DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2018/45

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G E U S

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GEUS

Content

Introduction

These results are part of the geothermal assessment project conducted by GEUS for A.P. Møller Holding (APMH) regarding the greater Århus area. The purpose of the analyses of detrital zircons is to contribute to the interpretation of possible sediment transport routes and to assess the entry points to the basin. The results supplement the previous analyses performed at GEUS, and are being integrated in the sequence stratigraphic interpretation targeting the distribution of Gassum Formation sandstones in APMH's area of interest.

Geological setting

The Århus area is located in the Norwegian-Danish Basin, which was formed by crustal stretching followed by late Carboniferous–early Permian rifting and Mesozoic–Cenozoic thermal-dominated subsidence (Vejbæk 1997). Thereby a km-thick succession of sandstones, siltstones, mudstone, carbonates and evaporites accumulated in the basin. Of these, the Triassic–Jurassic succession includes several potential geothermal reservoir sandstones such as the Bunter Sandstone Formation, the Skagerrak Formation, the Gassum Formation, the Haldager Sand Formation and the Frederikshavn Formation.

The Lower Triassic Bunter Sandstone Formation is widespread in the North German Basin and in the southern part of the Norwegian–Danish Basin, where it is synchronous with the oldest part of the Lower–Upper Triassic Skagerrak Formation that accumulated in the northern part of the basin (Michelsen & Clausen 2002). The arid to semi-arid climate resulted in deposition of aeolian and ephemeral fluvial sand interbedded with silt- and mudstones formed in shallow lakes with occasional evaporite deposition (Clemmensen 1985).

The Upper Triassic–Lower Jurassic Gassum Formation is present in most of the Norwegian–Danish Basin, except where major salt structures occur and on the basement blocks of the Ringkøbing–Fyn High (Michelsen et al. 2003, Nielsen 2003). The formation was deposited in a humid climate and consists of marine and fluvial sandstones interbedded with marine and lagoonal mudstones, minor siltstones and thin coal beds formed during periods with recurrent sea-level changes.

Samples

Eight new samples for zircon age analysis were selected from certain geographical areas and specific stratigraphic levels within the Gassum Formation to supplement GEUS' existing zircon age data from Frederikshavn-1, Flyvbjerg-1, Børglum-1, Thisted-3, Farsø-1, Gassum-1 and Horsens-1. The new samples include one cuttings sample from Horsens-1, one core sample from Gassum-1, two core samples from Aars-1, two cuttings samples from Voldum-1 and two core samples from Ullerslev-1 (Figure 1). The full data set, comprising both the new samples and the previous samples that are re-evaluated in context of the new data, is integrated in order to obtain a better understanding of the distribution of the Gassum Formation sandstones.

The sample depths given in this report each represent the average depth of the sampled interval. These intervals are up to 10 cm thick for the core samples and up to 18 m thick for the cuttings samples in order to ensure that a sufficient amount of material was sampled (c. 300 g). The stated depths are measured depths in the wells (MD). However, in some wells the core depths specified in this report do not correspond exactly to the well-log depths, so correction is required when comparing samples with well logs. The Horsens-1 core depths can be corrected to log depths by subtracting c. 10 m, the Gassum-1 core depths can be corrected to log depths by subtracting c. 6–8 m (20–25 ft.) and the Børglum-1 core depths can be corrected to log depths by subtracting c. 1 m (3 ft.) (Nielsen 2003).

