescence microscope, and some were examined with an SEM with an energy dispersive x-ray analyzer that permitted the chemical composition of heavy-mineral grains to be determined. Further details concerning the identification of individual minerals are included in subsequent sections.

OBSERVED HEAVY MINERALS

Volumetric Abundance of Heavy Minerals

The heavy-mineral content of the 1931 examined samples varies from zero to 11%. However, the point-counted volumes of heavy minerals are

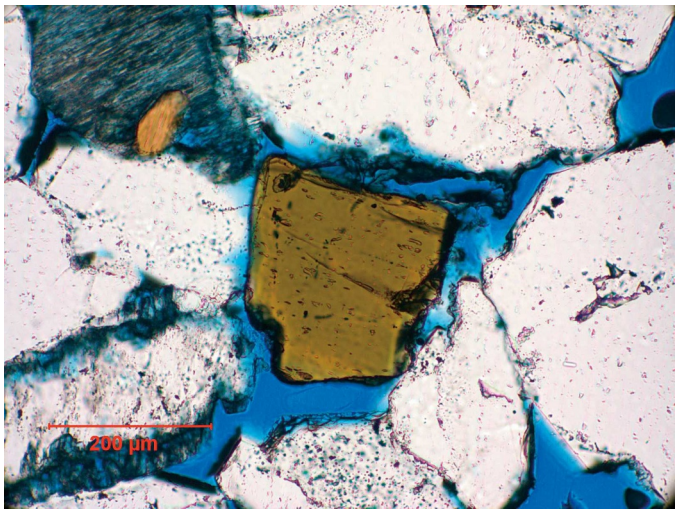

FIG. 3.—A subhedral and slightly rounded yellow tourmaline. Middle Jurassic Garn Formation, well 6406/3-6, 3375 m below the sea floor.

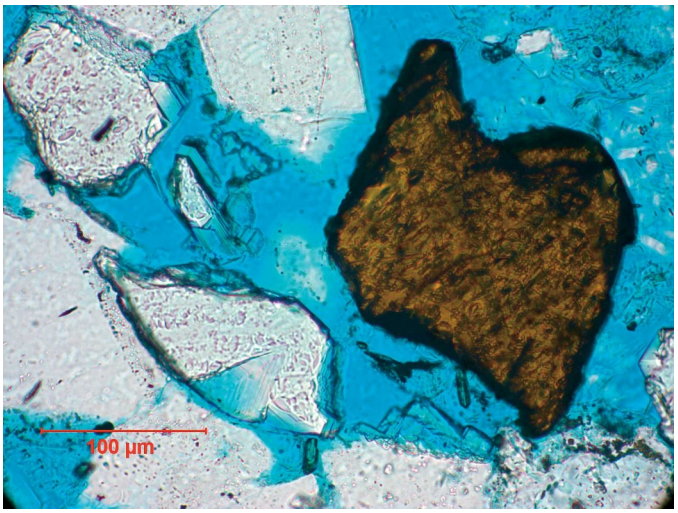

FIG. 4.—An anhedral brown rutile grain is seen to the right, to the left several faceted garnets are present. Middle Jurassic Garn Formation, well 6407/1-4, 3385 m below the sea floor.

dominantly less than 1%, and exceed 3% for less than one percent of the samples. Thirty-two samples, or 1.7% of all the examined thin sections, do not contain any heavy-mineral grains. Samples with unusually high contents of heavy minerals typically have most of the heavy minerals concentrated in certain laminae, and are very fine- or fine-grained lower-shoreface sandstones. The volumetrically most common heavy minerals in samples with high heavy-mineral contents are rutile, opaques, zircon, and more rarely garnet, although occasionally other heavy minerals such as apatite may dominate in a sample.

Zircon

Zircon was found in 91.6% of the samples, the highest frequency of occurrence for any heavy mineral in this study. Samples lacking zircon commonly do not contain any heavy minerals at all. Zircons are colorless to brownish, and grain size is typically in the silt to fine sand range, although crystals up to 0.4 mm long also occur. The zircon grains are

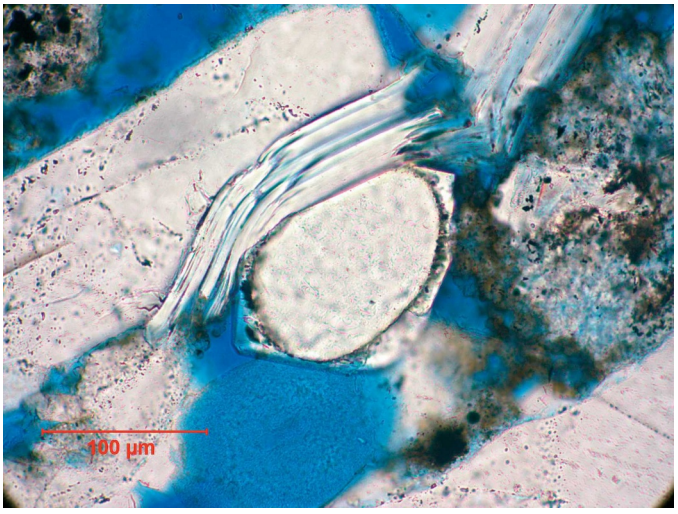

FIG. 5.—A well rounded apatite grain with a dust rim and an overgrowth with almost planar crystal faces. Upper Jurassic Draupne Formation, well 15/3-8, 4235 m below the sea floor.

