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Luminescence characteristics of Scandinavian quartz, their connection to bedrock provenance and influence on dating results

Helena Alexanderson [a,b,*]

[a] Department of Geology, Lund University, SE-22362, Lund, Sweden
[b] Department of Geosciences, The Arctic University of Norway, NO-9037, Tromsø, Norway

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ABSTRACT

The success of optically stimulated luminescence (OSL) dating relies to a large extent on suitable characteristics of the analysed mineral, in this case quartz. Previous OSL dating of Quaternary sediments in Scandinavia has shown that quartz characteristics vary widely across the region, resulting in dating studies with varied success. The aim of this study is to provide an overview of quartz luminescence characteristics in Sweden and Norway, evaluate their effect on dating results and discuss the underlying causes of their variability.

A qualitative assessment of luminescence signal characteristics of quartz from Late Quaternary sediment deposits, from a range of geological and geographical settings, has been made by re-analysing data from samples previously dated at the Lund Luminescence Laboratory, Sweden. This allowed a general characterisation of signals and a study of the relationship of these properties to dating result 'quality'. To quantify the results, selected samples were further analysed with single-grain measurements and with small aliquots.

The results show that the average luminescence signal from quartz is fairly dim but dominated by a fast signal component and changes little during measurement. Dose determination precision is ~4% for 8-mm aliquots and ~6% for 2-mm aliquots. However, the luminescence signal characteristics have a spatial variation across Sweden and Norway, which appears to correlate with large-scale bedrock units. In areas of sedimentary bedrock outside the Scandinavian mountains and within the Blekinge-Bornholm province, the quartz is brighter and has a stronger fast signal component, while in the Caledonian orogenic belt, the signal is very weak and lacks a fast component. These differences lead to a range in precision of doses, from ~2% to >40% (for doses in the order of 5–400 Gy), and in the number of rejected aliquots (0–100%) depending on location, but also implies that quartz luminescence can be used as a provenance indicator in part of Sweden and Norway.

1. Introduction

1.1. Background

Luminescence dating has been used successfully and extensively in numerous sedimentary environments around the world to provide ages of events recorded in siliciclastic deposits from the Middle and Late Quaternary (Wintle 2008; Rhodes 2011). Age ranges from ~10 yr to at least 500 ka can be dated, depending on choice of luminescence technique (e.g. Rhodes 2011; Thiel et al., 2011; Roberts and Lian 2015). Furthermore, the ubiquity of quartz and feldspar, which are the minerals used for dating, makes the method applicable to most terrigenous sediments, and it is in many instances the only practically applicable absolute dating method given material availability and long age range.

In Scandinavia, optically stimulated luminescence (OSL) luminescence dating on quartz has provided chronological frameworks for Late Quaternary glaciations and ice-free phases (e.g. Houmark-Nielsen and Kjær 2003; Alexanderson et al., 2010; Möller and Murray 2015; Möller et al., 2020), aeolian activity (e.g. Clemmensen et al., 2009; Alexanderson and Bernhardson 2016), coastal development (e.g. Nielsen et al., 2006; Kalińska-Nartiša et al., 2017) and archaeological sites (e.g. Häggström et al., 2004; Vafiadou et al., 2007). However, in a number of cases, luminescence dating has turned out to yield inconsistent or imprecise results (e.g. Alexanderson and Murray 2007; Lagerbäck 2007; Houmark-Nielsen 2008; Alexanderson et al., 2011; Alexanderson and Murray 2012). Some researchers have even refrained from publishing their luminescence ages since they 'didn't make sense', and some have had difficulty publishing their data due to 'poor' chronology.

* Department of Geology, Lund University, SE-22362, Lund, Sweden.
E-mail address: helena.alexanderson@geol.lu.se.

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Previous studies have shown that the geological history of the analysed material (quartz) and the depositional processes of the dated sediment play a crucial role for the accuracy and precision of a luminescence date (Preusser et al., 2009; Rhodes 2011). Empirical studies suggest that luminescence characteristics are controlled by the thermal and geological history of the quartz (genesis, provenance, age, weathering) and the transport history of the grains (number of erosional and depositional cycles, mode of transport), and thus that the compound luminescence characteristic is a function of regional geology that provides a provenance indicator (Kuhn et al., 2000; Tsukamoto et al., 2011; Gray et al., 2019). It is, however, poorly understood why and exactly how the quartz and luminescence characteristics correlate (Preusser et al., 2009; Jeong and Choi 2012). Systematic studies of regional variations in luminescence characteristics are largely lacking but are now starting to appear related to an increasing number of studies of quartz luminescence as a provenance tool (Gray et al., 2019).

In general, quartz grains from sedimentary rocks seem to be more sensitive than grains from igneous or metamorphic rocks, and are also more clearly dominated by a fast signal component (Fitzsimmons 2011; Sawakuchi et al., 2011; Jeong and Choi 2012; Lü et al., 2014). It has also been shown that luminescence sensitivity may increase with transport distance in a fluvial system (Pietsch et al., 2008; Sawakuchi et al., 2011; Gliganic et al., 2017) and varies between depositional settings (Fitzsimmons et al., 2010) and between areas with different uplift and erosion rates (Sawakuchi et al., 2018). These observations could explain the problems with luminescence dating encountered in parts of Fennoscandia (Alexanderson and Murray 2012) where the bedrock is dominated by igneous and metamorphic rocks (Lahtinen 2012) and transport distances are generally short, which could lead to e.g. dim quartz grains. Alexanderson and Murray (2012) hypothesised that the mineralogical properties of the quartz were important for the OSL characteristics for Swedish material and Alexanderson and Bernhardson (2016) have shown that the Jotnian Dala sandstone in central Sweden provided quartz with good characteristics (i.e. a bright and stable signal dominated by a fast component).

