DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/38**

Capture, Storage and Use of CO_2 (CCUS)

Provenance of the Gassum Formation: Implications for reservoir distribution and mineralogy (Part of Work package 6 in the CCUS project)

Mette Olivarius, Benjamin D. Heredia, Sebastian N. Malkki, Tonny B. Thomsen & Henrik Vosgerau

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G E U S

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Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO_2 capture technologies, (2) the potentials for both temporary and permanent storage of CO_2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO_2 usage potentials, including business case for converting CO_2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plants in Denmark.

The present report forms part of Work package 6 and focuses on provenance analysis of the Gassum Formation reservoir sandstones.

Content

Dansk resume

Proveniensanalyse af sandsten fra Gassum Formationen er udført for at vurdere deres potentiale for CO_2-lagring i forhold til reservoirudbredelse, aflejringsbetingelser og mineralogisk sammensætning i Danmark. Der lægges særlig vægt på Hanstholm og Havnsø strukturerne, hvor datamængden er begrænset, og hvorvidt henholdsvis Thisted og Stenlille udgør passende analoger.

Sandsten fra Gassum Formationen er blevet analyseret for at undersøge deres proveniens, det vil sige hvilke grundfjeldsområder sandkornene oprindeligt stammer fra. Til dette formål er benyttet U/Pb aldersdatering af zirkon-mineralkorn, da disse forefindes i alle sandstenene samt er fysisk og kemisk meget stabile og dermed ikke nedbrydes ved transport, aflejring og begravelse. I denne rapport er alle zirkon U/Pb analyser af sandsten fra Gassum Formationen blevet sammenstillet med henblik på en samlet provenienstolkning. Dette er essentielt for at kunne tolke transportveje, udbredelsen af reservoirsandstenene, fordelingen af aflejringsmiljøerne og den mineralogiske modenhed af det aflejrede sediment.

Resultaterne viser, at zirkonernes aldre kan inddeles i en række alderspopulationer, hvoraf zirkoner med aldre mellem 1,8 og 0,9 milliarder år primært stammer fra grundfjeldet i Sydnorge, mens de 0,65 til 0,28 milliarder år gamle zirkoner primært stammer fra grundfjeldet i Centraleuropa. Indenfor Gassum Formation er der markante variationer i proveniensen, hvilket afspejles i geografiske forskelle i sandstenstykkelse, aflejringsmønster og mineralogisk sammensætning, og årsagen bliver i denne rapport påvist via geokronologi af zirkoner.

Sandstenene i den nordvestlige del af det Danske Bassin har en lokal kilde i det sydligste Norge, som først leverede sediment til Gassum Formation i både Skagerrak og Jylland. I Jylland blev dette input erstattet af sedimenttilførsel fra det centrale Sydnorge, da den øverste del af formationen blev aflejret, hvilket var forbundet med længere sedimenttransport og dermed øget mineralogisk modenhed. Den markant højeste mineralogiske modenhed findes dog i den sydøstlige del af Gassum Formationens udbredelse, hvor lang sedimenttransport fra det centrale Sydnorge og fra Centraleuropa nedbrød de fleste ustabile korn, muligvis kombineret med omlejring, hvilket har produceret meget kvartsrige sandsten. Gassum Formation kan således opdeles i en nordvestlig og en sydøstlig region, der har forskellig proveniens resulterende i forskellig mineralogisk sammensætning.

Proveniensen har betydelig indflydelse på Gassum Formationens egnethed som CO_2 lager. Aflejringsområdet der rummer Hanstholm strukturen fik primært tilført sediment fra erosion af det sydligste Norge. Det vil sige at sedimentet kom fra NNV og var mineralogisk umodent. Thisted-områdets værdi som analog til mineralogisk at karakterisere reservoiret i Hanstholm strukturen anses som god, især for den nederste del af reservoiret, der har samme proveniens. Den øverste del af reservoiret i Thisted-området består

derimod af mineralogisk mere modent sand aflejret fra NNØ. Sandstenene i Havnsø strukturen er formentlig del af den mineralogisk meget modne region i det sydøstlige Danmark, hvor sedimentet blev transporteret langvejs fra både NNV og SØ, hvilket har betydelig indflydelse på sandstenenes mineralogiske sammensætning. Stenlille-områdets værdi som analog til mineralogisk at karakterisere reservoiret i Havnsø strukturen anses som god, under forudsætning af at strukturen er korrekt tolket som værende del af den mineralogisk modne region. I forhold til reaktiviteten af sandstenene ved CO_2 injektion er de mineralogisk modne sandsten i den sydøstlige del af Gassum Formation mindre tilbøjelige til at reagere i forhold til de mere umodne sandsten mod nordøst, der har større reaktionspotentiale.

For at kunne indarbejde proveniensanalysen i reservoirkarakteringen, og dermed få det bedst mulige estimat af reservoirkvaliteten, anbefales det at foretage en række videre analyser som indbefatter: 1) sekvensstratigrafisk tolkning for at placere proveniensresultaterne i en stratigrafisk ramme; 2) tolkning af aflejringsmiljøernes geografiske fordeling så der kan laves palæogeografiske kort bl.a. visende sedimentinput til bassinet; 3) mineralogiske analyser af sandsten fra flere boringer fra den sydøstlige region for at fastslå hvor langt denne mineralogisk modne region strækker sig; 4) detaljeret undersøgelse af hvordan mineralogien ændrer sig op gennem en sekvens i relation til aflejringsbetingelserne; 5) analyser af proveniens og mineralogi hvis nye boringer udføres især i grænseområdet mellem den nordvestlige og sydøstlige region for at indsnævre hvor grænsen går; 6) zirkon-aldersdatering af sandsten fra Centraleuropa for at få en direkte analyse af hvordan det sydlige provenienssignal ser ud; 7) aldersdatering af andre typer tungmineraler end zirkon for at kunne indsnævre proveniensområdet; 8) proveniensanalyse af lette mineraler for at afsløre om de har samme provenienshistorie som tungmineralerne, og i denne forbindelse bør grundfjeld fra Norge, Sverige og Centraleuropa også analyseres for at fastslå provenienssignalet for kvarts og feldspat; 9) proveniensanalyse af de yngre reservoirer for at afdække deres potentiale for CO_2-lagring; og 10) mere detaljeret proveniensanalyse af ældre reservoirer, da denne rapport viser at detaljegraden er væsentlig.

Summary

Provenance analysis of the Upper Triassic – Lower Jurassic Gassum Formation was performed to assess its potential for CO_2 storage in relation to reservoir distribution, depositional setting, and mineralogical composition in Denmark. Special focus is put on the Hanstholm and Havnsø structures where limited data are available, and whether the Thisted and Stenlille areas, respectively, represent appropriate analogues. This report is a compilation of detrital U/Pb zircon dating analyses of 46 sandstone samples supplemented by mineralogical information when relevant. The resulting density age distributions show that the Fennoscandian Shield is the primary provenance area where sediment inputs from several areas in Norway are identified, besides a sediment supply from the Variscan Orogen in Central Europe that only reached the southeastern part of the basin.

The sediment in the northwestern part of the Gassum Formation was supplied primarily from the Telemarkia Terrane in southernmost Norway during deposition of the lower part of the formation. This source area kept on supplying immature sediment to the Skagerrak area when the upper part of the formation was deposited, whereas the Caledonian Orogen in central southern Norway became the dominant provenance area of the sediment deposited in Jylland. The sediment in the southeastern part of the Gassum Formation was primarily supplied from the Caledonian Orogen, and a distinct supply of sediment from the Variscan Orogen is found in smaller amounts that decreases towards northeast.

In the northwestern part of the Gassum Formation, the short transport distance caused deposition of a mineralogically immature feldspar-rich sediment that became more mature in the upper part of the formation in Jylland, when the provenance changed to the Caledonian Orogen. In the southeastern part of the formation, the long transport distances from the Caledonian Orogen and the Variscan Orogen resulted in deposition of a mineralogically very mature sediment with high quartz content. Thus, the Gassum Formation can thus be divided into a northwestern and a southeastern region, which are of different provenance resulting in different mineralogical composition.

Small sediment inputs produced by erosion of reworked sediments on the Ringkøbing–Fyn High have probably mixed with the other sediments locally. Variscan ages occur in the Lower Triassic Bunter Sandstone Formation. However, this formation also contains other age populations that are not distinct in the Gassum Formation, and thus it cannot have received significant input of such reworked sediments. Small inputs of reworked sediment may have been supplied to the Gassum Formation from the Fennoscandian Shield like from the Oslo Graben from which a small sediment supply is identified in a few samples based on their Carboniferous–Permian zircon age proportion, corresponding to the time of the rifting. However, the basement in Sweden and its former cover sediments were peneplained during the Middle Triassic and is therefore not a primary source area, and a large supply of reworked sediment from southernmost Norway is also unlikely because it would have deposited a more mature sediment.

The changes in provenance that are identified between the lower and upper parts of the Gassum Formation have several implications for reservoir distribution and mineralogy. In the northwestern region in Jylland, the sediment became more mature and thus less prone to react with injected CO_2, whereas the sediment in the southeastern region began spreading further towards the west hence increasing the lateral extend of the reservoir. The sediment from the southeast was transported northwards in the basin by shoreface and delta progradation and it mixed with the sediment from the north, which in the eastern part of the basin may have been transported southwards by longshore drift.

The sediment in the Hanstholm structure was primarily supplied from local sources in the Telemarkia Terrane, so the sediment came from the north-northwest and was mineralogically immature. The value of the Thisted area as an analogue to characterize the mineralogical composition of the sandstones in the Hanstholm structure is considered good, in particular for the lower part of the reservoir, which has the same provenance. The upper part of the reservoir in the Thisted area on the other hand, consists of mineralogically more mature sand deposited from north-northeast. The sandstones in the Havnsø structure are probably part of the mineralogically very mature region in southeastern Denmark, where the sediment was transported long distances from both north-northwest and southeast, which had a significant influence on the mineralogical composition of the sandstones. The value of the Stenlille area as an analogue to characterizing the reservoir in the Havnsø structure is considered good, provided that the structure is correctly interpreted as being part of the mineralogically mature region.