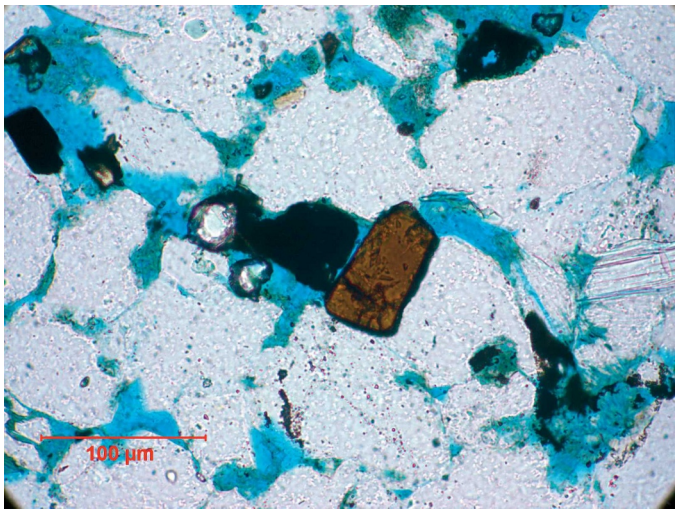

FIG. 6.—A pale brown spinel to the right of an opaque iron-titanium oxide grain and two zircons. Middle Jurassic Ness Formation, well 30/2-3, 3681 m below the sea floor.

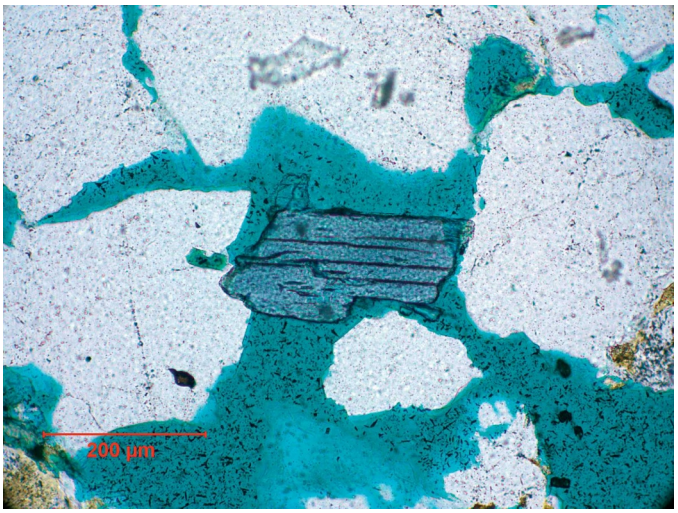

FIG. 8.—A subhedral, poorly rounded blue grain of chloritoid with prominent cleavage. The grain appears yellow when the microscope stage is rotated 90°. Middle Jurassic Etive Formation, well 34/8-8, 2644 m below the sea floor.

often prismatic crystals (Fig. 2) with more or less rounded corners, but anhedral angular grains are also common, and very well rounded ellipsoidal grains occur too. Zircon grains often show quite intense and commonly zoned pale yellow, pale blue, green, and occasionally pale pink cathodoluminescence, whereas other zircons appear black on cathodoluminescence micrographs.

Tourmaline

Several varieties of tourmaline were found, and a classification according to color was attempted, although definition of color classes is somewhat subjective. For pleochroic grains the color at maximum absorption was used for the classification. Grains showing two colors, for instance those with differently colored cores and rims, are reported in both color classes. Yellow tourmaline is the most common variety and was seen in 69.3% of the samples (Fig. 3). The frequency of occurrence for green, gray to black, and blue tourmaline is 37.2%, 14.2%, and 4.8%, respectively. Each of these four main color groups, especially the yellow one, includes substantial color variation. The yellow group might possibly be split in two according to whether or not black graphite inclusions are present. This type of inclusion is very common in the small yellow tourmalines found in many phyllites from western Norway.

The tourmaline grains vary in size from silt to coarse sand. Shape and rounding are also very variable: from euhedral to anhedral and from angular to perfectly rounded. The tourmalines appear black on cathodoluminescence micrographs.

Rutile

Rutile is very common and was seen in 89.6% of the thin sections. Rutile grains usually vary in color from yellow to brown (Fig. 4) and almost opaque, although some reddish grains also occur. Grain size varies from silt to medium sand. Grains are mostly anhedral or subhedral and angular or slightly rounded. Rutile is black on cathodoluminescence micrographs.

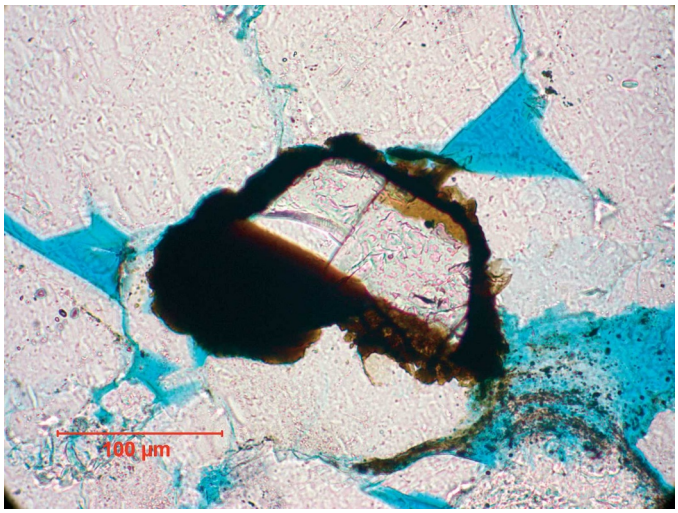

FIG. 7.—A monazite grain surrounded by dark brown heavy hydrocarbons. Middle Jurassic Garn Formation, well 6407/1-4, 3381 m below the sea floor.

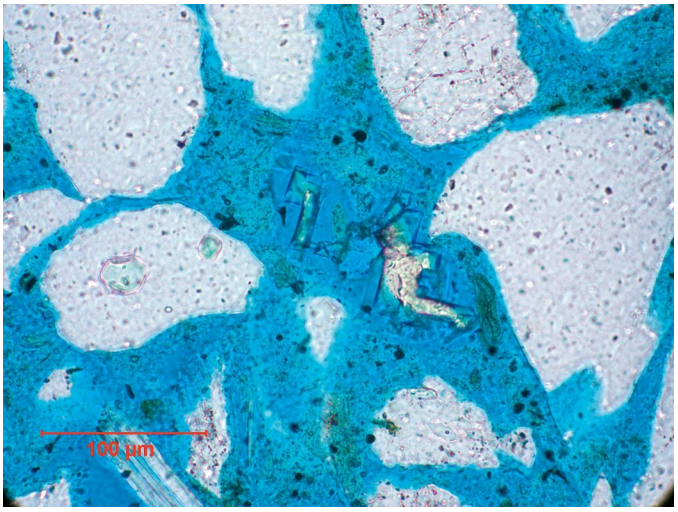

FIG. 9.—A partly dissolved skeletal grain of yellow staurolite. Paleocene Tang Formation, well 6610/3-1, 1250 m below the sea floor. Present depth is not the maximum burial depth.