The aim of this study is to provide an overview of quartz luminescence characteristics in Sweden and Norway, and quantify some aspects and issues often referred to in OSL dating such as 'poor luminescence characteristics' and 'well-behaved quartz'. Such expressions are commonly used to anecdotally explain the quality of OSL dating results but are seldom described or analysed in detail in publications. The results provide guidelines for future luminescence dating, particularly for work in Scandinavia. A secondary aim is to examine the relationship between geology of the sediment source areas and luminescence, and the potential of using quartz luminescence as a proxy for provenance in Scandinavia. The focus is on quartz luminescence characteristics, i.e. the sensitivity of the fast OSL component and shape of the OSL decay curve, and any changes in these that take place during measurements, and which are then related to dating results (e.g. precision) and to geological setting (bedrock type and age, sediment genesis). Other factors that affect a luminescence age, such as incomplete bleaching or uncertainties in environmental dose rate, will not be discussed here.

1.2. Regional setting

The largest part of Sweden and Norway is located on the Baltic shield, with Precambrian bedrock that is divided into different provinces according to age and history (Fig. 1) (Koistinen et al., 2001; SGU 2016). The most extensive are those belonging to the *Svecokarelian orogenic belt* (1.9–1.8 Ga; mainly magmatic rocks) in eastern Sweden and the *southwest Scandinavian province* (1.1–0.9 Ga Sveconorwegian orogenic belt with magmatic and metamorphic rocks) in western Sweden and SW Norway (Lundqvist and Norling 2007). These provinces are separated by the N–S extending *Transscandinavian Igneous Belt* (TIB, 1.85–1.7 Ga granites and volcanites), which in turn borders the *Blekinge-Bornholm province* with 1.9–1.6 Ga old magmatic and metamorphic rocks in the

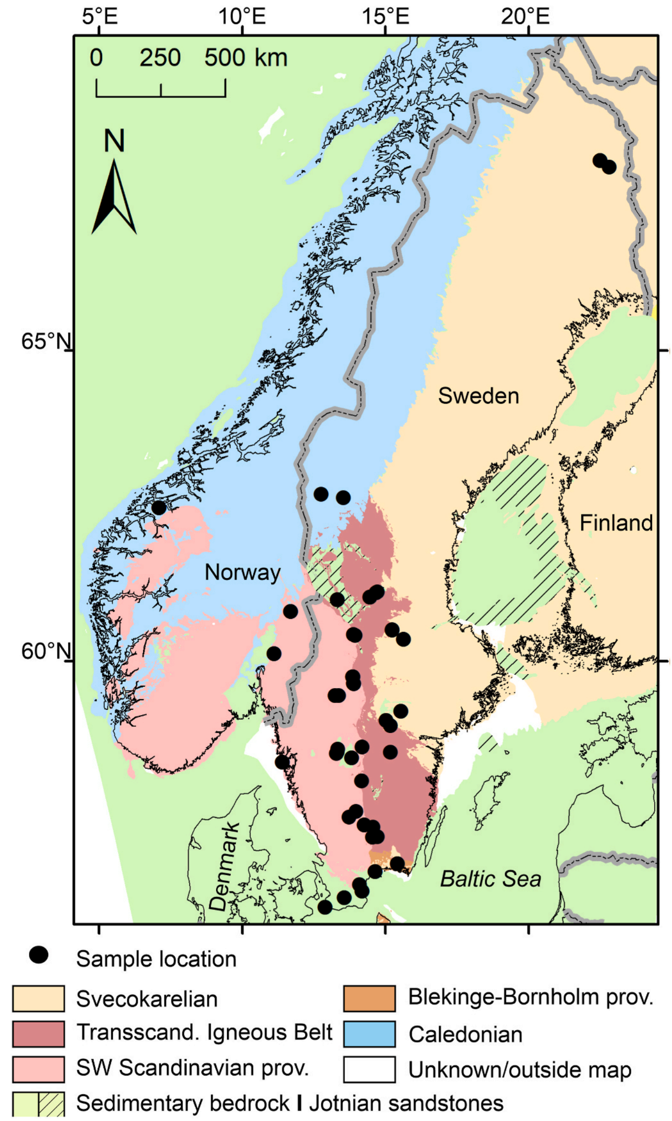

Fig. 1. Bedrock map of Sweden and Norway and the location of samples used in this study. The classification of bedrock units is according to Koistinen et al. (2001) and SGU (2016). For details on the samples and their context, see Table S 1 and Table S 2. Map data from Koistinen et al. (2001).

south (Koistinen et al., 2001; Lundqvist and Norling 2007). The Scandinavian mountains, which make up most of Norway and part of Sweden, belong to the *Caledonian orogenic belt* (510-400 Ma) and consist of metamorphic and sedimentary rocks (Koistinen et al., 2001). Outside the Caledonides, *sedimentary bedrock* is found as patches of Palaeozoic and Mesozoic platform cover mainly in southern Sweden and as Jotnian sandstones, partly within the TIB in central Sweden but also in the Bothnian Sea (Koistinen et al., 2001) (Fig. 1). Overall, the large-scale bedrock morphology is characterised by domes in the west and stepped, flat or hilly palaeosurfaces in the east and south (Lidmar-Bergström and Näslund 2002).