Further analyses are recommended to be able to incorporate the provenance analysis into the reservoir characterization and thus obtain the best possible estimate of the reservoir quality. This includes: 1) sequence stratigraphic interpretation to place the provenance results in a genetic stratigraphic framework; 2) interpretation of the depositional environments such that paleogeographic maps including sediment inputs can be made; 3) mineralogical analyzes of sandstones from more wells from the southeastern region to determine how far this mineralogical mature region extends; 4) detailed study of how mineralogy changes up through a sequence compared to the depositional conditions; 5) analyzes of provenance and mineralogy if new wells are drilled mainly in the border area between the northwestern and southeastern regions to narrow where the border goes; 6) zircon U/Pb dating of sandstones from Central Europe to get a direct analysis of what the southern provenance signal looks like; 7) radiometric U-Th/Pb dating of other types of heavy minerals than zircon to narrow the provenance area; 8) provenance analysis of light minerals to reveal whether they have the same provenance history as the heavy minerals, and in this connection bedrock from Norway, Sweden and Central Europe should also be analyzed to determine the provenance signal for quartz and feldspar; 9) provenance analysis of the younger reservoirs to assess their potential for CO_2 storage; and 10) more detailed provenance analysis of older reservoirs as this report shows that the degree of detail is vital.

1. Introduction

Subsurface storage of CO_2 is considered an important part of the puzzle of green solutions that jointly can succeed to meet the goals of reduced greenhouse gas emission into the atmosphere (Metz et al. 2005). In Denmark, several sandstone reservoirs appropriate for CO_2 storage are present in the subsurface both onshore and offshore, and many structural traps have been identified in the reservoirs (Fig. 1) (Anthonsen et al. 2011, Hjelm et al. 2020). These structures may comprise suitable CO_2 storage sites, of which two were selected as special focus for this report, comprising the Hanstholm and Havnsø structures. The Hanstholm structure is situated offshore to the northwest of the city of Hanstholm, and the Havnsø structure is positioned mostly onshore to the northeast of the city of Kalundborg (Fig. 1) (Mathiesen et al. 2020a). Both structures contain Gassum Formation reservoir sandstones sealed by Fjerritslev Formation mudstones (Holmslykke et al. 2020, Springer et al. 2020).

The Gassum Formation sandstones typically have reservoir properties ideal for CO_2 storage because the sandstones generally have high permeability at low to intermediate burial (Kristensen et al. 2016, Weibel et al. 2017a). This means that injected CO_2 can quickly be dispersed in the reservoir, and large volumes of CO_2 can be stored due to high porosity. The Gassum Formation reservoir in the Hanstholm and Havnsø structures is positioned deeper than 800 m (Mathiesen et al. 2020a). At this depth CO_2 becomes supercritical and the volume is reduced to 0.3% compared to surface conditions. Despite the increased density of the compressed CO_2, the density of the formation water is still higher so the CO_2 will move upwards. Therefore, a seal must be present above the reservoir such as a tight mudstone. CO_2 injected in a geological structure ensures control with the CO_2 migration, which will be confined within the structural trap.

Zircon is a heavy mineral that occurs in small amounts in most sandstones. Zircon mineral grains are physically and chemically very stable so they can survive multiple episodes of sediment reworking while still preserving the radiometric age of the crystalline rock in which it was formed. This ability makes U/Pb dating of detrital zircon a unique provenance tool. The zircon U/Pb analyses included in this report were carried out during the last decade under the auspices of various projects focusing on the potential of the Gassum Formation for either geothermal energy or CO_2 storage. Thus, new information has gradually been added. The full dataset was compiled for this report to generate an integrated provenance interpretation of the Gassum Formation and thereby give valuable information about the sediment transport routes, the sediment entry points to the basin, and the distribution of sandstones, which are crucial when interpreting the depositional environments. The provenance also gives important insights into variations in the detrital mineralogy, which can be used for modelling the diagenetic processes and reservoir properties and the possible hydrogeochemical reactions that may occur when CO_2 is injected into the sandstones.

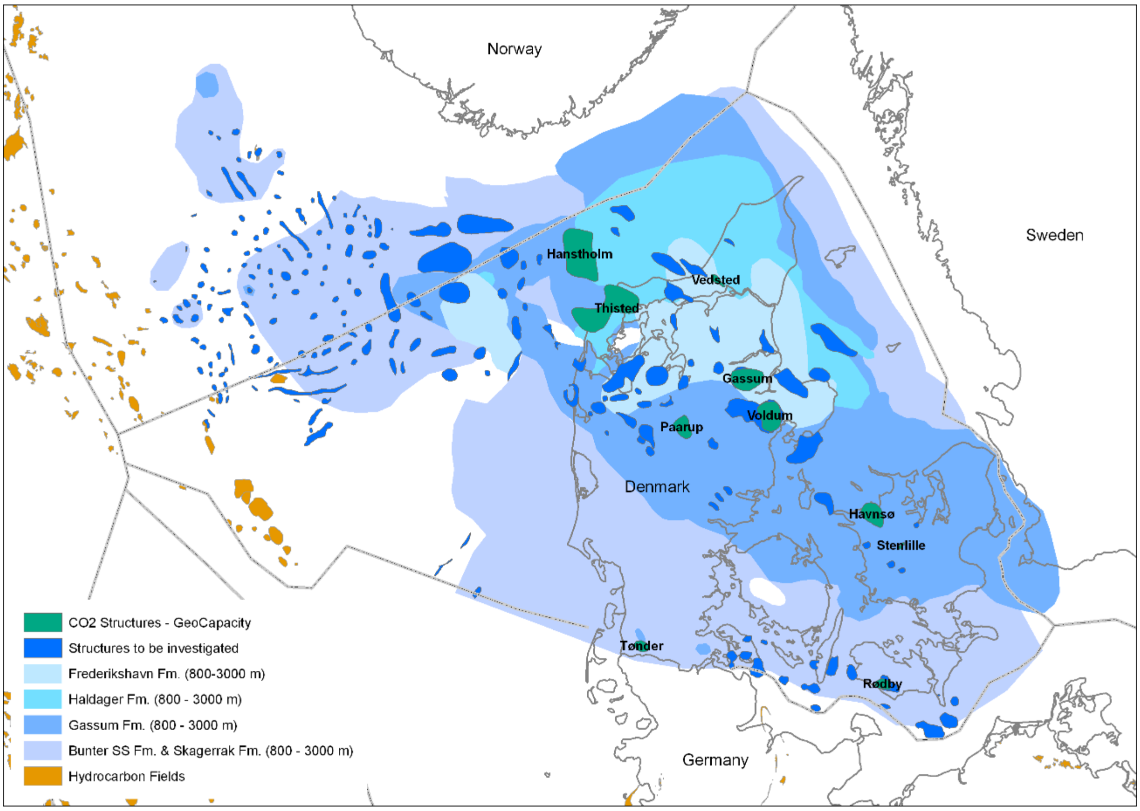

Figure 1: *Map from Anthonsen et al. (2011) of the Danish area showing the distribution of sandstone formations (Fm) with potential for CO_2 storage and the structures that may be used as traps for injected CO_2. The Hanstholm and Havnsø structures with reservoir in the Gassum Formation are in focus in this report. No storage potential occurs on Bornholm due to the shallow position of the basement.*

2. Geological setting

The Upper Triassic to Lower Jurassic Gassum Formation was initially defined in Denmark by Larsen (1966) and was later redefined by Bertelsen (1978) and described in more detail by Michelsen et al. (2003) and Nielsen (2003). The Gassum Formation occurs mainly in the Norwegian–Danish Basin and locally in the North German Basin, which were formed during regional subsidence following rifting phases (Vejbæk 1997). The basins are divided by the Ringkøbing–Fyn High comprising shallow basement crosscutting the southern part of Danish area (Fig. 2). The Gassum Formation is only locally preserved on and south of the Ringkøbing–Fyn High since the sediments were deeply eroded during the Middle Jurassic when the high itself and parts of the surrounding basins were uplifted (Nielsen 2003).

The thickness and depth of the Gassum Formation vary considerably across Denmark due to differences in depositional regimes and burial histories (Nielsen 2003, Japsen et al. 2007), which has resulted in variable reservoir quality (Weibel et al. 2017a). The formation has thicknesses of mostly 50 to 300 m and is locally thicker, for example in the Sorgenfrei–Tornquist Zone (Nielsen and Japsen 1991, Michelsen et al. 2003, Nielsen 2003, Mathiesen et al. 2020b). The largest depths of the formation of >3 km occur in the basin centre in central Jylland and the smallest depths of <1 km are found near the basin margins to the north and south. The formation was deposited in a humid climate during repeated sea-level fluctuations and comprises fluvial, estuarine and shoreface sand interbedded with marine, lagoonal and lacustrine mud (Nielsen 2003).

Two basement provinces occur sufficiently close to the Danish area to constitute possible sediment source areas, namely the Fennoscandian Shield to the north and the Variscan Orogen to the south (Fig. 2). The southern part of the Fennoscandian Shield comprises the Sveconorwegian Orogen in southern Norway and southwestern Sweden consisting of the Telemarkia Terrane, the Idefjorden Terrane and the Eastern Segment that formed at 1.52–1.48 Ga, 1.66–1.52 Ga and 1.80–1.64 Ga, respectively (Bingen and Solli 2009). Intrusions formed at 1.47–0.91 Ga and metamorphism occurred at 1.14–0.90 Ga, which was most pronounced in the Telemarkia Terrane (Bingen et al. 2008). The Caledonian Orogen covers central southern Norway and further north. It includes the Lower and Middle Allochthons in which most ages are 1.69–1.62 Ga corresponding to the basement windows in southern Norway, whereas magmatic (Caledonian) ages of 0.50–0.42 Ga are present in the Upper and Uppermost Allochthons (Bingen and Solli 2009). Magmatism at 0.30–0.28 Ga resulted in extrusion of lavas in the Oslo Graben (Heeremans and Faleide 2004). The Variscan belt comprises primarily rocks of the Cadomian and Variscan orogeneses formed at 0.65–0.28 Ga (Breitkreuz and Kennedy 1999, Anthes and Reischmann 2001).