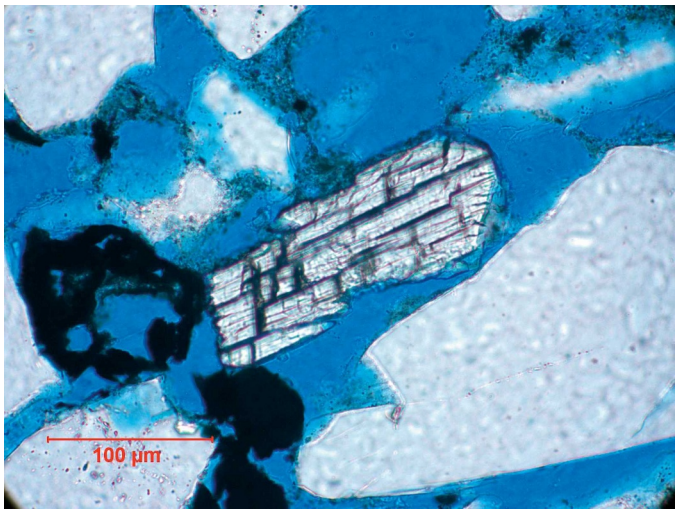

FIG. 10.— A kyanite grain showing typical cleavages. Lower Jurassic Åre Formation, well 6608/11-2, 1373 m below the sea floor. The sample may possibly have been buried more deeply than at present.

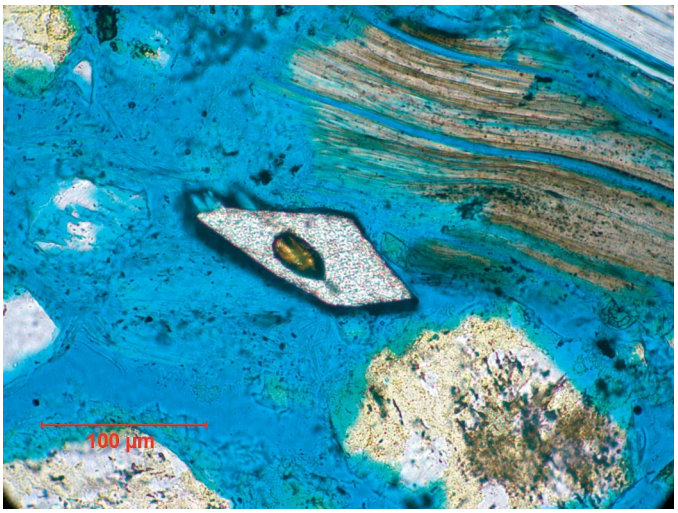

FIG. 12.— A wedge-shaped grain of sphene with a brown rutile inclusion. Middle Jurassic Fensfjord Formation, well 36/7-2, 808 m below the sea floor. Present depth is not the maximum burial depth.

Apatite

Apatite was observed in 34.2% of the samples. In parts of the study area the apatite grains are typically ellipsoidal and very well rounded whereas apatite grains in other wells are dominantly anhedral and poorly rounded or angular. Apatite grains sometimes show a euhedral hexagonal outline or at least some planar crystal faces. The size of the apatite grains is mostly within the silt to fine sand range. The apatite grains have a strong yellow cathdodoluminescence, occasionally with an orange-luminescent rim that probably is a diagenetic overgrowth (Fig. 5). Planar faces on some apatite grains are therefore at least partly a result of diagenetic apatite precipitation within the sandstones.

Garnet

Garnet was seen in 39.5% of the thin sections. Most garnets are colorless, but a few are pale yellow. The garnets vary in size from silt to very coarse sand, and are commonly larger than the other heavy-mineral grains in a given sample. Grains are often anhedral, angular, and irregularly shaped. Garnet grains often have more or less faceted surfaces (Figs. 2, 4), features that indicate corrosion of the garnet grains (Morton et al. 1989a). Corrosion features are especially common in the deeper samples. Some garnets show a weak brownish cathodoluminescence.

Spinel

Spinels are present in 32.0% of the samples. The colors of the spinels include brown, orange brown, reddish brown, and deep red (Fig. 6). SEM analysis indicates that the deep red spinels are chromite whereas brown varieties are rich in other elements such as iron, manganese, and magnesium. However, because identification of chromite by color alone was considered too subjective, all spinels have been grouped in one class. Spinels typically occur as rather small grains in the silt to fine sand range and are normally anhedral or subhedral and angular, although some well

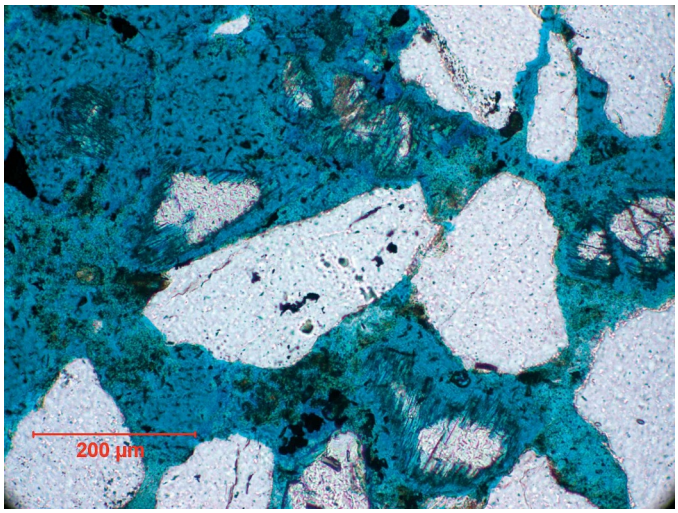

FIG. 11.—Several corroded epidote grains are seen between quartz grains. The epidote grain in the upper left corner is almost totally dissolved. Upper Jurassic Sognefjord Formation, well 6204/11-1, 2258 m below the sea floor. The sample may possibly have been buried more deeply than at present.