Much of the bedrock is covered by Quaternary unconsolidated deposits, mainly formed during Late Quaternary glaciations, particularly the Late Weichselian (Last Glacial Maximum), and the subsequent deglaciation and the Holocene interglacial. The most common sediment is till, which covers ~60% of Sweden, not including thin (<0.5 m) till drapes in e.g. mountainous regions (SGU 2005). Glacifluvial deposits are concentrated in valleys, at the marine limit and in large esker systems. Glacimarine and glacilacustrine clays and silts cover large areas below the marine limit (highest shoreline). Fluvial, alluvial, colluvial, littoral and aeolian deposits are not extensive but are locally important. In addition, there are organic deposits (mainly peat), but these are not considered in this study.

Though tills and glacifluvial deposits may contain far-transported material, petrographic and mineralogic studies suggest that most of the sediment is relatively locally derived (within a few km; e.g. Lundqvist 1969; Lindén 1975). This leads to a key assumption in this study: that quartz grains in Quaternary sediments at a particular site originate from the bedrock underlying that site within the scale of bedrock provinces.

2. Material and methods

2.1. Sample selection

Sixty-five samples were selected from samples previously analysed at the Lund Luminescence Laboratory (LLL) on the basis of getting material from as large a range of geological settings (bedrock units and Quaternary depositional environments) as possible, as well as a wide geographical distribution (Fig. 1, Table S 1). All samples were prepared in the same way and all multi-grain aliquots were analysed in the same Risø TL/OSL reader model DA-20 (Bøtter-Jensen et al., 2000). Further sample information including location is presented in Table S 1, where references to original publications are also listed. Data from 27 aliquots of Risø calibration quartz (Hansen et al., 2015) have been included to serve as a comparison.

2.2. Luminescence data sets

Three datasets have been created from the selected 65 samples. Dataset 1 consists of historical data retrieved from the archive of LLL and comprises results from measurements according to single aliquot regeneration (SAR) protocols (Murray & Wintle 2000, 2003; Banerjee et al., 2001) (Table S 3, Table S 4). Dataset 1 is mainly used to evaluate how luminescence characteristics impact dating result and contains information on e.g. measurement settings, equivalent doses, dose recovery ratios, quality criteria, fast ratio and brightness. To reduce the technical variability (different protocol settings, aliquot size, etc.) in Dataset 1, 63 of the 65 samples have been measured again; three small (2-mm) aliquots per sample have been measured with one and the same sequence and settings (Table S 5) and make up Dataset 2 (Table S 6). Dataset 2 contains information on e.g. sensitivity, fast ratio and signal components. Dataset 3 consists of data from single-grain measurements of 19 samples, including number of grains with detectable signals and calculated total sensitivity (Table S 7). Further description of the datasets is found in the respective supplementary tables (Table S 3-Table S 7).

2.3. Analyses of luminescence signals

Based on the requirements for successful quartz luminescence dating as indicated by the assumptions and quality checks that are part of standard dating analyses (Murray and Wintle 2000, 2003), the analyses focus on three aspects of the luminescence signal: presence of a fast signal component, signal intensity and signal change during measurement. Properties describing these aspects provide the means to put numbers to key characteristics of the luminescence signal that affect the material's suitability for luminescence dating (Wintle and Murray 2006). They also help identify issues that have previously caused problems in quartz luminescence dating both in Scandinavia and elsewhere, such as a weak fast component/strong medium or slow components, dim signals or large changes during measurement (e.g. Preusser et al., 2006; Steffen et al., 2009; Anjar et al., 2018). There are different ways to determine these properties; here methods that can be applied effectively to large datasets and which are not technically complex or introduce large additional uncertainties have been chosen. The properties are briefly described below, for technical details see Table S 8.

The *fast ratio* (FR; Durcan and Duller, 2011) was used as a measure of the strength of the fast signal component, which also reflects the shape of the decay curve. Durcan and Duller (2011) use a threshold value of 20 to identify signals that are dominated by a fast component and the *proportion of aliquots with a fast ratio* ≥ 20 was calculated. The *detrapping probability* and the *photoionisation cross-section* of identified signal components were calculated through analysis (component fitting) of LM-OSL curves in RStudio (Kreutzer 2021).

The signal intensity, i.e. the number of photons emitted during stimulation, reflects both material properties and the dose (age) of the sample. The OSL counts were integrated in Risø Analyst v. 4.57 and then divided by dose and mass for that aliquot to calculate the *sensitivity* (in counts/Gy·mg·s). Aliquot mass was determined by weighing each disc with and without grains. For Dataset 1, the aliquot mass is not known and the *brightness* (in counts/Gy·s) of the signal was determined instead (see Table S 8 for details). For Dataset 3, *the number of grains that gave a detectable luminescence signal* (with a peak $\gg$ background) were also counted.

Any sensitivity change that takes place during measurement is monitored by the test signal (Murray and Wintle 2000) and the *sensitivity change*, i.e. the ratio between the last and the first signal with the same laboratory irradiation in the measurement, represents this change. The first five channels (0.8 s) in each signal were integrated in Risø Analyst v. 4.57 and the T_{last}/T_n ratio was calculated. The *change in the fast ratio* between the natural and the first regenerated signal (FR_{Ln}/FR_{R1}) has also been used to study changes in the relative strength of signal components during measurement.

2.4. Estimates of luminescence dating quality

The variable luminescence characteristics have practical implications; they are reflected both in how measurements are carried out, and in the final results of the analyses, i.e. the luminescence age. 'Good' luminescence characteristics tend to make analyses easy and to give precise and accurate doses, while the opposite is usually the case for 'poor' luminescence characteristics. Here, properties reflecting the precision of dose determinations, the 'ease' of measurement from the point of view of the luminescence practitioner, and SAR-protocol quality checks are used (Table S 8).