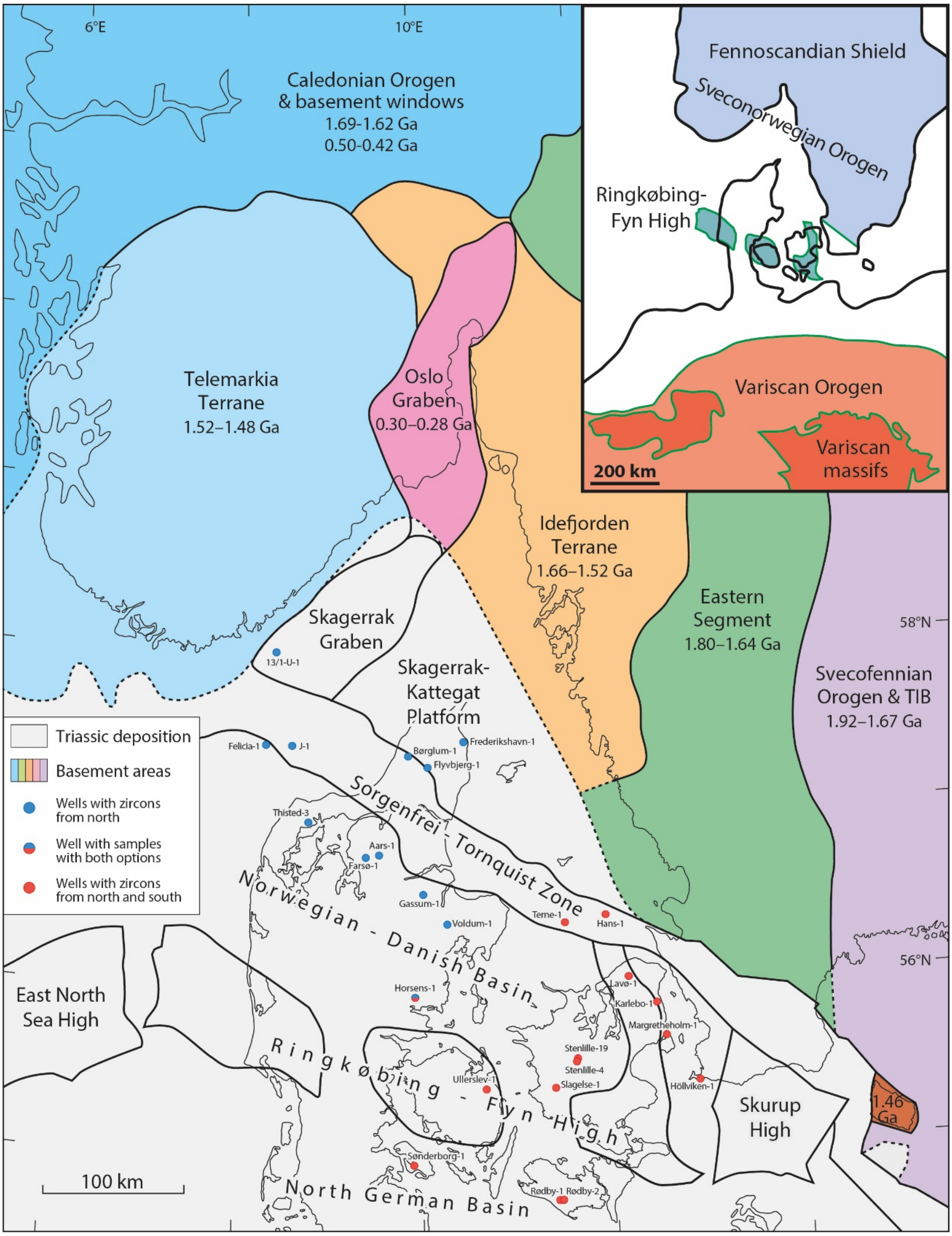

Figure 2: *Map of the wells from which zircon U/Pb ages have been obtained from the Gassum Formation. The zircon ages and locations of the basement terranes in the Fennoscandian Shield are included, and the location of the Variscan Orogen is shown on the overview map.*

3. Samples and methods

Samples from the Gassum Formation were collected from sandstones in cores and from sandy intervals in cuttings in 25 selected wells (Fig. 2). Zircon grains from 46 samples were analyzed, of which 24 of the samples are from the northwestern part of the study area i.e. from the wells 13/1-U-1, Felicia-1, J-1, Frederikshavn-1, Flyvbjerg-1, Børglum-1, Thisted-3, Farsø-1, Aars-1, Gassum-1, Voldum-1, and Horsens-1, and 22 of the samples are from the southeastern part of the study area i.e. from the wells Terne-1, Hans-1, Lavø-1, Karlebo-1, Margretheholm-1, Höllviken-1, Stenlille-4, Stenlille-19, Slagelse-1, Ullerslev-1, Rødby-1, Rødby-2, and Sønderborg-1. The sample selection focused on 1) covering the large geographical area, 2) covering the stratigraphic variation, and 3) deciphering the mineralogical difference observed in the western versus eastern part of the Gassum Formation.

The sample depths of the core samples given in this report represent the average depth of the sampled interval, which is up to 10 cm thick, except for samples from the 13/1-U-1 and Höllviken-1 wells that are Norwegian and Swedish, respectively. In these wells, limited material was available, so the sample intervals are larger. Cores from the Gassum Formation are scarce in the offshore areas and in the southeastern part of the study area so some of the samples were obtained from cuttings. The cuttings samples are marked by “cu” and the sample intervals are from 1.5 to 18.0 m thick to ensure that enough material was sampled (c. 300 g). The stated depths are measured depths in the wells (MD). However, in some wells the core depths do not correspond exactly to the well log depths, so correction is required when comparing samples with well logs (Nielsen 2003).

Radiometric dates of U-rich minerals like zircon usually represent the time at which the minerals formed during an igneous or high temperature metamorphic event. Zircon is a physically and chemically stable mineral that can survive many cycles of sedimentation and reworking while still preserving the radiometric age of the crystalline rock in which it was formed and later eroded from. This makes dating of detrital zircon grains an important provenance tool that is employed to tie the zircon grains in the sediments to the original source area. Thus, the zircon age information can give important insights of sediment transport routes, sediment distribution in the basin and thereby also the depositional environments. However, one should be aware that zircon due to its high closure temperature of Pb in the U/Pb isotopic system (>800°C), do not necessarily record all metamorphic (or magmatic) events that the mineral grains might have experienced.

Zircon U/Pb dating was carried out at GEUS. The cuttings samples were washed to remove drilling mud. All samples were crushed and sieved to extract zircons from the 45–750 µm grain size fraction. The zircon grains were handpicked from heavy mineral concentrates obtained by density sorting using a Holman-Wilfley water-shaking table, and then embedded in epoxy, imaged and checked by scanning electron microscopy (SEM), and analyzed by laser ablation inductively coupled plasma mass spectrometry (LA-

ICPMS), using an NWR 213 laser ablation instrument coupled to an Element2 magnetic sector-field ICPMS.

The zircons were ablated for 30 s in an air-tight helium-flushed chamber using a focused laser beam with a diameter of 25 or 30 micrometres (µm), a repetition rate of 10 Hz and an output energy density of ~10 J/cm^2. The liberated material was transported through inert Tygon tubing by the helium carrier gas to the mass spectrometer for isotopic determination. To minimize instrumental drift, a standard-sample-standard analysis protocol was followed, bracketing the zircon analyses by measurement of the zircon standard GJ-1 (Jackson et al. 2004). For quality control, secondary zircon standards were used, i.e. Plešovice (Slama et al. 2008) and for the newer analyses also Harvard 91500 (Wiedenbeck et al. 1995, 2004), both yielding an average age accuracy and precision (2σ) within 3% deviation.

Data reduction was performed using the Iolite v2.5 software for most of the data (Hellström et al. 2008, Paton et al. 2011, Petrus and Kamber 2012) and the in-house software Zirchron for the remaining data (Olivarius 2015). Combined histogram and probability-density plots were produced through the software jAgeDisplay (Thomsen et al. 2016). All zircon U/Pb age data obtained from the Gassum Formation including 4816 zircon grains collected from 46 samples was merged to determine the optimal procedure for data plotting, as illustrated in Figure 3.

The discordance of the analyses is calculated according to the Wetherill Concordia (1956, 1963). Based on adjustment of the concordance threshold, it is chosen only to plot dates with up to ±10% discordance since higher discordance relates to complexity or inadequate data quality, which distorts the age distributions (Fig. 3A). Data quality might be okay, but complexity is added in terms of understanding partial Pb-loss from processes like diffusion, leaching, recrystallisation, residence time, etc. Discordant dates may be related to geological processes but in this case, discordant data will most probably not add useful information. Reducing the allowed discordance to less than ±10% is not necessary as evident by the good resemblance of the age distributions obtained by including data with discordance up to ±5 and ±10%, respectively, showing that the applied ages are of high quality. This ±10% concordance threshold is often applied in provenance studies with detrital zircon U/Pb analyses.

The $^{206}Pb/^{238}U$ dates represent the direct dates from the counting statistics in the mass spectrometer and these are plotted for the data up to a certain crossover date. The derived $^{207}Pb/^{206}Pb$ dates are used for the older zircons because they give a better uncertainty and thus measure of the older dates due to a large proportion of the uranium has decayed in these zircon mineral grains producing more radiogenic lead. Based on fine-tuning of the crossover between $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ dates, it is chosen to use a crossover age at 1200 Ma primarily based on the lowest possible uncertainties (2σ) of the dataset. This is evident from the uniform appearance of the different age populations in the probability-density plots revealing as much detail as possible, whereas lower crossover ages cause a less detailed appearance of age peaks due to the higher uncertainties (Fig. 3B). The estimation of a crossover age is in part instrument-specific, so the plotted zircon age distributions of the Gassum Formation are fully comparable to age distributions plotted with other crossover ages also if the analyses were performed on other instruments.

Common-lead correction was applied to a subset of the analyses when required, including about a quarter of the data. The correction was made using measured mass 204 (i.e. $^{204}Hg + ^{204}Pb$) corrected for Hg through the $^{202}Hg/^{204}Hg$ natural abundance ratio. Skewing of some of the age populations towards younger ages is evident for the common-lead corrected data when comparing them with the remaining age data, thus these data were excluded (Fig. 3C). According to e.g. Andersen et al. (2019), age displacement may happen because old Pb-loss can be hidden by younger Pb-loss such that the common-Pb correction of grains that have experienced several episodes of Pb-loss produces an age that is younger than the true age.

The data selection thus involves a discordance of ≤10%, a crossover age of 1200 Ma and exclusion of common lead containing zircon grains. This provides a total of 4108 zircon mineral grains. Divided between the 46 samples, this gives an average zircon dates content of ca. 89 analyses per sample, which is somewhat low considering the multiple age populations present in the age distributions. However, it is high enough to determine which of the primary age populations are present, except for the few samples with very low zircon content. The applied data selection has removed the zircon dates younger than 200 Ma since they either had too high discordance or contained common lead, so this supports the effect of the data selection since dates younger than the depositional age are obvious errors. Dates older than 2000 Ma are not shown in the diagrams as they are relatively few in the samples (viz. a total of 138 zircon grains) and in the source areas, and because these old zircons are not within the scope of this report.