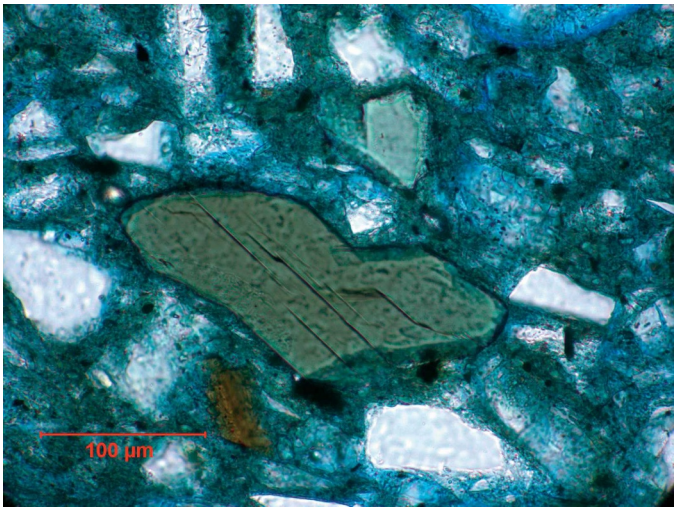

FIG. 13.— A green amphibole grain with a shape determined by the two intersecting cleavages typical of amphibole. Paleogene Brygge Formation, well 6710/10-1, 504 m below the sea floor. The sample may possibly have been buried more deeply than at present.

rounded grains also occur. Spinels appear black on cathodoluminescence micrographs.

Monazite

Monazite was found in 26.7% of the thin sections. Identification of monazite was greatly aided by reddish brown to black coatings on the monazite grains (Fig. 7). All grains with such coatings analyzed with the SEM turned out to be monazite, and the widespread occurrence of such brown coatings on monazite has also been reported more than sixty years ago (Smithson 1941) and confirmed in recent studies (Turner and Morton in press). The coatings contain carbon and sulfur, and probably consist of heavy hydrocarbons precipitated due to emission of radiation during radioactive disintegration of thorium and uranium contained within the monazite grains (Rasmussen et al. 1989; Rasmussen and Glover 1990). Monazite grains are mostly of very fine and fine sand size, anhedral, and in some cases well rounded. Monazite is black on cathodoluminescence micrographs.

Chloritoid

Chloritoid is present in 1.3% of the samples. The chloritoid grains are typically anhedral or subhedral and angular (Fig. 8). Grain size is mostly in the very fine and fine sand range. Chloritoid grains appear black in the cathodoluminescence mode.

Staurolite

Staurolite was recorded in 4.8% of the samples. The staurolite grains are mostly in the very fine and fine sand range, are normally anhedral and angular, and are often corroded (Fig. 9). The staurolite grains appear black in the cathodoluminescence mode.

Kyanite

Kyanite was found in 1.7% of the thin sections. Grains are typically anhedral with prominent cleavage and angular to moderately rounded (Fig. 10). Many kyanite grains are more or less corroded. Kyanite grains show an intense red cathodoluminescence.

Epidote

Epidote was seen in 1.9% of the samples. Grains are typically colorless or pale yellow. The grains are of coarse silt to medium sand size, anhedral, angular to rounded, and are in some cases corroded (Fig. 11). Epidote grains were not examined in the cathodoluminescence mode.

Sphene

Sphene was found in 0.7% of the thin sections. Grains are typically in the very fine to fine sand range, anhedral to euhedral, and poorly rounded (Fig. 12). Many grains seem to be corroded. Sphene was not examined in the cathodoluminescence mode.

Amphibole

Amphibole was seen in only 0.4% of the samples. The amphibole is green or pale yellow and often pleochroic (Fig. 13). Grains are normally silt to fine sand size, anhedral, and angular to moderately rounded. Grains are often elongate parallel to cleavage, and some are corroded. Amphibole was not examined in the cathodoluminescence mode.

Opaques

The presence or absence of opaque heavy-mineral grains was noted for each sample, but no attempt was made to differentiate between different opaque minerals. Opaque heavy minerals were found in 85.0% of the samples.

RESULTS

Heavy Minerals versus Depth

Zircon, tourmaline (all of the different varieties), rutile, apatite, spinel, and opaques occur at all depths from the surface down to more than 5000 m below the sea floor (Fig. 14). Obvious signs of corrosion were not seen for the mentioned non-opaque minerals. Monazite is present down to 4858 m whereas the deepest occurrence of garnet is at 4589 m, 259 m below the second deepest occurrence. Small crystal faces suggestive of corrosion features start occurring on some garnets in several wells at depths of around 2 km, and deeper than 3.5 km all garnets have surfaces consisting of larger crystallographically determined plane surfaces (Figs. 2, 4). A similar increase in the size of crystal facets on garnets with depth has previously been reported from the North Sea by Morton (1984, 1987). In some cases the faceted garnets are surrounded by dissolution porosity, with the original shape of the grain defined by a clay rim. No obvious corrosion features were seen on monazite grains, although the coatings of heavy hydrocarbons make observation of monazite grain surfaces difficult. Chloritoid was found between 1047 m and 3811 m below the sea floor, but its rare occurrence makes the definition of depth trends difficult for this mineral. Staurolite is present from the surface down to 2810 m, epidote to 2559 m, and kyanite to 2199 m. Epidote, kyanite, and staurolite grains are commonly irregular to skeletal, suggesting partial dissolution (Figs. 9, 11). Sphene was seen from the surface down to 1093 m, and in two Triassic samples from 3735 m and 3748 m in well 6510/2-1. Amphibole is restricted to the depth range 307–841 m.