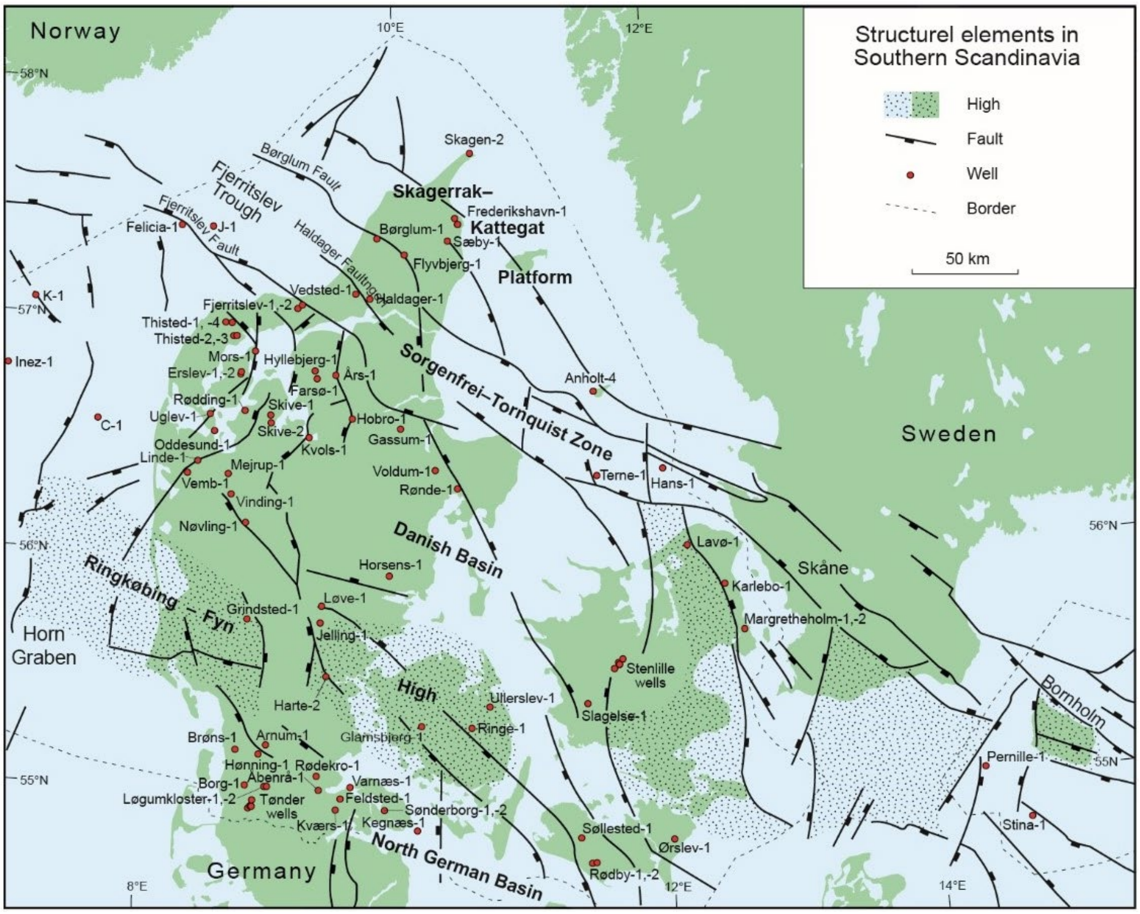

Figure 1: *The new samples analyzed in this study are from Horsens-1, Gassum-1, Aars-1, Voldum-1 and Ullerslev-1, and the results are integrated with existing GEUS-data of zircon ages from the Gassum Formation.*

Methods

Radiometric ages of U-rich minerals like zircon usually represent the time at which the minerals formed during an igneous or metamorphic event. Zircon is a chemically and physically 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. Thus, age dating of detrital zircon grains is an important provenance tool that is utilized to tie the zircon grains in the sediments to the original source area. In this way, the ages contribute to investigation of sediment transport routes and sediment distribution.

Zircon U-Pb ages were obtained from hand-picked zircon grains collected from crushed samples that were sorted by density using a Holman-Wilfley water-shaking table. The radiometric U-Pb dating was performed by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) microanalysis at GEUS. Basically, the general procedures of Frei & Gerdes (2009) were followed. The LA-ICPMS analysis involved ablation of the sampled material for 30 s using a focused laser beam with a diameter of 25 or 30 micrometres (µm) in an air-tight helium-flushed chamber. The ablation liberated ca. 200 to 300 nanograms of material, which 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 new 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 software for the new data (Hellström et al. 2008; Paton et al. 2011; Petrus et al. 2012), and the in-house software Zirchron for the previously measured data.

Ages calculated from the $^{207}Pb/^{206}Pb$ ratio are used for zircons older than 700 million years (Ma), whereas the $^{206}Pb/^{238}U$ ages are used for younger zircons because the $^{206}Pb/^{238}U$ ages yield more robust ages in the younger age interval. The analytical uncertainties for the ages are 2σ. Common-lead correction was applied to a subset of the analyses when required. Combined histogram and probability-density plots were produced through the software jAgeDisplay (Thomsen et al. 2016). Ages older than 2000 Ma are not shown on the diagrams because only a few grains with ages >2000 Ma occurred, which are of no relevance in the specific provenance context.