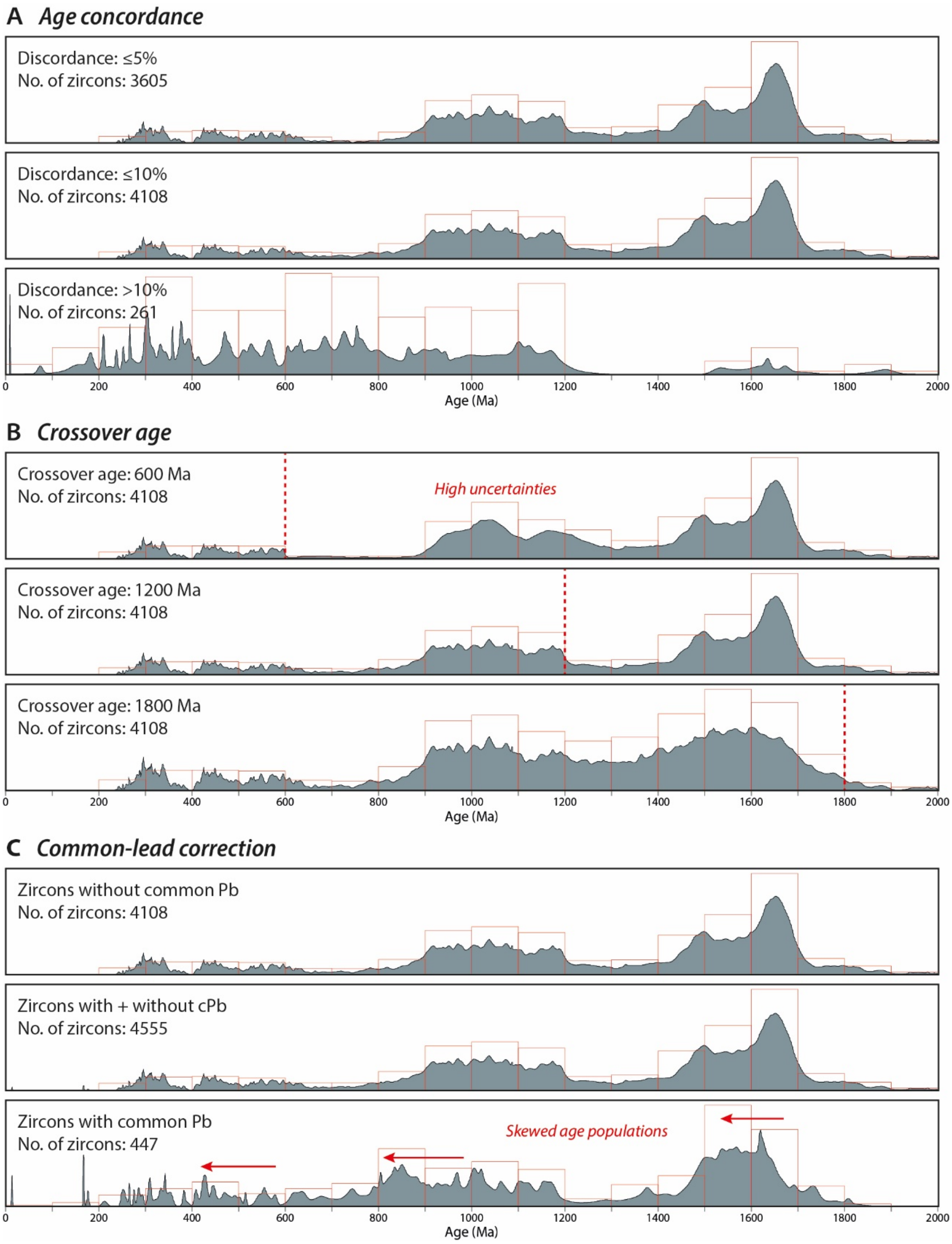

Figure 3: *All zircon U/Pb age data obtained from the Gassum Formation including 46 samples from 25 wells are merged to determine the optimal procedure for data plotting. A: Based on concordance threshold adjustment it is chosen to exclude ages with a discordance >10%. B: Based on fine-tuning of the crossover age between* $^{206}Pb/^{238}U$ *and* $^{207}Pb/^{206}Pb$ *it is chosen to be at 1200 Ma. C: Based on the skewing of the age distribution for the common-lead corrected data compared to the non-corrected data, the corrected data are excluded. Note that some data shorting has been made: Only analyses without common lead are plotted in A and B, except in the plot of discordant data. The crossover age is 1200 Ma in A and C. Ages with a discordance ≤10% are plotted in B and C.*

4. Zircon U/Pb age distributions

The results of the zircon U/Pb dating of the Gassum Formation are plotted as age distributions for each sample. The results from the northwestern part of the study area including Skagerrak and Jylland are presented in Figure 4. The results from the southeastern part of the study area including Kattegat, Sjælland, Amager, Skåne, Lolland, Fyn, and Als are illustrated in Figure 5.

The age distributions reveal that the zircon grains in all 46 samples are primarily derived from the Fennoscandian Shield as seen by the multiple age populations present in the 1.8–0.9 Ga age interval. Fennoscandian zircon dates younger than this are restricted to Paleozoic ages corresponding to the Ordovician to Early Devonian Caledonian orogeny and the Late Carboniferous to Permian Oslo rifting. These fall within age ranges of 0.50–0.42 and 0.30–0.28 Ga, respectively, which overlap with the age range of 0.65–0.28 Ga that characterize the Variscan Orogen. The small contents of young zircons from the Caledonian Orogen and Oslo Graben found in some of the samples from the northwestern part of the Gassum Formation can be clearly distinguished by their narrow age ranges (Fig. 4) as compared to the multiple age populations from the Variscan Orogen present in the samples from the southeastern part of the formation (Fig. 5). However, it is not possible to recognize if small contents of young zircons from Fennoscandia are present in the southeastern part of the Gassum Formation since such ages would be masked by the larger content of zircons from the Variscan Orogen.

In samples from the northwestern part of the study area, the content of young Caledonian zircons is very small when present, constituting no more than 1-2 grains, whereas the content of zircons from Oslo Graben in some cases is higher such as in two of the samples from the Aars-1 well (Fig. 4). However, the prominent appearance in these samples of the age population sourced from the Oslo Graben is partly related to the small uncertainties associated with these young ages resulting in high probabilities producing high age peaks. No pattern is evident in the distribution of the young zircon grains of Fennoscandian affinity in the Gassum Formation. In the lower sample from the J-1 well, ages corresponding to the Timanian Orogen of 0.75–0.49 Ga are found (Olivarius et al. 2019). Such ages are rare in Fennoscandia since the Timanian Orogen is located far to the northeast. However, it was eroded during the Cambrian-Ordovician and some of the detritus was deposited in southern Norway where it is locally preserved (Slama 2016).

A qualitative estimate of the relative amount of Variscan ages found in the samples has been made where "High" refers to a significant Variscan sediment input, "Medium" refers to a clear but moderate input, and "Low" refers to a small indistinct input. High Variscan input is found in all samples from the Höllviken-1, Stenlille-4, Stenlille-19, Slagelse-1, Ullerslev-1, Rødby-1, Rødby-2, and Sønderborg-1 wells (Fig. 5). High Variscan input is also found in one of the samples from the Margretheholm-1 well, whereas the other sample from this well has a medium Variscan input. From each of the Terne-1, Hans-1, Lavø-1, and Karlebo-1 wells are analyzed two samples of which one has medium and the other has low Variscan input, but a stratigraphic pattern is not evident. Medium Variscan input is found in the upper sample from the Horsens-1 well, whereas the other samples from this well show no Variscan input. Variscan ages are neither identified in the remaining samples from the northwestern part of the Gassum Formation, although it cannot be excluded that a few Variscan zircon grains may be present in some samples (Fig. 4).

Except for the geographical variations found in the abundance of Variscan ages, the age distributions from the southeastern part of the Gassum Formation are very uniform (Fig. 5). A dominance of ~1.65 Ga dates is found in them all, which corresponds to the old zircon ages in the Caledonian Orogen since such ages are not prominent in the Sveconorwegian Orogen, although they do exist in the Idefjorden Terrane and the Eastern Segment. Some sediment supply from these Sveconorwegian terranes in southwestern Sweden to the eastern part of the Gassum Formation is possible, but it can only have been minor since dates corresponding to the broad spectrum of ages present in the Idefjorden Terrane and the Eastern Segment are not prominent in the sediments (Fig. 5).

The multiple age populations present in the 1.8–0.9 Ga age interval in the northwestern part of the Gassum Formation correspond to the ages occurring in the Sveconorwegian Orogen including intrusions and metamorphic overprint (Fig. 4). A local provenance is evident from the high content of zircons with ages corresponding to the metamorphosis that was most pronounced in the Telemarkia Terrane in southernmost Norway. This is therefore the likely provenance of most of the sediment in the northwestern part of the study area. However, the Caledonian Orogen is the primary source area of the uppermost samples from the Frederikshavn-1, Flyvbjerg-1, Børglum-1, Thisted-3, Aars-1, Gassum-1, and Horsens-1 wells, which have age distributions that resemble those from southeastern Denmark with dominance of ~1.65 Ga ages, except that the samples from northwestern Denmark do not contain Variscan zircons with the exception of the uppermost sample from Horsens-1 (Fig. 4, 5). Only the upper part of the Gassum Formation is present in the Frederikshavn-1, Flyvbjerg-1, and Børglum-1 wells (Nielsen 2003), so just one sample has been analyzed from each well.