Heavy Minerals versus Quartz Cement

Volumes of quartz cement in the studied samples span all values from zero to 31%. In addition one sample contains 34.7% quartz cement. Zircon, yellow tourmaline, green tourmaline, rutile, apatite, monazite, and opaques are present in the samples with more than 30% quartz cement, and also at almost all values of quartz cement between zero and 30% (Fig. 15). Gray to black tourmaline and spinel also occur in samples with more than 30% quartz cement and at most other quartz cement values, although not so often for quartz cement values above 22%. Blue tourmaline is quite common from zero to 27% quartz cement, whereas garnet is very common from zero to 18% and much less abundant from 18% to 25% quartz cement. Data for chloritoid is scarce, but chloritoid is found together with 0–4%, 12% and 24% quartz cement. Volumes of quartz cement in samples containing staurolite are 0–6%, and 0–1% for epidote, with the exception of a single Paleogene sample from only 1585 m below the sea floor, where the quartz cement is probably derived from dissolution of biogenic silica. Maximum content of quartz cement in samples containing kyanite is a few tenths of a percent. Amphibole does not occur together with quartz cement, and neither does sphene, except in the two Triassic samples from well 6510/2-1, where quartz cement volumes are 4.3% and 5%.

DISCUSSION

Dissolution versus Depth

The occurrence of zircon, tourmaline, rutile, apatite, and spinel at all depths, plus lack of corrosion features, strongly suggest that these minerals are not subject to significant intrastratal dissolution within the investigated depth range, i.e., down to 5–5.5 km below the sea floor. Opaques are also present at maximum investigated depth, although, because the opaque group contains several undifferentiated minerals, the

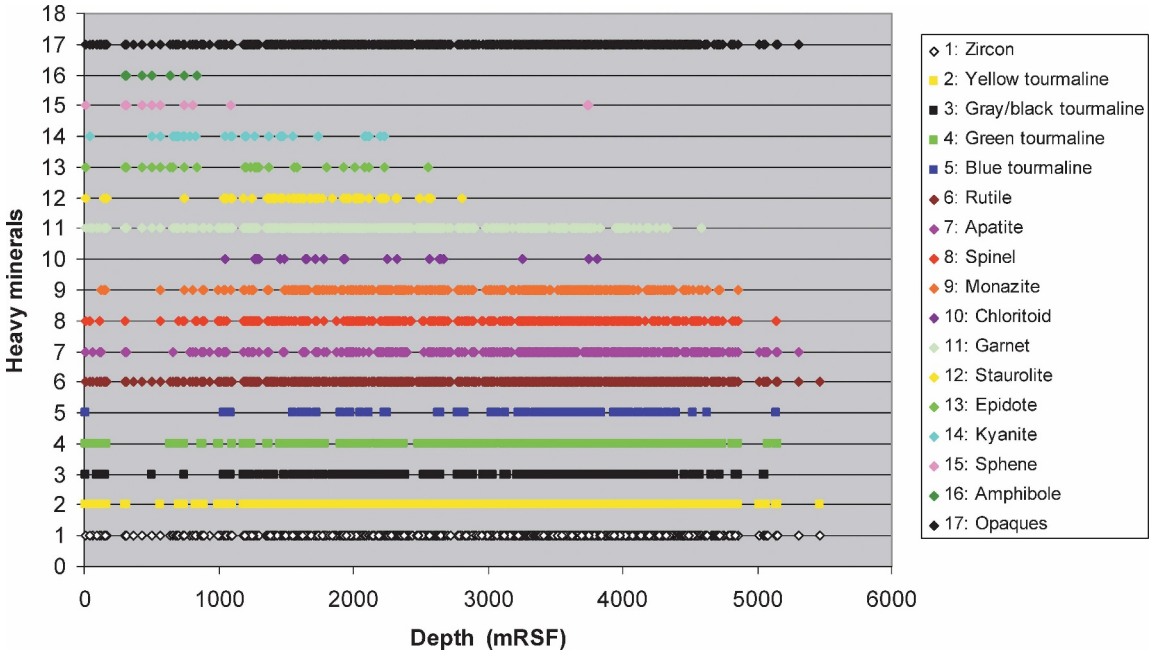

FIG. 14.—Heavy minerals versus depth below the sea floor.

data from the present study alone do not exclude that the diversity of opaque heavy mineral species is less at depth than close to the surface. The deepest observation of monazite is at 4858 m below the sea floor, whereas the deepest samples are from 5463 m. However, because the number of samples deeper than 4858 m is quite low, and because corroded monazite was not seen, it is not obvious that the lack of monazite in the deepest samples is due to monazite becoming unstable at around 5 km depth. Similar considerations apply to chloritoid. Although chloritoid was not found below 3811 m, this may be due to the rare occurrence of this mineral rather than to intrastratal dissolution. No obvious signs of corrosion are seen for the deepest grains of chloritoid.

Garnet is common from the surface and down to around 4000 m, although not in all formations. A few samples in the depth range 4000–4600 m contain garnets; the deepest occurrence is at 4589 m below the sea