Results

The results of the new zircon age analyses reveal that the grains are primarily derived from the Fennoscandian Shield in Scandinavia (illustrated with blue boxes in Figure 2), similarly to the existing zircon age analyses from the Gassum Formation in Jylland. However, Fennoscandian zircon ages younger than 800 Ma are restricted to Paleozoic ages corresponding to the Ordovician to Early Devonian Caledonian orogeny and the Late Carboniferous to Permian Oslo rifting. These ages are illustrated with narrow blue boxes overlapping parts of the red box that illustrates the broad age span of young zircons present in the Variscan Orogen in Central Europe.

For most samples, ages <800 Ma are presumably derived from the Caledonian Orogen and the Oslo Graben as the ages match with these areas. However, the upper sample from Horsens-1 at 1550–1568 m MD (representing the mid-part of the Gassum Formation) and the samples from Ullerslev-1 contain a distinct broad age span of young zircons of which some ages do not occur in Fennoscandian basement areas but are present in the Variscan Orogen. Such young zircon grains from the Variscan massifs were transported northward by wind across the North German Basin during the Early Triassic at times when the basin was dried up. The sediment was deposited in the Bunter Sandstone Formation in the southern Danish area together with material derived from the Fennoscandia Shield and the Ringkøbing–Fyn High basement, whereas Variscan ages are not present in the Skagerrak Formation further north in the Danish area (Olivarius & Nielsen 2016, Olivarius et al. 2017).

Thus, the Gassum Formation sandstones in Ullerslev-1 and the upper sample from Horsens-1 must have received an input of sediment with zircon grains younger than 800 Ma. The supply of these zircons could be directly from their Variscan source area in Rhaetian time or by reworking of the Bunter Sandstone Formation. However, the ca. 1.65 Ga peak age that is dominant in especially the upper part of the Gassum Formation and also is distinct in Ullerslev-1 and Horsens-1 shows that a large amount of the sediment is derived from the Caledonian Orogen located in the central part of southern Norway. This age is not distinct in the Bunter Sandstone Formation. So, some of the sand in the Gassum Formation in Ullerslev-1 and Horsens-1 was probably transported directly from Norway prior to deposition (Figure 3). The mixture of northerly and southerly derived zircons emphasizes that the sediment routes and depositional environments probably were more complex than assumed by Nielsen (2003).

Recent studies at GEUS have shown that the Gassum Formation in Sønderborg also contains young zircon grains of Variscan origin and likewise in Sjælland where the content becomes smaller northwards from Stenlille to Margretheholm and toward Karlebo-1 and Lavø-1. This may testify to erosion of the Bunter Sandstone Formation along some parts of the Ringkøbing–Fyn High or the Skurup High further to the east (Figure 3). In parts of the Skurup High, Cretaceous sediments rest on basement, so Triassic or Permian sediments with Variscan zircons were possibly exposed to erosion in Rhaetian time. Alternatively, the Skurup High functioned as a by-pass area for sands eroded from the Variscan Orogen in Rhaetian time. Additionally, it is possible that minor parts of the Bunter Sandstone Formation just north of the Ringkøbing–Fyn High were exposed to erosion in Rhaetian time in small local areas; the zircon age distribution of the Bunter Sandstone is unknown here. The high mineralogical maturity of the eastern Gassum sandstones is consistent with a high content of reworked material. Thus, the zircons and the maturity points to either reworking of older sedimentary rocks situated south and/or east of basin or alternatively supplied via long-distance transport from the Variscan Orogen.