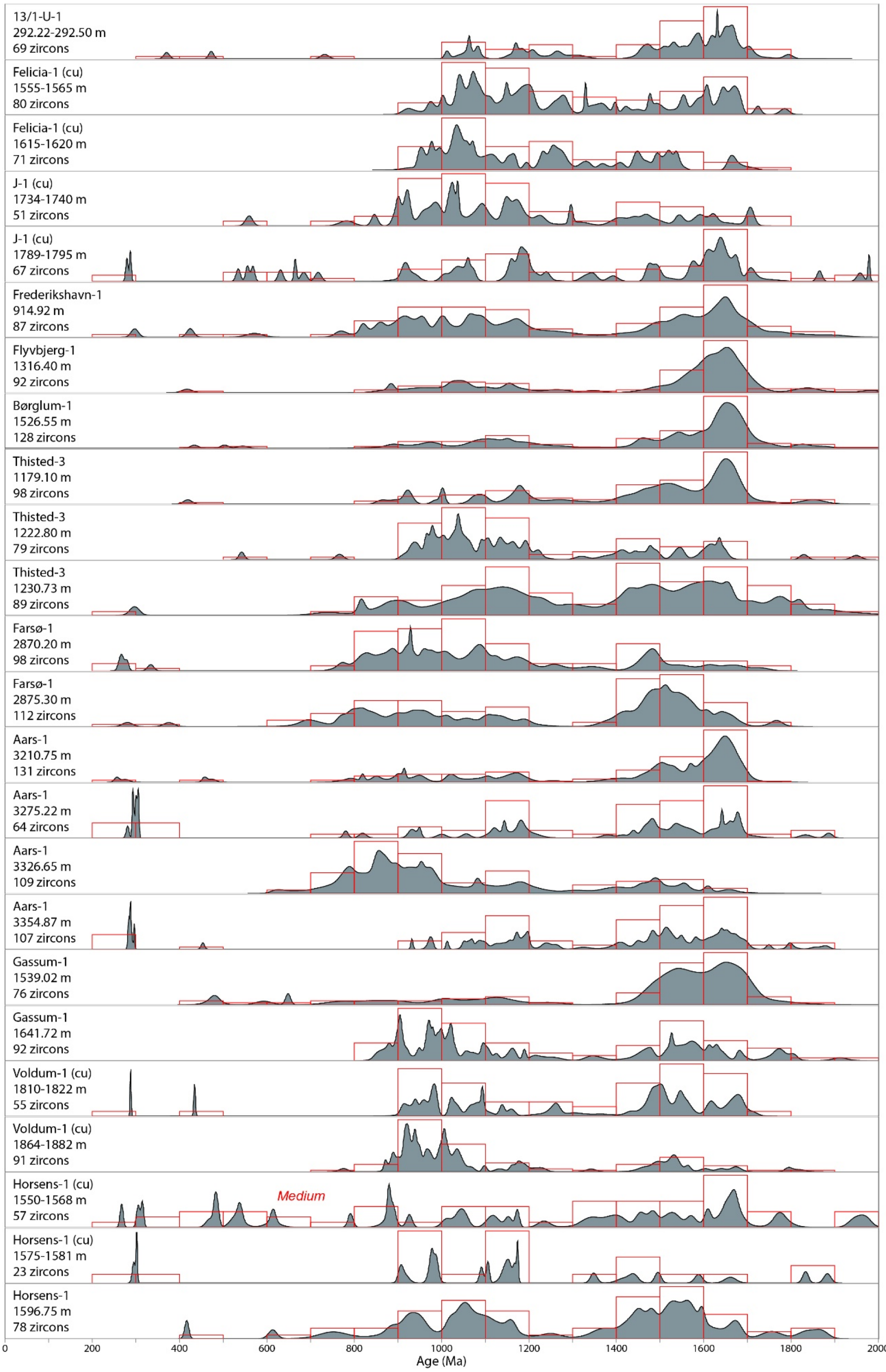

Figure 4: *Zircon U/Pb age distributions for the northwestern part of the Gassum Formation. The well name, depth and number of concordant zircons are shown for each sample.*

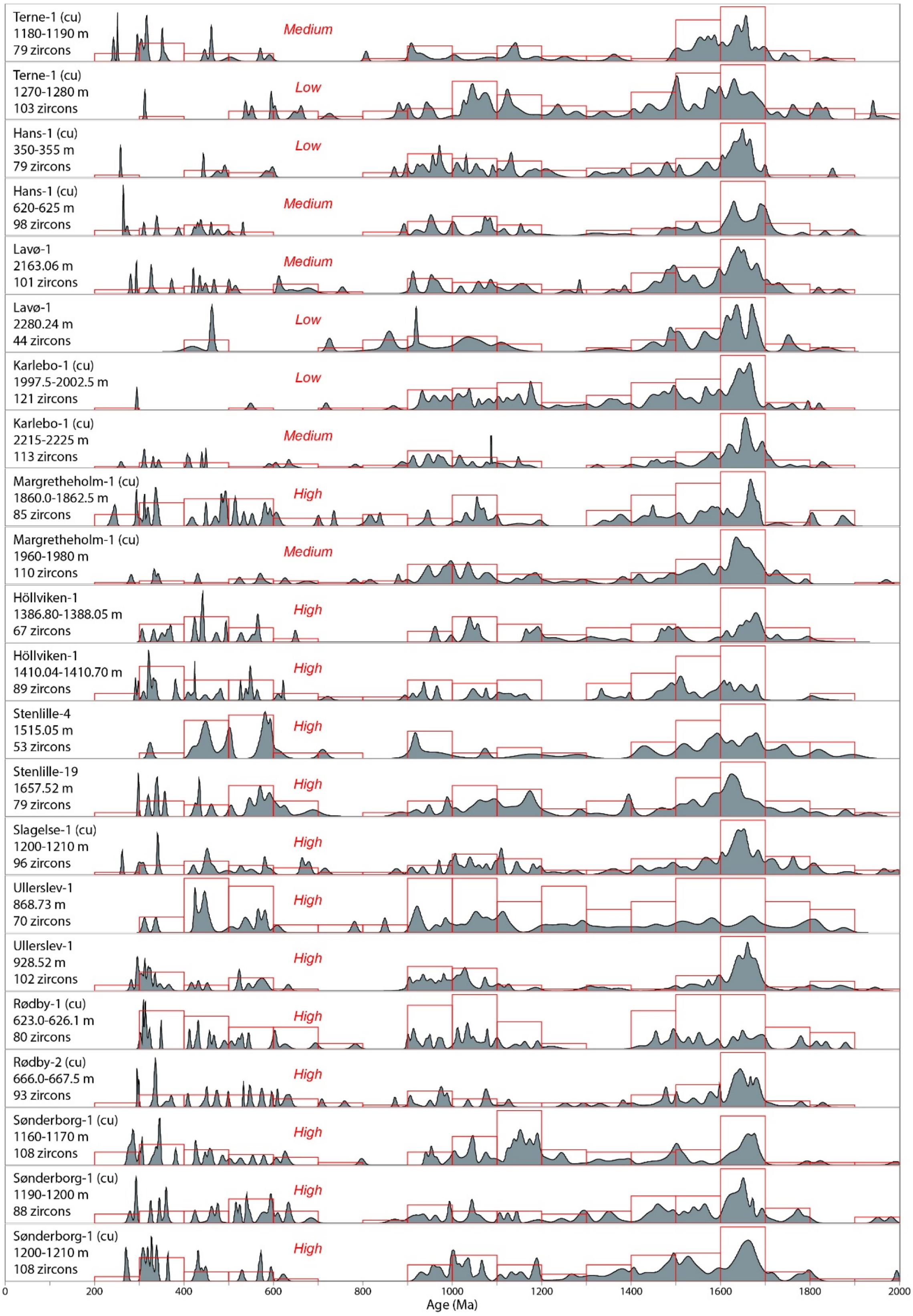

Figure 5: *Zircon U/Pb age distributions for the southeastern part of the Gassum Formation. The well name, depth and number of concordant zircons are shown for each sample. The relative content of Variscan zircons is indicated as high, medium, or low based on a qualitative estimation. Some samples are from cores and some are from cuttings (cu).*

5. Provenance analysis of the Gassum Formation

A Fennoscandian provenance of the Gassum Formation has long been assumed based on the facies distribution in the basin (Bertelsen 1980). This is now confirmed by the provenance analysis of detrital zircon grains and an additional sediment input with Variscan affinity is identified. Some of the zircon U/Pb dating results from the Gassum Formation were recently described in other contexts (Olivarius 2015, Vosgerau et al. 2016, Weibel et al. 2017b, Olivarius et al. 2018a, 2018b, 2019). By comparing the results, an integrated provenance analysis can be performed with emphasis on the issues relevant for CO_2 storage.

A Palaeozoic sediment cover once existed in southwestern Sweden. This cover was mostly removed during Middle Triassic uplift (Japsen et al. 2016) by which the area had been peneplained and did therefore not supply much sediment to the Gassum Formation since the peneplain consisted mostly of resilient basement. Some Palaeozoic sediments are locally preserved in the Sveconorwegian Orogen in down-faulted areas such as the Oslo Graben (Dahlgren and Corfu 2001, Andersen et al. 2011, Kristoffersen et al. 2014). A small sediment supply from the Oslo Graben is identified in a few samples based on Carboniferous–Permian zircon ages corresponding to the timing of the rifting (Fig. 4). Sediments constituted probably only a minor part of the exposed rocks in the Fennoscandian Shield when the Gassum Formation was deposited, meaning that the sediment is primarily derived from erosion of basement terranes without significant sediment reworking.

In the northwestern part of the Gassum Formation, the highly varying proportion of the individual zircon age populations indicates a local provenance where limited homogenization of the provenance signal has occurred along the short sediment transport pathways (Fig. 4). The opposite is found in the southeastern part of the formation as evident by the uniform age distributions implying that intensive homogenization and mixing of sediment from the different source areas has occurred (Fig. 5).

Most of the sediment in the northwestern part of the Gassum Formation was only transported a short distance from its source comprising the Telemarkia Terrane in southernmost Norway, which is in accordance with the low mineralogical maturity (Fig. 6). In Jylland, the feldspar content decreases upwards and especially the plagioclase content is diminished while the K-feldspar content decreases less (Weibel et al. 2017a). This is in accordance with the longer sediment transport route from the Caledonian Orogen in central southern Norway interpreted for the upper part of the formation in this area, which would have caused more breakdown of feldspars and in particularly of plagioclase than in the lower part of the formation. This change may be related to the general backstepping of the basin edge due to the marine drowning that culminated with deposition of the Fjerritslev Formation (Nielsen 2003). However, in Skagerrak, sediment was continuously supplied from the Telemarkia Terrane to the Gassum Formation so a change in provenance did not occur here.