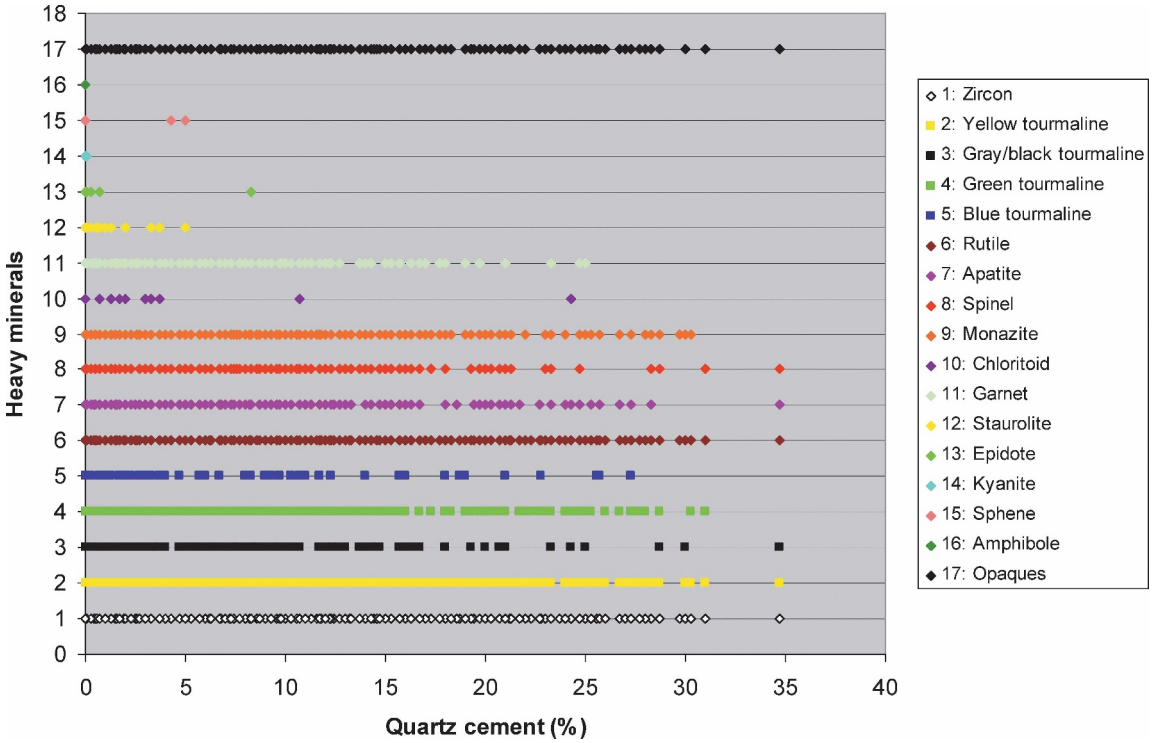

FIG. 15.—Heavy minerals versus point-counted volume of quartz cement.

floor. This depth distribution together with increasing signs of corrosion from 2 km and downwards (Figs. 2, 4) indicates that garnets are subject to intrastratal dissolution, although this becomes obvious only at advanced burial depths.

Garnets are also dissolved during surface weathering (Dryden and Dryden 1946; Sindowski 1949; Hester 1974; Walderhaug 1998), and one might therefore expect to find partly dissolved garnets at all depths, not just deeper than around 2 km. However, garnets from recent weathering profiles have been found to be either rounded or pitted, and without the outward-projecting crystallographically controlled facets that seem to be typical of intrastratal dissolution at high temperatures (Velbel 1984; Morton et al. 1989a).

The depth trend for staurolite, and the occurrence of skeletal staurolite grains (Fig. 9), clearly points to staurolite being subject to intrastratal dissolution, because there is no obvious alternative geological explanation for why staurolite is moderately common down to around 2.6 km below the sea floor, occurs once at 2810 m, and is not present below this depth at all. Epidote and kyanite are also present from the surface and down to moderate depths only. The deepest occurrence of epidote is at 2559 m and for kyanite at 2231 m, which together with the presence of highly corroded grains of these two minerals (Fig. 11) strongly suggests that they also are prone to dissolution during burial.

Sphene is confined mainly to shallow depths. With the exception of two Triassic samples at 3735 m and 3748 m below the sea floor in well 6510/2-1, the deepest occurrence of sphene is at 1093 m below the sea floor. The quite abundant sphene in the two deep samples shows no signs of corrosion, and it is suspected that it may be authigenic. The two samples with possible authigenic sphene have a composition which is very unusual on the Norwegian Shelf. Feldspar, mainly plagioclase, makes up 50–55% of sample volumes and is almost twice as common as quartz. Common rutile and opaque iron-titanium oxide grains and around 5% calcite cement suggest that considerable Ca and Ti may have been available for precipitation of sphene. It is therefore thought most likely that sphene normally will not survive to depths much in excess of 1 km in the study area, but that authigenic sphene may start forming at diagenetic temperatures if the sediment composition is favorable. Authigenic sphene has previously been reported from Jurassic sediments in the North Sea in the form of euhedral crystals up to 0.12 mm long (Morad 1988), as crystals up to 0.3 mm long and cement patches in Permian sandstones from Scotland (van Panhuys-Sigler and Trewin 1990), and as very small crystals (5–20 μm) in sandstones from California (Merino 1975; Helmold and van de Kamp 1984).

Amphibole is present only in very shallow samples; the deepest occurrence is at 841 m below the sea floor. This suggests that amphibole is the most unstable of the examined heavy minerals, and is totally dissolved at depths of less than 1000 m in the study area.

The two deepest samples containing sphene, probably authigenic sphene, at 3735 m and 3748 m below the sea floor in well 6510/2-1 have probably been uplifted around 0.5 km. Maximum burial depth for the deepest sample containing detrital sphene may possibly be a few hundred meters more than the present value of 1093 m below the sea floor in well 6710/10-1. The deepest present occurrences of the other heavy minerals are in wells where there are no indications of uplift.

Dissolution versus Temperature

The maximum temperatures of occurrence for the studied heavy minerals have also as far as possible been determined. The temperatures in the deepest samples included in this study are around 200°C, which suggests that zircon, tourmaline, rutile, apatite, spinel, and at least some opaques are all stable up to this temperature within the study area. This may possibly also be the case for monazite, although the maximum temperature of occurrence for monazite is 182°C according to the temperature measured during a drill-stem test 55 m above the sample. Similarly, the absence of chloritoid in the deepest and hottest samples may be due to the rare occurrence of this mineral and not to intrastratal dissolution. However, the temperature in the deepest sample where chloritoid was actually found is 149°C based on a drill-stem test 4 m below this sample.

The three deepest occurrences of garnet are at 4303 m, 4330 m, and 4589 m in three wells in the Jurassic Garn Formation. This corresponds to 165°C, 166°C, and 175°C respectively according to temperatures from drill-stem tests for the two deepest samples, and Horner-corrected bottom-hole temperatures for the shallowest sample. This shows that some garnets survive to these temperatures, although the common corrosion features present at far shallower depths suggest that other garnets are less stable and are dissolved at much lower temperatures.