As estimates of the precision of the end result, the *relative standard error (RSE) of the equivalent dose* and of the *dose recovery ratio* are used. The RSE values are calculated from data stated by the original authors, as this is assumed to be the 'best possible' outcome of the dating analyses and dose recovery of a specific sample. The *proportion of rejected aliquots* (due to test dose signal error, recycling ratio or recuperation) is used to give an estimate of how straightforward measurements are. A high rejection ratio indicates that many more aliquots need to be measured to get a sufficient number of aliquots to calculate an equivalent dose, while a sample with few rejected aliquots requires less machine time, other factors being alike. Information from the quality checks built into the SAR-protocol (*recycling ratio*, *recuperation*) as well as *the dose recovery ratio* has also been analysed.

2.5. Geological classification

Each sample was classified according to its genesis (depositional system) and the bedrock substrate at the site. The genetic classification was based on interpretations in original publications and included the classes glacial, glacifluvial, glacilacustrine, paraglacial, fluvial, littoral, aeolian and anthropogenic (earthen floor). Bedrock province details were extracted from Koistinen et al. (2001), with supplemental information on subunits from SGU (2016). Six main units were distinguished: the Svecokarelian orogenic belt (SKO), the Transscandinavian igneous belt (TIB), the southwest Scandinavian province (SWS), the Blekinge-Bornholm province (BBP), the Caledonian orogenic belt (COB) and sedimentary bedrock (SED).

3. Results

3.1. Luminescence signal characteristics

The brightness of the natural signal (B_{Ln}) from individual aliquots in Dataset 1 (65 samples, 1921 aliquots) has a median value of 441 ± 50 counts/Gy·s for large aliquots and 76 ± 20 counts/Gy·s for small aliquots (Fig. 2A; Table S 4). For those samples where both large and small aliquots have been measured, the small-aliquot B_{Ln} is between 5 and 50% of the large-aliquot B_{Ln} for the same sample. The sensitivity of the test signal (S_{Tn}) of individual aliquots from the 63 samples (189 aliquots, average weight of quartz 1.18 mg/disc) in Dataset 2 range over four magnitudes from 3 to 3870 counts/Gy·mg·s, but almost two-thirds (63%) are relatively dim with a sensitivity of <200 counts/Gy·mg·s (Fig. 2B; Table S 6).

The fast ratio FR has a larger range for the natural than for the regenerated signals for both Dataset 1 and 2, and 59% (Dataset 1) and 53% (Dataset 2) of the aliquots (natural signal) have a FR ≥ 20 (Fig. 2C). On sample level, the proportion of aliquots with FR ≥ 20 ranges from 0 to 100% for Dataset 1 (Table S 4). Nine percent of the aliquots in Dataset 1 had negative or inflated FRs with RSE>100% for the natural signal and were thus rejected.

Component fitting of the LM-OSL curves was done on one aliquot per sample of Dataset 2; for one of the samples (16015) the fitting was unsuccessful and no data were retrieved. Fifty-two (84%) of the remaining 62 samples have a fast signal component, though for some samples it is relatively weak (Fig. 3). Seven samples (11%) show an ultrafast component, nine a medium component and all samples have one or more slow components. Between one and five components were identified for any individual sample, for most two or three components (Table S 6). The mean values of trap parameters (photoionisation cross-section, detrapping probability) are presented in Table S 9.

While there is an increase in signal sensitivity during measurement (median ratio of last to first test signal 1.15–1.38), the FR remains relatively unchanged from the natural to the first regenerated signal for most aliquots (0.91 ± 0.14; Table S 10). However, individual aliquots with an order of magnitude change in sensitivity or fast signal proportion (FRp) during SAR measurement have been noted (Table S 4, Table S 6).

In terms of signal characteristics, samples located within the Caledonian orogenic belt (COB) and/or of glacilacustrine origin stand out as having the lowest signal sensitivity (5 ± 2 and 40 ± 128 counts/Gy·mg·s, respectively) and the weakest fast signal component (median FR < 5, and no COB aliquots had FR > 20; Table S 10). Sediments from an archaeological setting in the Blekinge-Bornholm province (BBP) have the strongest signals (1292 ± 517 counts/Gy·mg·s) and also the highest median FR (47 ± 8; Table S 10).

3.2. Dose determination 'quality'

Of the analysed samples in Dataset 1, 80% have acceptable dose recovery ratios (i.e. within 10% of unity; Table S 3). Most aliquots also fulfil the standard recuperation (<5% of the natural signal) and recycling ratio (within 10% of unity) criteria (96% and 67% of samples, respectively; Table S 3). The relative standard error of the equivalent dose (RSE_{De}) ranges from 1.3% to 44%, with a median value of 4.0% (large aliquots; Table S 3). This is similar to the dose recovery RSE_{DR} (3.8%; Fig. 4A, Table S 3). Between 0 and 100% of aliquots per sample were rejected based on standard rejection criteria (see above), but for 41% of the samples, less than 10% of the aliquots had to be rejected (Fig. 4B, Table S 3). Around 60% of rejected aliquots are rejected based entirely or partly on test-dose error, the rest on recycling and/or recuperation problems. Of the rejected aliquots, 90% have test dose signal brightness less than ~500 counts/Gy·s (P_{90} = 522 counts/Gy·s). Translated into sensitivity, for comparison, this is approximately 60 counts/Gy·mg·s (assuming 500–700 grains/disc, cf. Table S 8). Very few samples with a test dose signal brightness >1000 counts/Gy·s have more than 10% rejected aliquots (Fig. 4B). Single-grain results (Dataset 3) show that between 1 and 66% of grains per sample display a luminescence signal above background (M = 8%; Table S 7).