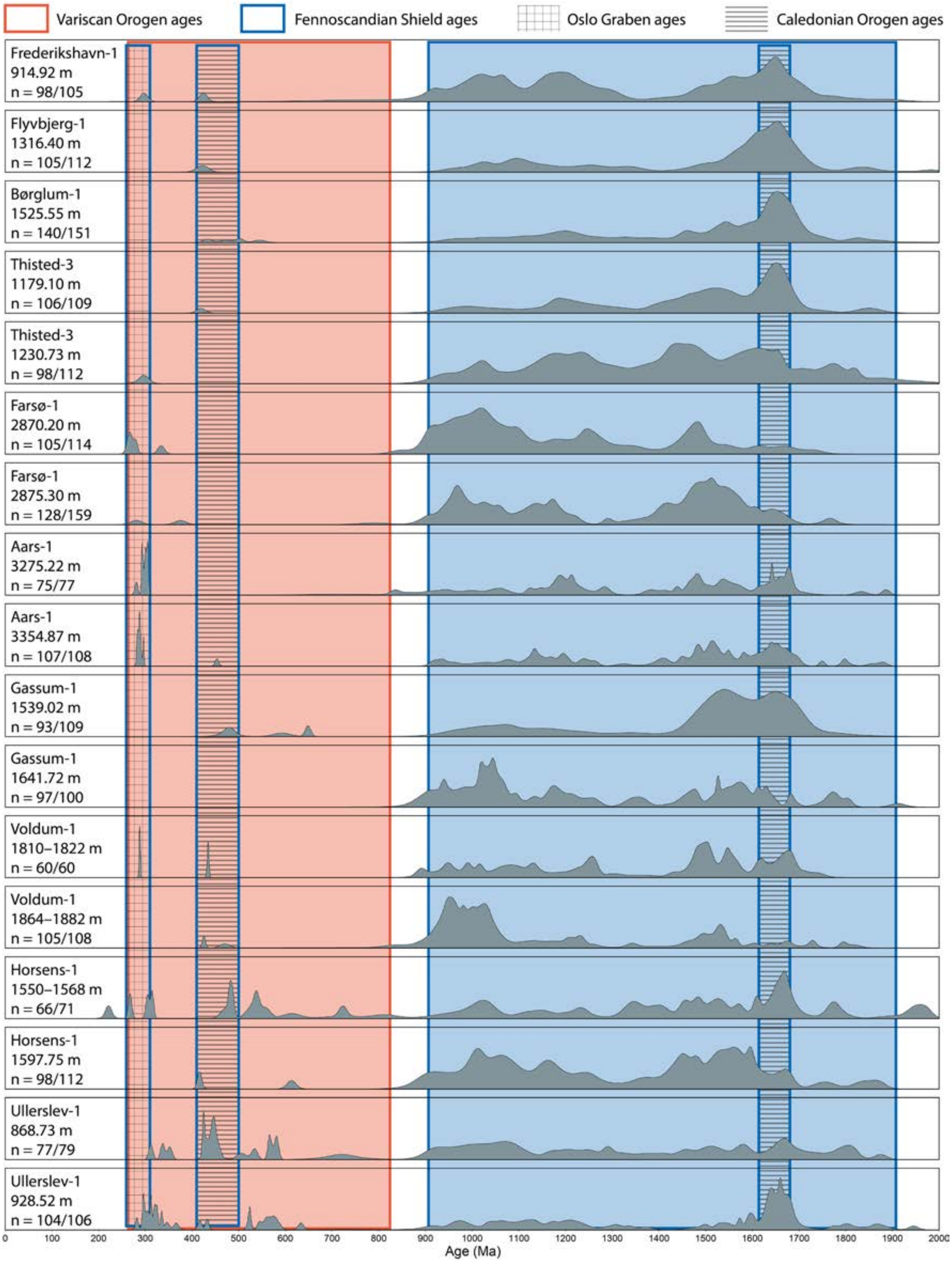

Figure 2: *Zircon age distributions of detrital zircons from the Gassum Formation. The number of employed concordant ages out of the total number of measured ages is shown by 'n'. Depths are in MD. The ages of the Oslo Graben and the youngest ages of the Caledonian Orogen overlap with some of the ages present in the Variscan Orogen. Zircon grains from both the Fennoscandian Shield and the Variscan Orogen are present in the Bunter Sandstone Formation in southern Denmark.*