The deepest and warmest occurrence of staurolite is at 2810 m below the sea floor at a temperature of 109°C. This temperature is considered to be reliable because temperature was measured during a drill-stem test 20 m above the sample. Four occurrences of staurolite in the depth range 2495–2572 m probably correspond to temperatures of 95–100°C, although only Horner-corrected bottom-hole temperatures are available for these samples.

The deepest occurrences of kyanite are at 2199 and 2231 m in the same well. Horner-corrected bottom-hole temperatures suggest that present temperature at 2231 m is 92°C. Epidote also occurs at 92°C in the sample from 2231 m, and at 2559 m in a different well. Horner-corrected bottom-hole temperatures give a value of 89°C for the deepest occurrence of epidote at 2559 m, but comparison with temperature data from neighboring wells suggests that true formation temperature may be around 95°C.

In the well where sphene occurs at 1093 m, corrected bottom-hole temperatures suggest that present temperature is around 45°C. Due to possible slight uplift, temperatures may have been around 55°C in the past. The probable authigenic sphene at 3748 m would have been subjected to temperatures of 155–175°C when around 0.5 km of uplift is taken into account.

Temperature measurements are not available from the well with the deepest occurrences of amphibole, but data from other wells suggest that temperatures in the area at 841 m below the sea floor may be around 40°C.

Dissolution versus Volume of Quartz Cement

The occurrence of the different heavy minerals versus volumes of quartz cement defines the same stability series as when their occurrence is plotted against depth or temperature. Zircon, tourmaline, rutile, apatite, spinel, monazite, and at least some species of opaques are found together with volumes of quartz cement exceeding 30%, i.e., up to the maximum time – temperature exposure encountered in this data set. Garnet, or at least some types of garnet, survives up to levels of time – temperature exposure corresponding to 25% quartz cement, whereas garnets do not occur in samples with 25–35% quartz cement. Maximum volume of quartz cement in samples containing chloritoid is 24%, but this may be due to the rare occurrence of this mineral rather than to dissolution. Staurolite does not occur together with more than 6% quartz cement, and epidote is confined to samples with 1% quartz cement or less except in one case where the 8% quartz cement present is believed to be derived from biogenic silica. Maximum content of quartz cement in samples containing kyanite is a few tenths of a percent, whereas sphene and amphibole do not occur together with quartz cement at all except for the presence of sphene in two deep Triassic samples where sphene is thought to be diagenetic.

Comparison with Previous Studies

The stability sequence established by Morton (1984) for Paleocene sandstones from the British sector of the North Sea is almost identical

to the results from our study. Of the minerals considered in both studies, Morton (1984) found amphibole to be least stable, i.e., it disappeared at the shallowest depth, followed by epidote, sphene, kyanite, staurolite, and garnet. Apatite, chloritoid, spinel, rutile, tourmaline, and zircon occurred at all depths. The only clear difference is for epidote, which Morton (1984) found to be less stable than sphene, and kyanite, whereas in the present study epidote was found deeper than sphene and slightly deeper than kyanite. Etching of chloritoid has, however, been reported from 2.8 km depth in the Jurassic Brent Group in the British sector of the North Sea (Morton and Hallsworth 1999), and from Cretaceous samples in the Norwegian Sea (Turner and Morton in press), suggesting that the lack of chloritoid in our deepest samples might possibly be a result of intrastratal dissolution. Very small (< 5 μm) etch pits that may be a sign of incipient dissolution have recently been documented on monazite grains in Jurassic sandstone in the North Sea at depths exceeding 5 km (Turner and Morton in press). It therefore should not be excluded that the absence of monazite in our samples from 4.9–5.5 km below the sea floor could be a result of intrastratal dissolution and not a consequence of few very deep samples in our data base.

Cogen (1940), although he did not interpret this to necessarily be a result of intrastratal dissolution, found that in the Cenozoic sandstones of Louisiana heavy minerals disappeared with depth in the order amphibole, sphene, epidote, kyanite, and finally staurolite. This is the same order as observed in the present study except for epidote and kyanite having switched places.

Smithson (1941) studied the Jurassic and Triassic sandstones of Yorkshire, England, and by mapping the distribution of heavy minerals from the periphery to the center of this more or less uplifted basin concluded that amphibole dissolved first, followed by kyanite, staurolite, garnet, and lastly monazite. Apatite, tourmaline, rutile, and zircon did not show evidence of intrastratal dissolution. The only difference from the results of the present study is that Smithson (1941) considers monazite to be not quite as stable as apatite, tourmaline, rutile, and zircon. As discussed above, the data from the present study could also be interpreted in this way.

The stability sequence established by Wiesender (1953) for Tertiary sandstones in the Vienna Basin from least to most stable is amphibole, epidote, kyanite, staurolite, apatite, and garnet. Tourmaline, rutile, and zircon were considered not to dissolve within the studied sandstones. This largely agrees with the results of the present study, although Wiesender (1953) considers intrastratal dissolution to affect apatite, and epidote to be totally dissolved at shallower depths than kyanite.

Milliken (1988), in a study of the Plio-Pleistocene of the northern Gulf of Mexico, also found tourmaline and zircon to be unaffected by intrastratal dissolution, kyanite to disappear somewhat shallower than epidote, and garnet to be the most stable of the heavy minerals affected by intrastratal dissolution. This is the same interpretation as in the present study, but Milliken (1988) found amphibole to persist to the same depth as epidote, and sphene to be present down to a depth between the deepest occurrences of epidote and garnet.

In addition to the stability sequence, the greatest depths of occurrence for the various heavy minerals are given by both Morton (1984) and Milliken (1988). The depths given by Morrton (1984) for the species prone to intrastratal dissolution are only 200–400 m less than in the present study for amphibole, sphene, kyanite, and staurolite, but 1450 m less for epidote. Slightly deeper occurrence for several unstable minerals may be due to the large number of samples and the large geographic and stratigraphic range of these samples in the present study. The difference in maximum depth of occurrence for epidote is, however, not so easy to explain.