4. Discussion

4.1. Overall characteristics

Looking at the median or mean values of the different luminescence signal properties, quartz from Quaternary sediments in Sweden and Norway can be described in general as having relatively low sensitivity (~130 counts/Gy·mg·s or ~20–4500 counts/Gy·s), just barely being dominated by a fast signal component (M_{FR} = 22), and being fairly stable during heating, irradiation and stimulation in an OSL reader. Their sensitivity falls into the lower range of values from quartz from elsewhere in the world (Gliganic et al., 2017; Bartyik et al., 2021; Mineli et al., 2021).

The mean values of trap parameters determined from analysis of LM-OSL data (Table S 7) differ somewhat from those of other studies (Jain et al., 2003; Singarayer and Bailey, 2003; Durcan and Duller 2011) and also show a larger spread between samples. There is some uncertainty

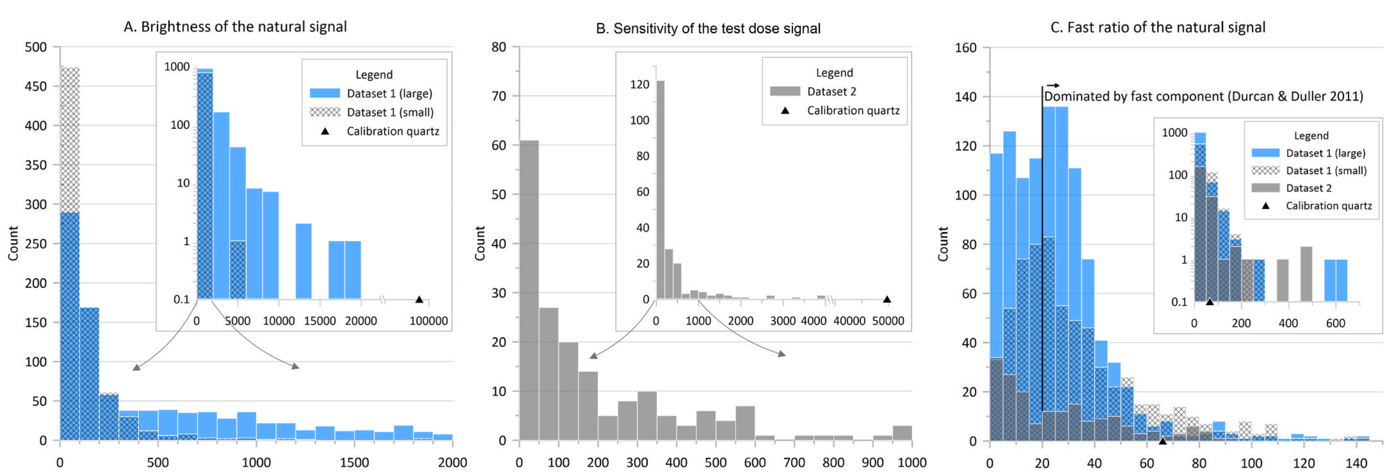

Fig. 2. Histograms of luminescence characteristics. Calibration quartz values are the mean of the values of 24 small aliquots (Dataset 1) or of three aliquots (Dataset 2). Insets show full range while the main plots show the lower range only. A. Brightness of the natural signal. B. Sensitivity of the test dose signal. C. Fast ratio (FR) of the natural signal. For additional information, see Table S 4 and Table S 6.

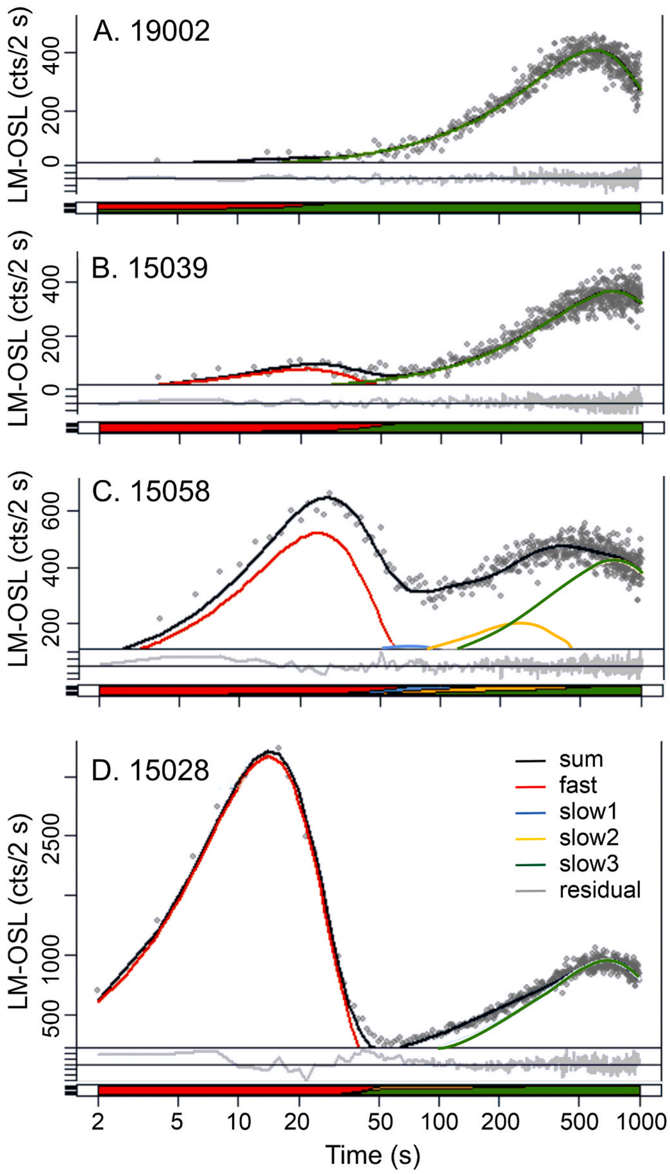

Fig. 3. Selected LM-OSL curves showing signal components (main plot), residual fitting error (grey curve) and relative contribution of the components to the total signal (lower plot). A. Sample 19002, littoral sand from the COB, is dominated by a slow component. Its FR is 5. B. Sample 15039, aeolian sand from TIB, has a weak fast component and a larger slow component. FR = 10. C. Sample 15058, aeolian sand from SWS, has a more intense fast component but also a slow component that contributes to the initial part of the signal. FR = 5. D. Sample 15028, glacifluvial sand from SED, is dominated by a fast component. FR = 43. Please note that not all components are present for all samples.