Most of the sediment in the southeastern part of the Gassum Formation was transported a long distance from the Caledonian Orogen, and some Sveconorwegian sediment has probably been added to the detritus in the fluvial system when passing through this area. The southeastern part of the Gassum Formation is positioned further away from the Caledonian Orogen than the northwestern part, which is part of the explanation for the lower feldspar content in the southeastern part (Fig. 6). The sediment supplied from the Variscan Orogen to the southeastern part of the Gassum Formation has also been transported a long distance before deposition. It is not evident whether the long transport routes of the sediment supplies are enough to explain the high mineralogical maturity present to the southeast, or if the Variscan sediment is reworked from an older sedimentary source farther to the south, or whether a high-energy depositional environment has been present in the eastern part of the Gassum Formation hence increasing the mineralogical maturity even further.

The Bunter Sandstone Formation present in the southern part of the Danish area, contains Variscan zircons, which were transported across the North German Basin from the Variscan massifs by aeolian processes in this arid Early Triassic climate (Olivarius et al. 2017). However, the Bunter Sandstone Formation contains other age populations that are not prominent in the southeastern part of the Gassum Formation, so reworking of the Bunter Sandstone Formation cannot have sourced the Variscan zircons. The very prominent ~1.65 Ga zircon ages found in all samples from the southeastern part of the Gassum Formation is not present in the Bunter Sandstone Formation since erosion of the Caledonian Orogen was not yet a prominent sediment source in Early Triassic.

Seismic mapping of the Ringkøbing–Fyn High indicates that the basement and cover sediments can only have been eroded in limited amount during deposition of the Gassum Formation (Morten Sparre Andersen, pers. comm.). The content of reworked sediment identified in the Sønderborg-1 well identified by rounded overgrowths on some of the quartz grains is then presumed to be a local occurrence of mixing with reworked sediment from the high. In parts of the Skurup High, Cretaceous sediments rest directly on crystalline basement of assumed Sveconorwegian affinity, so Triassic or Permian sediments perhaps containing Variscan zircons may have been exposed to erosion during deposition of the Gassum Formation. Alternatively, the Skurup High functioned as a by-pass area for sediment eroded from the Variscan Orogen.

The Variscan zircons in the Gassum Formation have probably been supplied directly from erosion of the Variscan Orogen and the sediment must then have been transported northwards by fluvial processes. When the Variscan sediment reached the marine environment, it was probably transported further northwards by shoreface and delta progradation. The southerly sediment mixed with sediment from the north that was likely transported southwards by longshore drift in the eastern part of the basin. However, how the mixing between the northerly and southerly derived zircons occurred is not fully understood, and it emphasizes that the sediment routes and depositional environments probably were more complex than assumed by Nielsen (2003).

A contour map of the Variscan input to the Gassum Formation is produced based on the qualitative estimation of the relative content found in each sample (Fig. 7). All the 12 samples from the eight southernmost sampled wells have high Variscan input relative to the other samples, so the Variscan zircon grains must have been supplied to the Danish area from the south or southeast, which is in accordance with their source area in the Variscan Orogen present in Central Europe. The Variscan input decreases to a medium to low relative amount in the samples from northern Sjælland and Kattegat. In Jylland, Variscan input is only distinct in the upper sample from the Horsens-1 well so it appears that the deposition of Variscan sediment spread to a wider area extending further towards west during deposition of the upper part of the Gassum Formation. Variscan input has not been found in the samples from the 11 remaining wells, which are present farthest to the northwest with the Voldum-1 well being the most southeasterly. Based on the distribution of Variscan zircons in the Gassum Formation, transport of sediment from the southeast across the Skurup High seems likely to have occurred and simultaneous sediment supply directly from the south is possible (Fig. 7).

The Variscan sediment could probably not be transported onto the Skagerrak–Kattegat Platform, so the Sorgenfrei–Tornquist Zone may have been the northern limit of the southerly derived sediment (Fig. 7). It cannot be determined how far to the west the Variscan sediment spread across southern Jylland since the Gassum Formation is mostly missing here due to Middle Jurassic erosion. In eastern Denmark, the large sediment supply from the north caused the smaller sediment supply from the south to become diluted in a northward direction. However, the amount of Variscan sediment may be underestimated since Variscan ages are overrepresented both among the discordant ages and among those with common lead content (Fig. 3), so it is possible that the amount of sediment supplied from the southeast may have been as large or even larger than the amount supplied from the north. The zircon fertility of the Variscan source rocks is not known so the content of Variscan versus Caledonian zircons cannot give a precise estimate of how large a proportion of the sediment that was supplied from each source area. Furthermore, some fractionation between zircon and quartz grains may have occurred during the sediment transport. Too few mineralogical analyses have been performed for the eastern part of the Gassum Formation to determine whether the amount of Variscan zircons impacts the sandstone mineralogy (Fig. 6, 7).

The fluvial system that transported sediment from the Caledonian Orogen to the Norwegian–Danish Basin must have been of a substantial size to be able of transporting such a large amount of sediment to the basin and further south into the North German Basin. The sediment must have been produced by the pronounced Triassic exhumation of southern Norway where a succession of several kilometres thickness was eroded off (Rohrman et al. 1995, Japsen et al. 2016). Renewed uplift may have occurred during deposition of the Gassum Formation, which would explain why the sediment from the Caledonian Orogen began spreading to the whole Norwegian–Danish Basin instead of only the eastern part.

The provenance of the lower and upper parts of the Gassum Formation are summarized in Figure 8 and 9, respectively. Further sequence stratigraphic interpretations are necessary before the timing of the provenance change can be better constrained. The figures show the known extend of sediment supplied from each of the appointed source areas, which is based on the zircon U/Pb dates of samples from the 25 wells on the maps. How the sediment became distributed within each of the appointed areas by the prevailing depositional environments is not the scope of interpretation herein.

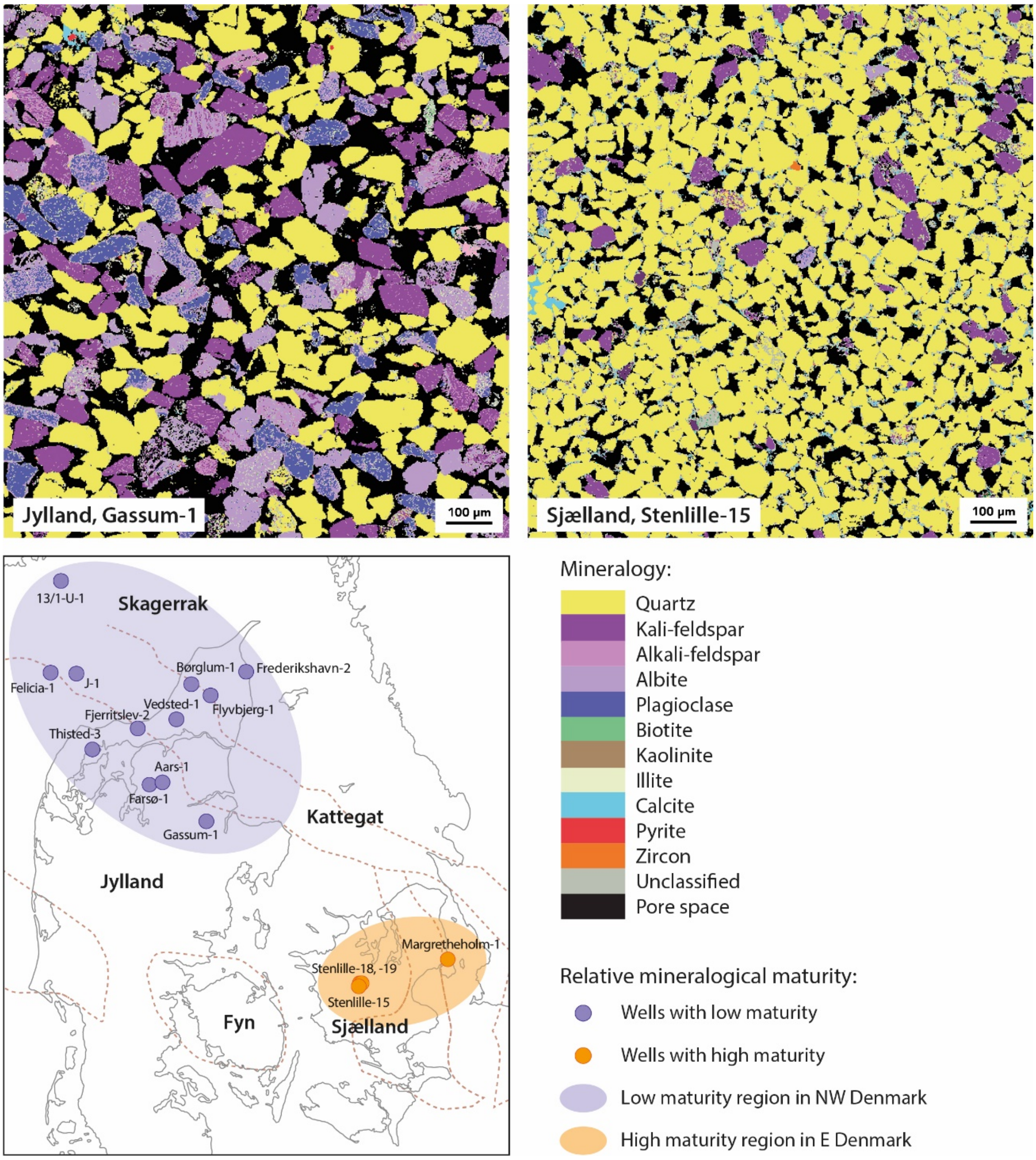

Figure 6: *The mineralogical maturity of the Gassum Formation varies across the Danish area. The AQM-BSE images (method: Keulen et al. 2020) of two sandstone samples show the mature mineralogical composition on Sjælland with high quartz content, whereas a less mature composition with higher contents of e.g. feldspars is found in Jylland. The map shows where the mineralogy of the Gassum Formation has been examined (Vosgerau et al. 2016, Weibel et al. 2017a, Olivarius et al. 2019). Based on this information, the formation can be divided into regions with relatively high versus low mineralogical maturity.*