The depths of persistence for amphibole, kyanite, epidote, and sphene found by Milliken (1988) in the Plio-Pleistocene sediments of the northern Gulf of Mexico are 2.5 km, 1.2 km, 0.8 km, and 3.1 km deeper, respectively, than found in the present study. Using the expression for temperature versus depth given in Milliken (1988), the maximum temperatures of occurrence for amphibole, kyanite, epidote, and sphene in her study are approximately 93°C, 84°C, 93°C, and 109°C, respectively. The maximum temperature of occurrence for amphibole in the present study is 53°C lower, for sphene it is 54°C lower, whereas for epidote the maximum temperatures of occurrence are approximately equal, and in the case of kyanite the maximum temperature of occurrence is 7°C higher in the present study. The rapid burial and short time available for dissolution in the Plio-Pleistocene sandstones studied by Milliken (1988) might explain the occurrence of amphibole and sphene at far greater depths and higher temperatures than in the present study, although this explanation implies that epidote and kyanite should have been present at even greater depths and temperatures in the Gulf Coast data set. A possible explanation of these observations could be that epidote and kyanite have never been present in the deepest samples examined by Milliken (1988). Alternatively, the chemistry of amphibole and possibly epidote may be significantly different in the two study areas. Persistence of amphibole and epidote to unusually great depths in Pliocene sediments has also been reported by Morton et al. (2003) from the Southern Caspian Basin, where the very low heat flow, 25–52 mW/m^2 according to Morton et al. (2003), probably also contributes to the preservation of these minerals to depths in excess of 3.5 km.

Sinks for Dissolved Heavy Minerals

Authigenic silicates present in the studied sandstones over the depth range where kyanite, staurolite, and epidote disappear are normally restricted to kaolinite and more rarely K-feldspar overgrowths. A possible sink for the aluminum from dissolution of these three heavy minerals could therefore be precipitation of trace amounts of kaolinite. Calcium and iron from dissolution of epidote and staurolite may possibly be incorporated in carbonate cements such as siderite and calcite, cements that are typically present in varying amounts in the studied rocks.

Using almandine as an example, dissolution of garnets may possibly lead to precipitation of kaolinite, quartz, and a carbonate according to the reaction

$$\underset{\text{almandine}}{Fe_3Al_2Si_3O_{12}} + 2H_2O + 3CO_2 = \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{quartz}}{SiO_2} + \underset{\text{siderite}}{3FeCO_3} \quad (1)$$

Garnets are present to greater depths and temperatures than kyanite, staurolite, and epidote, and aluminum from garnet dissolution may therefore possibly be incorporated into illite at temperatures where kaolin becomes unstable, i.e., above approximately 125°C (Bjørlykke et al. 1986; Ehrenberg and Nadeau 1989). The net reaction could then be the sum of the reaction given in Equation 1 and the illitization reaction for kaolinite, or dickite, which may be the stable polytype above 125°C (Ehrenberg et al. 1993). The total reaction for almandine dissolution at temperatures above approximately 125°C may therefore be:

$$\underset{\text{almandine}}{Fe_3Al_2Si_3O_{12}} + \underset{\text{K-feldspar}}{KAlSi_3O_8} + H_2O + 3CO_2 = \underset{\text{illite}}{KAl_3Si_3O_{10}(OH)_2} + \underset{\text{quartz}}{3SiO_2} + \underset{\text{siderite}}{3FeCO_3} \quad (2)$$

The actual compositions of garnets on the Norwegian continental shelf and in adjoining areas of the North Sea have been shown to often be quite close to almandine, but magnesium-rich garnets are also common, and both iron-rich and magnesium-rich varieties typically contain some

calcium and manganese (Morton 1985b, 1987; Gjelberg et al. 1987; Hurst and Morton 1988; Morton et al. 1989b; Morton and Berge 1995). Other carbonates than pure siderite will therefore probably also precipitate if garnet dissolution takes place according to the reactions outlined above. The minor volumes of siderite, magnesium-rich siderite, dolomite, ferroan dolomite, and calcite present in many of the samples included in this study might therefore possibly include material from garnet dissolution.

CONCLUSIONS

The results from the present study indicate that amphibole, sphene, kyanite, epidote, staurolite, and garnet dissolve during burial, whereas zircon, tourmaline, rutile, apatite, and spinel survive without any signs of dissolution to depths exceeding 5 km and to temperatures approaching 200°C. Monazite and chloritoid were not found at temperatures above 182°C and 149°C respectively, but the rare occurrence of chloritoid and the low number of very deep and hot samples makes it difficult to determine if this is due to intrastratal dissolution. The maximum depths and temperatures of occurrence for the unstable minerals are: 841 m and 40°C for amphibole, 1093 m and 45°C for sphene, 2231 m and 92°C for kyanite, 2559 m and 95°C for epidote, 2810 m and 109°C for staurolite, and 4589 m and 175°C for garnet. Due to possible uplift the temperature in the deepest sample containing sphene may previously have been around 10°C higher than at present.

When using volume of quartz cement as a proxy for time-temperature exposure, the same sequence of stability was found as for heavy minerals versus depth and versus present temperature. No quartz cement was found where amphibole and sphene are present, maximum content of quartz cement is a fraction of a percent where kyanite is preserved, up to 1% for epidote, 6% for staurolite, 24% for chloritoid, 25% for garnet, and 25–35% for the other heavy minerals.

There is good agreement between the present study and several previous similar studies concerning which heavy minerals are prone to intrastratal dissolution. The order of persistence versus depth for the unstable minerals is also very similar, although there are some differences concerning the position of epidote and sphene in the sequence of stability, and unstable heavy minerals survive to greater depths in young and very rapidly buried sandstones.

The dissolution of heavy minerals during burial creates a few secondary pores, and may possibly cause precipitation of kaolinite, illite, quartz, and carbonates, but the volumes of precipitated cements from this source will typically be insignificant.

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