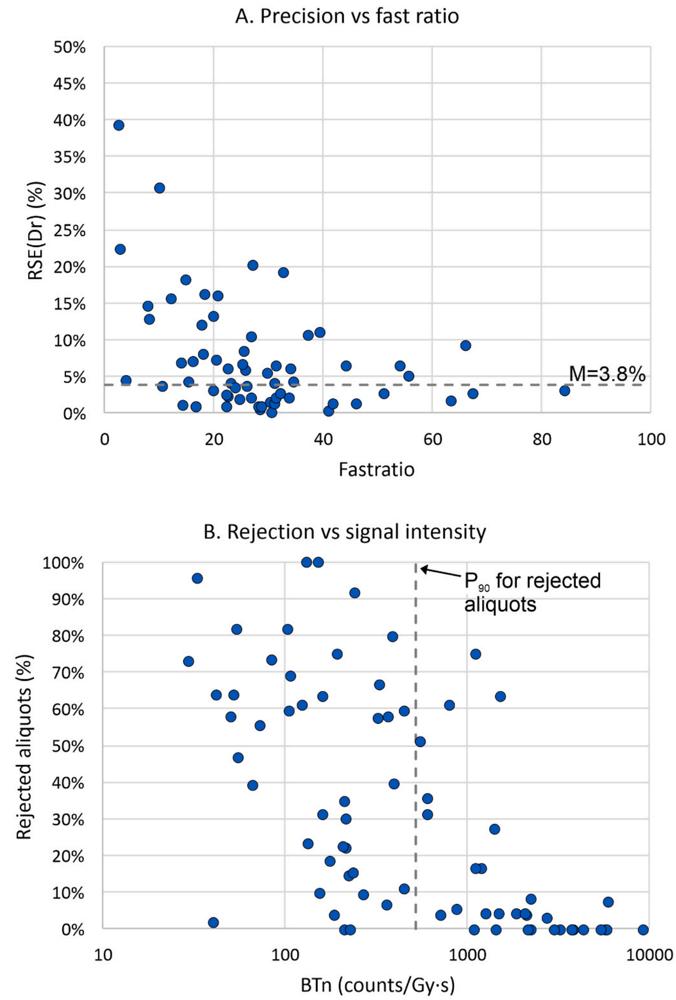

Fig. 4. Luminescence 'quality' plots from Dataset 1. A. The highest relative standard errors (RSE) of the dose recovery ratio, i.e. the lowest precision, are found for samples with a low FR. The median RSE_{DR} is shown by the horizontal hatched line. B. The proportion of rejected aliquots per sample is largest for samples with low signal intensity (here represented by the brightness of the test dose signal B_{Tn}). The vertical hatched line at 522 counts/Gy·s is the 90th percentile of the brightness of rejected aliquots; aliquots with a signal intensity less than this value thus run an increased risk of rejection. The rejection criteria were recycling ratio not within 10% of unity, test dose error >10% and/or recuperation >5%.

due to the reader stimulation power not being exactly known, which could be a reason for the differing mean parameter values but should not affect the spread. Instead, the larger spread likely reflects the larger number of samples (62) included in this study than in the others (9).

4.2. Implications for dating

For OSL dating, luminescence characteristics have practical implications for precision in final age determination, and with regard to machine measurement time. The RSE of the dose recovery ratio is used here as an estimate of the best possible precision of dose determination of the material in question since the variability and heterogeneity of bleaching and irradiation history in the natural environment is removed (cf. Medialdea et al., 2014; Guérin et al., 2017); for the Scandinavian material in this study the dose recovery RSE_{Dr} is 3.8% (large aliquots, 6.1% for small; Table S 10). The median RSE of the dose determinations is slightly larger (4.0%) for large aliquots, most likely owing to some of the samples having wide dose distributions from incomplete bleaching; for example, sediments from known low-light settings such as glacifluvial and fluvial have the highest equivalent dose RSE_{De} (~8%; Table S 10). Even so, with the added uncertainties associated with environmental dose rates, the error values of the Scandinavian material compares well to the typical precision of OSL ages (5–10%; Rhodes 2011). However, ~10% of the samples have a RSE >20% (Table S 3), which would lead to ages with much lower precision.

Previous studies have shown that precision in dose determinations is largely controlled by signal intensity (Preusser et al., 2009; Alexanderson and Murray 2012), which is supported by data in this study (Table S 3, Table S 4). There is also a relationship between precision and FR, i.e. how dominant the fast signal component is (Fig. 4A). At least, the lowest precision is found for samples with low FR, and the samples with highest precision have FR close to or above 20, the limit set by Durcan and Duller (2011) for signals dominated by a fast component (Fig. 4A). This is not surprising since samples lacking a strong fast component are poorly suited to the routinely applied SAR protocol, which was developed for the fast signal component (Murray and Wintle 2000, 2003). Medium and slow components may suffer from instability issues which could also lead to dose underestimation (e.g. Steffen et al., 2009). Additionally, dim signals would also mean that young samples are more difficult to date since low doses cannot be resolved.