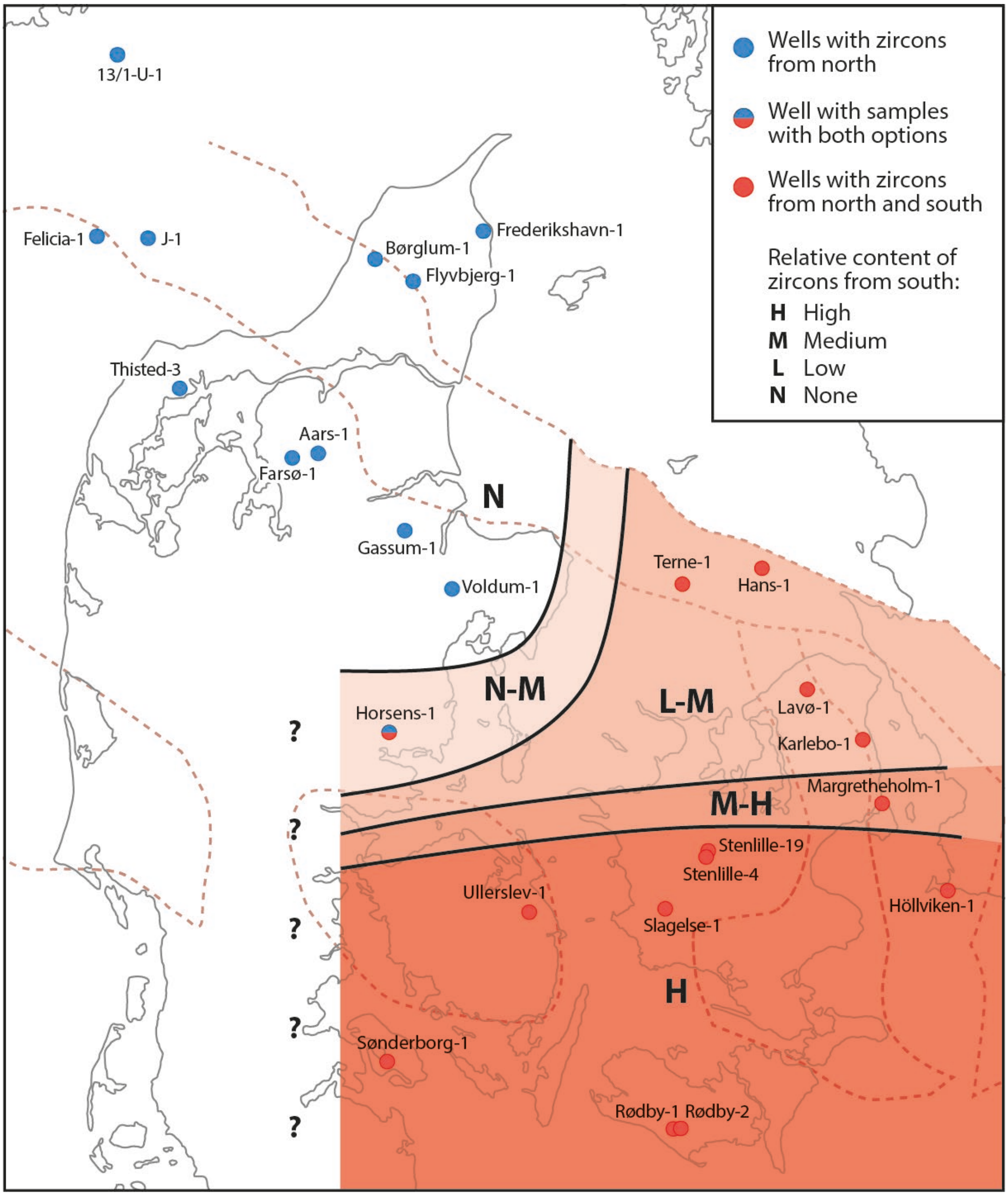

Figure 7: *Contour map of the content of Variscan zircon grains in the Gassum Formation. The relative content of Variscan zircons in each sample has been classified as high, medium, low or none based on a qualitative estimation as seen in Figure 5. Only one of the three samples from Horsens-1 contains Variscan zircons. It is evident that the zircons with Variscan ages have been supplied from the south or southeast, which is in accordance with their source area location.*

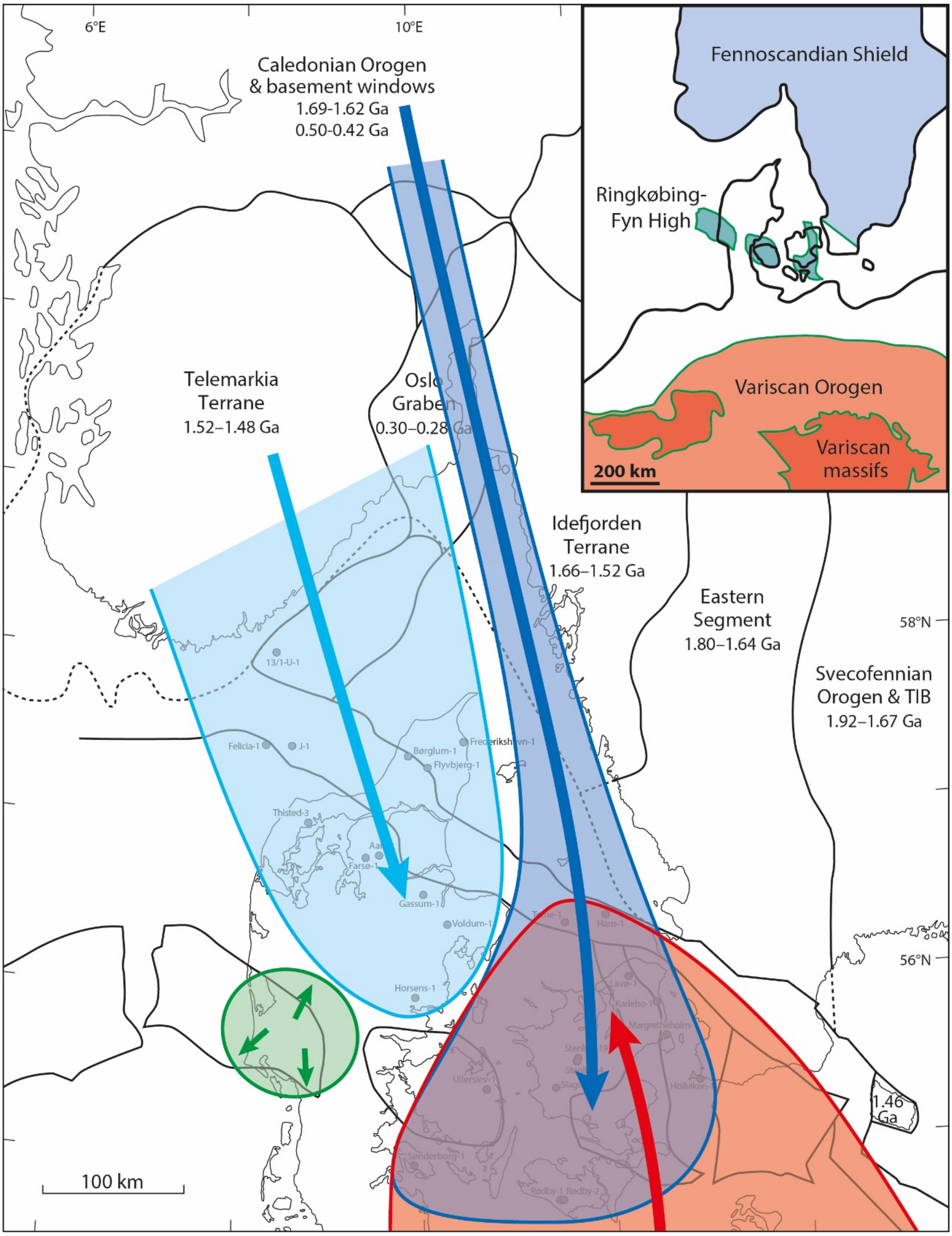

Figure 8: *Provenance of the lower part of the Gassum Formation showing the primary sediment inputs into the Norwegian–Danish Basin and the northern North German Basin as interpreted based on zircon U/Pb ages. How the sediment became distributed within each of the appointed areas by the prevailing depositional environments is not in the scope to interpret here.*

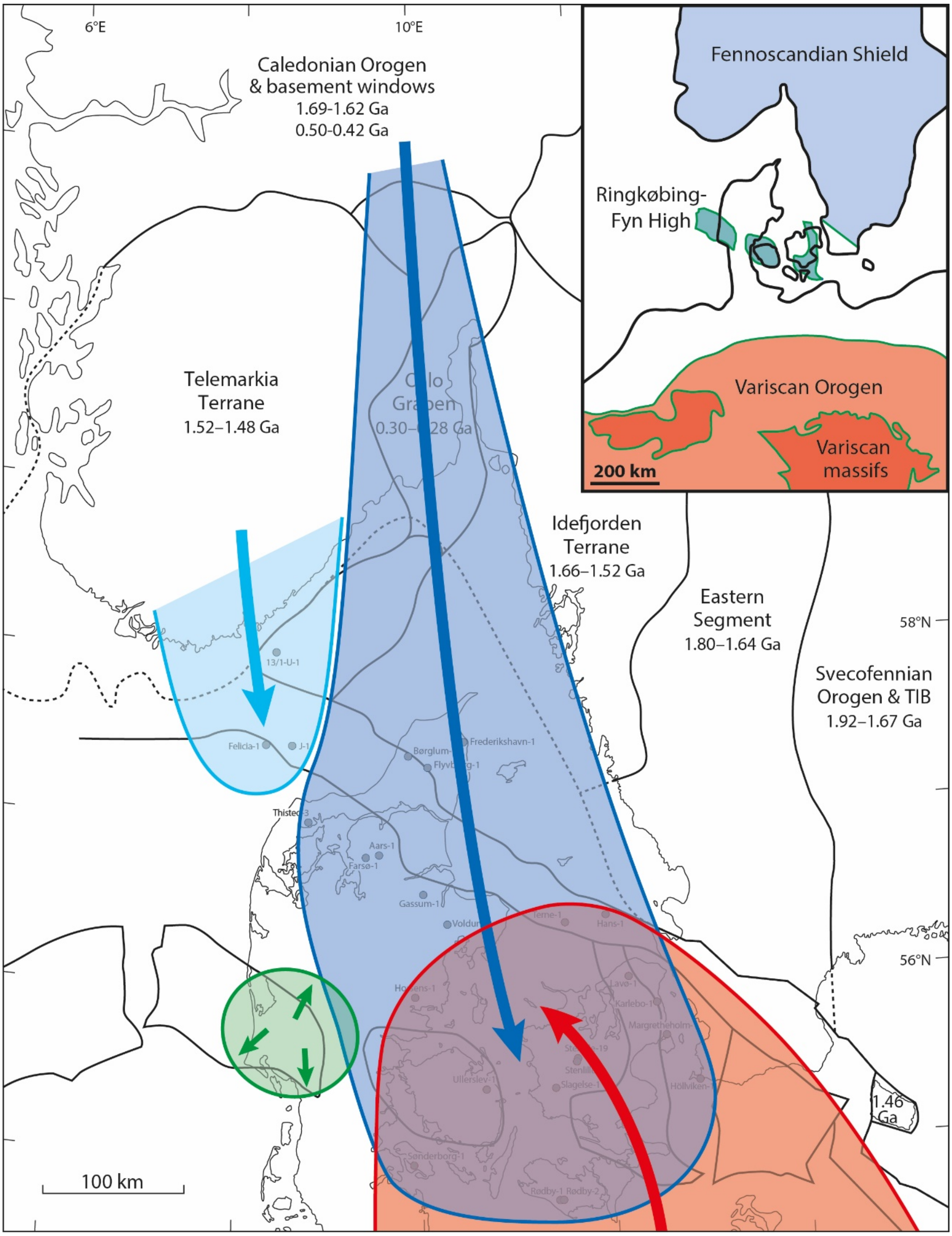

Figure 9: *Provenance of the upper part of the Gassum Formation showing the primary sediment inputs into the Norwegian–Danish Basin and the northern North German Basin as interpreted based on zircon U/Pb ages. How the sediment became distributed within each of the appointed areas by the prevailing depositional environments is not in the scope to interpret here.*

5.1 Provenance interpretation for the Hanstholm structure

Based on the provenance interpretation, it is assumed that the sediment in the Hanstholm structure was supplied from the Telemarkia Terrane. The provenance change that occurred during deposition of the Gassum Formation in Jylland is not evident in samples from the Felicia-1 and J-1 wells (Fig. 4). Thus, this area was located so close to the source area in southernmost Norway that it was still the primary source even when the rest of the formation received most of its sediment from the Caledonian Orogen (Fig. 9). The mineralogy of the Felicia-1 and J-1 wells is only known from small crumbling sidewall cores and is thus only qualitatively described. However, the transport route was short making a relatively low mineralogical maturity of the sandstones very likely, as is found in all wells from the northwestern part of the formation (Fig. 6).

Interpreted provenance-controlled reservoir characteristics in the Hanstholm structure:

- The Telemarkia Terrane is the primary source area
- Short sediment transport route from the source area
- Relatively low mineralogical maturity
- Intermediate reactivity of the sandstones

The value of the Thisted area as an analogue to characterize the mineralogy in the Hanstholm structure is considered good, especially for the lower part of the reservoir which has the same provenance, whereas the upper part of the reservoir in the Thisted area consists of mineralogically more mature sand from a different source area.

5.2 Provenance interpretation for the Havnsø structure

Based on the provenance interpretation, it is assumed that the Havnsø structure is part of the eastern region of the Gassum Formation with high mineralogical maturity (Fig. 6) caused by long transport routes from the source areas comprising the Caledonian, Sveconorwegian and Variscan Orogens. The contour map of the content of Variscan zircons indicates why the Havnsø structure is presumably part of the eastern region (Fig. 7), which received Variscan sediment from the southeast that mixed with sediment supplied from the north (Fig. 8, 9).

Interpreted provenance-controlled reservoir characteristics in the Havnsø structure:

- The Caledonian and Sveconorwegian Orogens are the primary source areas
- The Variscan Orogen supplied a smaller proportion of the sediment
- Long sediment transport routes from the source areas
- High mineralogical maturity
- Low reactivity of the sandstones

The value of the Stenlille area as an analogue to characterizing the mineralogy in the Havnsø structure is considered good, provided that the structure is correctly interpreted as being part of the mineralogically mature region.

6. Conclusions

The dominant provenance of the Gassum Formation sandstones in Denmark is the Fennoscandian Shield in Scandinavia with subordinate sediment contributions from the Variscan Orogen in Central Europe, which is evident from this compilation including all existing zircon U/Pb data for the formation.

During deposition of the lower part of the Gassum Formation, sediment with relatively low mineralogical maturity was deposited in the northwestern part of the basin supplied from a local source area in the Telemarkia Terrane, whereas sediment with high mineralogical maturity was deposited in the southeastern part of the basin supplied from the Caledonian Orogen to the north and the Variscan Orogen to the south.

When the upper part of the Gassum Formation was deposited, the sediment supply from the Caledonian Orogen spread to the whole basin, except for in the Skagerrak where sediment was still supplied from the Telemarkia Terrane. The sediment from the Variscan Orogen also became distributed in a larger area extending further to the west.

Reworking of sediment may have occurred locally on the Ringkøbing–Fyn High and the Skurup High but is not likely to have supplied much of the sediment to the Gassum Formation since the Bunter Sandstone Formation has a different provenance signature. Both highs may primarily have served as sediment bypass areas during the deposition.

In the Hanstholm structure, the provenance interpretation implies that the Telemarkia Terrane was the dominant source area, so the sediment was only transported as short distance before deposition resulting in a relatively low mineralogical maturity. This is also the case for the lower part of the formation in the Thisted area which is therefore considered a good analogue for the Hanstholm structure, except in the upper part of the formation which has a different primary source area.

In the Havnsø structure, the provenance interpretation indicates that the sediment was primarily sourced by the Fennoscandian Shield with a smaller proportion of the sediment originating from the Variscan Orogen. Both sediment supplies involve long transport distances resulting in a high mineralogical maturity of the deposited sediment. Based on the provenance interpretation, the Stenlille area is considered a good analogue for the Havnsø structure, provided that the structure is correctly interpreted as being part of the mineralogically mature region.

The implications of the provenance analysis for the CO_2 storage potential include the distribution of sandstones in the basin, the depositional setting, the net sand content, and the mineralogical maturity relevant for the reactivity of the sandstones when exposed to injected CO_2.

7. Recommendations for future research

Sequence stratigraphic correlations

- Sequence stratigraphic interpretations of the Gassum Formation are recommended for those areas where it has not yet been performed. This will enable more detailed comparison between the provenance samples by taking their specific stratigraphic levels into account and thus be able to better constrain the depositional history including the timing of provenance changes.

Distribution of depositional environments

- Integration of the knowledge obtained from provenance analysis, sedimentological investigations, and sequence stratigraphy is recommended to enable interpretation of the distribution of depositional environments in the Danish area. On this basis, maps of the changing positions of depositional environments of the Gassum Formation up through the sequences can be made, which will highlight the overall trends such as backstepping of the basin margins and changing sediment entry points.

Mineralogical maturity regions

- Mineralogical quantification of sandstone samples from additional wells is recommended with special focus on the southeastern part of the Gassum Formation to determine if the region with high mineralogical maturity has the same extent as the southeastern provenance region sourced by the Variscan and Caledonian Orogens. On this basis, it will be possible to evaluate whether the provenance controls all the geographic and stratigraphic differences in mineralogy or if the depositional environments including the amount of reworking also affect the mineralogical composition.

Mineralogy in relation to depositional regime

- Detailed mineralogical investigation with closely spaced sampling of a single depositional sequence in two selected wells from the northwestern and southeastern parts of the Gassum Formation, respectively, is recommended to understand how the mineralogy and degree of reworking are affected by changes in depositional regimes. This is important to understand how much the distance of sediment transport from the source area versus the amount sediment reworking in the depositional environment affects the mineralogical maturity of the sediment, which determines the reactivity of the reservoir when applied for CO_2 storage.

Analyses of new wells

- If new wells are drilled, especially in the boundary area between the northwestern and southeastern regions of the Gassum Formation, it is recommended to subject them to provenance analysis and mineralogical quantification. Thus, it can be constrained whether a sharp or gradual boundary exists between the different provenance signals and mineralogical compositions of the northwestern and southeastern regions, which is of great importance to understand the depositional processes.

Deciphering the southern provenance signal

- Sampling of Upper Triassic – Lower Jurassic sandstones from outcrops in Germany and Poland is recommended to obtain their zircon U/Pb ages and thereby quantify the provenance signal of the Variscan sediment supplied from the southeast to the Gassum Formation. This is necessary to obtain unbiased analyses where the Variscan provenance signal is not mixed with the Fennoscandian provenance signal.

Analysis of other heavy mineral grains

- Zircon U/Pb dates are highly valuable as provenance indicators in the Danish area. Nevertheless, zircon has a high closure temperature for the isotopic U/Pb system. Thus, zircons do not automatically record all the geological events (e.g. low- and medium-temperature metamorphosis) that the zircon mineral has experienced through its lifetime. Such information can instead be obtained through U/Pb dating of other heavy minerals like rutile, titanite, apatite, or garnet, because the closure temperatures for the U/Pb system in these minerals are lower than for zircon. Therefore, ages obtained from these minerals potentially offer new additional information to the sediment contributions from e.g. metamorphic rock terrains, which in turn may enable a more detailed provenance analysis.

Analysis of light-density mineral grains

- Newly developed provenance methods enable analysis of light minerals such as quartz and feldspar, which constitute the dominant mineral fraction in sandstones. Hence, it is of great importance to know if the light minerals have similar provenance as the heavy minerals such as zircon to better know whether the zircon provenance is representative for the entire sediment or if only a fraction of it is. It is therefore recommended to perform radiometric dating of feldspar combined with trace element analysis of quartz and feldspar. These analyses should be performed both on samples from the reservoir and from representative samples from the source areas since the light mineral signature of the source rocks is unknown.

Provenance analysis of younger reservoirs

- Other sandstone reservoirs with potential for CO_2 storage in Denmark could also benefit from detailed provenance analysis to help determine the distribution of the reservoirs, their depositional environments, and the dependence of the mineralogy on the source areas. These geological formations comprise the Middle Jurassic Haldager Sand Formation, the Upper Jurassic Flyvbjerg Formation, the Upper Jurassic to Lower Cretaceous Frederikshavn Formation, and unnamed sandstone intervals in the Lower Jurassic Fjerritslev Formation and in the Lower Cretaceous deposits.

Provenance analysis of older reservoirs

- The provenance of the Lower Triassic Bunter Sandstone Formation and the Lower to Upper Triassic Skagerrak Formation has already been analyzed. However, a more closely spaced sampling is recommended since it has proven to give highly valuable knowledge of the Gassum Formation, from which it is also evident that cuttings samples are usable for zircon U/Pb dating, thus enabling more sampling since few cores exist from the Bunter and Skagerrak Formations.

8. Acknowledgements

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