Another practical aspect of luminescence dating is how time-consuming measurements for dose determination are. Disregarding the difference in time needed to measure samples with low and high doses, an important factor is how many aliquots are rejected, i.e. not passing the quality checks, and the time needed for preheat and hot bleach, for example. More rejected aliquots lead to longer measurement times and given the basis for the standard rejection criteria, aliquots with low sensitivity, weak fast signal components or large changes during measurement will be rejected. This is seen in Dataset 1, where the samples with high rejection ratios are characterised by low brightness and low FR (Fig. 4B, Table S 3, Table S 4). It can also be noted that some of these samples were considered undateable and were rejected from dating analysis (Alexanderson and Murray 2012).

Given the above, knowing the sensitivity and the FR of a sample could be used to predict how successful and straightforward its luminescence dating may be. Samples with a low FR and low sensitivity (i.e. 'poor quartz') would likely provide low-precision doses (ages) and take a long time to measure, while samples with a strong signal and a high FR (i.e. 'well-behaved quartz') would be easier to measure and yield higher-precision ages (Fig. 5). To quantify these anecdotal expressions, a FR of 20 (Durcan and Duller 2011) and the P_{90} signal intensity of rejected aliquots (522 counts/Gy·s or ~60 counts/Gy·mg·s) could be used as tentative limits (Fig. 5). It should be noted that these limits are at least partly laboratory or reader specific, as they are influenced by e.g. reader stimulation power and PM-tube sensitivity. The expected precision from these two types of quartz is estimated from the average RSE_{DR} of samples with all of their aliquots in Dataset 2 classified as either 'well-behaved' or 'poor' and is 2% and 19%, respectively. These different types of quartz are not randomly distributed but appear to be connected to geological properties as discussed below (also Fig. 5).

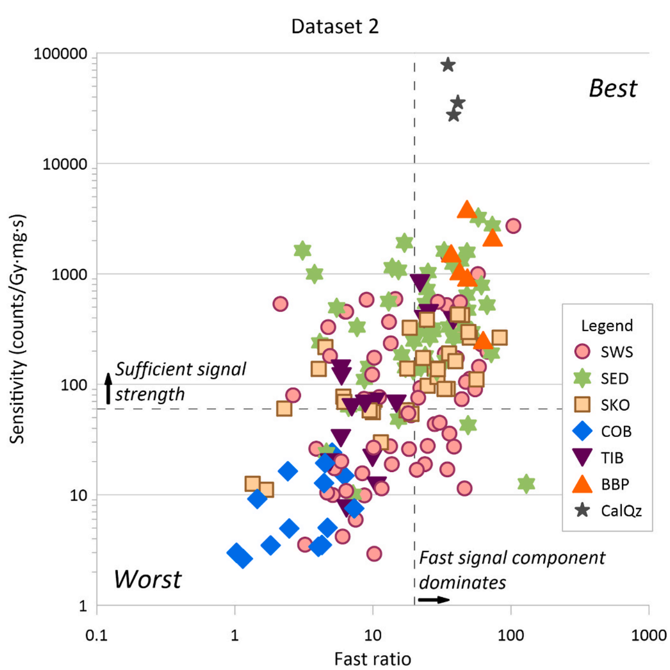

Fig. 5. Plot of the sensitivity vs fast ratio for all aliquots in Dataset 2, classified by bedrock province. Samples plotting in the lower, left corner have poor luminescence characteristics, while those in the upper left corner have good characteristics. The vertical hatched line represents a FR value of 20, over which the signal is dominated by the fast component according to Durcan and Duller (2011). A sensitivity lower than ~60 counts/Gy·mg·s (the horizontal line) seems to be associated with low precision in final dose determination and likely many rejected aliquots during measurement. SWS = southwest Scandinavian province, SED = sedimentary bedrock, SKO=Svecokarelian orogenic belt, COB=Caledonian orogenic belt, TIB = Transscandinavian igneous belt, BBP=Blekinge-Bornholm province. CalQz is the Risø calibration quartz (Hansen et al., 2015).

4.3. *Luminescence characteristics and geological properties*

Most of the samples in this study come from sediments with a relatively short depositional history (short transport distance and/or few cycles of erosion and deposition; see references in Table S 1) and would be expected to have luminescence characteristics more influenced by the parent rock than of the depositional process (Alexanderson and Murray 2012; Alexanderson and Bernhardson 2016). The data from this study support that hypothesis to some extent: there are some bedrock provinces that apparently yield quartz with a more or less distinct combination of characteristics for all or most of its samples (e.g. COB and SED; Fig. 5), and no clear trend of improved luminescence properties with expected transport distance/sediment maturity can be seen for samples from within a particular bedrock province (Table S 6); this is similar to observations by Sawakuchi et al. (2018). However, there are also some genetic classes with certain characteristics (e.g. glacilacustrine deposits with low FR and anthropogenic sediments with strong, fast-component dominated signals; Table S 6). The other bedrock provinces and genetic classes show large internal variability (Fig. 5, Table S 6). No significant relationship between elevation and luminescence characteristics was seen (Table S 6).

That the sedimentary bedrock (SED) contributes generally good quartz luminescence properties (Fig. 5) is not surprising. Repeated sedimentary cycles have been shown to increase OSL sensitivity (Pietsch et al., 2008; Gliganic et al., 2017) and grains derived from sedimentary bedrock such as sandstone could be expected to have an inherited high sensitivity (Fitzsimmons 2011). Among the SED samples with the 'best' properties (highest S_{Tn} and FR) are those from the area of Jotnian sandstones (15028, 15030; Figs. 1 and 3D). The sandstone itself has also been shown to have very good luminescence characteristics (Dala sandstone; Alexanderson and Bernhardson 2016). The majority of SED samples have strong signals (M_{STn} = 315 counts/Gy·mg·s) and a high (M = 22%) proportion of grains that give signal.

Samples from the Blekinge-Bornholm province (BBP) also stand out with high FR and strong signals. However, this province is poorly represented with only two samples, which are also the only two samples of anthropogenic origin – from the floor of an iron-age hut (B. Nilsson, pers. comm. 2020). Its summary data should therefore be treated with caution, and it is not clear if the good characteristics are due to the bedrock or the sedimentary process. Previous OSL dating of Late Quaternary sediments in that area reported high doses (up to ~400 Gy) with variable precision (5–30%), but no information on luminescence characteristics was presented (Houmark-Nielsen 2008).

The Transscandinavian igneous belt (TIB) samples fall into two groups in Fig. 5. Three of the four aliquots in the group to the upper right in Fig. 5 plot are from sample 15112, located within the Dala province and close to the Dala sandstone mentioned above. Sediments in this area contain some amounts of Dala sandstone clasts (Lundqvist 1951) and it is possible that the characteristics of this sample reflects that instead of the igneous bedrock at the site, which was shown by Alexanderson and Bernhardson (2016) to have a weak signal and largely lacking a fast component. The TIB group in the lower, central part of Fig. 5 (also Fig. 3B) plot may therefore be more representative of the province.

The Svecokarelian orogenic belt (SKO) and the Southwest Scandinavian province (SWS) are geographically large (Fig. 1) and contain bedrock types with quite different temperature and pressure histories

(Sigmond and Roberts 2007) and their samples show a large range of sensitivities and FR (Fig. 5). There are fewer dim samples among the SKO samples but otherwise their characteristics largely overlap. Dim quartz occurs also in other shield areas, e.g. in eastern Canada (Rémillard et al., 2016), which like the Baltic shield has been repeatedly glaciated, with associated erosion and clearing out of much sediment. In contrast, the not-recently-glaciated central Brazil shield provides quartz with high OSL sensitivity, interpreted to be owing to e.g. slow denudation rates (Sawakuchi et al., 2018). Most of the low-sensitivity SWS samples come from aeolian deposits (Table S 6), but aeolian transport and reworking was short and brief (Alexanderson and Henriksen 2015; Alexanderson and Bernhardson 2016) and apparently not sufficient to sensitise the quartz.

The five samples from the Caledonian orogenic belt (COB) show similar characteristics with very weak signals, almost no fast component and few grains that give a luminescence signal (Fig. 5, Table S 7). Geologically, the COB is similar to other areas also characterised by low-sensitivity quartz: metamorphic rock, mountainous, short transport paths and short sediment residence times that provide initially low-sensitivity quartz and small opportunities for sensitisation during transport (Preusser et al., 2006; Lukas et al., 2007; Sawakuchi et al., 2018; Gray et al., 2019). The lack of a fast component in COB samples make them very difficult to date and some have been completely rejected for dating (Alexanderson and Murray 2012), while others have been dated but with large uncertainties (Anjar et al., 2018).

The variation in luminescence characteristics show that there is potential for using quartz luminescence as a proxy for provenance in Sweden and Norway, and the COB and SED (possibly also BBP) as source areas stand out in particular, with contrasting signal sensitivity and presence of a fast signal component (weak, small for COB and strong, large for SED/BBP). The other bedrock provinces are more similar in this respect, but their internal variability may allow for successful application on a smaller scale.

5. Conclusions

Quartz extracted from unconsolidated Quaternary deposits in Sweden and Norway have in general dim OSL signals, but the signal intensity varies over several magnitudes from ~5 counts/Gy·mg·s to ~3500 counts/Gy·mg·s. For ~40% of the samples, >10% of grains give a discernible luminescence signal (peak $\gg$ background). A fast signal component could be identified in most (84%) of the samples, but it is dominant (FR > 20) for just over half of them (53–59%). Significant signal change during measurement appears to be of concern only to few samples.

When dating this type of material, a precision in dose of 4–6% can be expected, but it varies with the different types of quartz. 'Poor quartz' (sensitivity <~60 counts/Gy•mg•s, FR < 20) is found in the Caledonian orogenic belt and in parts of the SW Scandinavian province and Trans-scandinavian igneous belt. It yields low-precision dose estimates (~19%) and requires long measurement times owing to high aliquot rejection ratios. Sedimentary bedrock and anthropogenic sediments in the Blekinge-Bornholm province are dominated by 'well-behaved quartz' (sensitivity >~60 counts/Gy•mg•s, FR > 20), which also occurs in parts of Svecokarelian orogenic belt and the SW Scandinavian province. This quartz gives better precision in dose determinations (~2%) and few aliquots are rejected, leading to straightforward measurement. Quartz from other parts of Sweden and Norway either have sufficient signal strength but lacks a dominant fast component, or vice versa.

The variation in luminescence characteristics, particularly the sensitivity and the presence of a fast component signal, appear to be at least partly correlated to local bedrock (i.e. the origin of the quartz), rather than to depositional process (last mode of transport for the sampled sediment). Strongly contrasting OSL characteristics between two major bedrock units – the Caledonian orogenic belt and sedimentary bedrock – shows promise for using quartz luminescence as a proxy for provenance in Scandinavia.

Data availability

Supplementary material contains supporting methods descriptions, data tables and figures.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Helena Alexanderson reports financial support was provided by the Geological Survey of Sweden and by the Royal Physiographic Society of Lund, Sweden.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quageo.2022.101272.

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