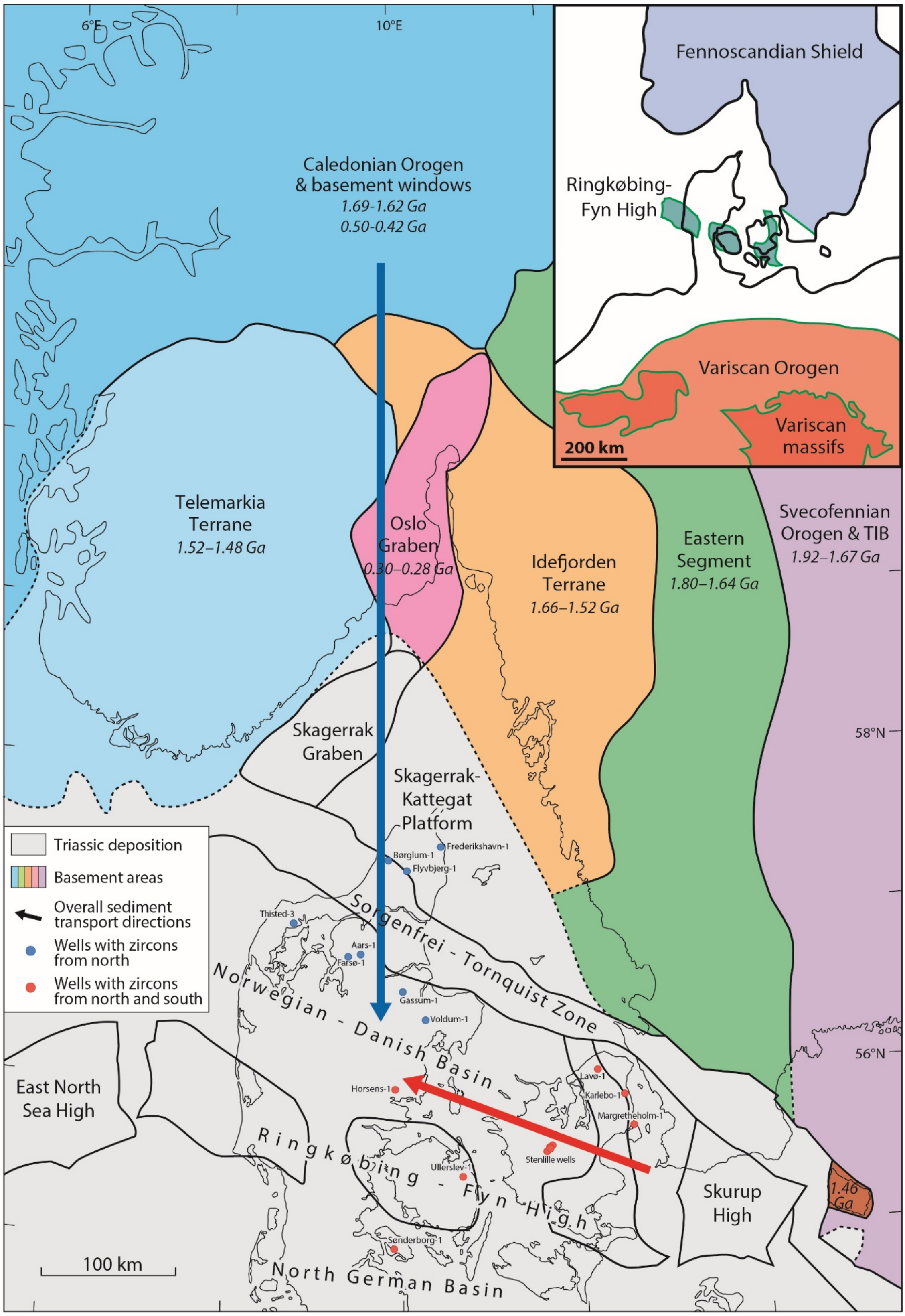

Figure 3: *Interpreted overall primary sediment transport directions during deposition of the Gassum Formation. Much of the sand across the Norwegian–Danish Basin was supplied from the Fennoscandian Shield, whereas contents of sand originating from the Variscan Orogen are found in the eastern part of the basin and in some intervals in the southern part of the basin and may have been reworked from older sediments. The magmatic ages of the basement provinces are shown in billion years (Ga). Based on Olivarius & Nielsen (2016).*

Conclusions

Several source areas have supplied sediment to the Gassum Formation, which is positive for the net sand content in the greater Århus area. The sand from the north was transported at least as far south as Horsens, whereas the sand from the south/east was at times transported at least as far north/west as Horsens.

Zircon age analyses of samples from Voldum-1, Gassum-1, Aars-1, Farsø-1, Thisted-3, Børglum-1, Flyvbjerg-1, Frederikshavn-1 and the lower sample from Horsens-1 show that these sediments were derived solely from the Fennoscandian Shield. The sediment was primarily supplied from southern Norway and sub-ordinarily from southwestern Sweden and transported southwards by rivers.

The zircon age analyses from Ullerslev-1 and the upper sample from Horsens-1 show that some of the sediment has a southern provenance, either from reworking of the Bunter Sandstone Formation or direct Rhaetian transport from the Variscan Orogen in central Europe. This indicates a north/westward-directed sediment transport into the southern part of the Norwegian–Danish Basin, e.g. from the Skurup High and possibly smaller contributions from the Ringkøbing-Fyn High where the Bunter Sandstone Formation may have been exposed locally at the time.

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References

Clemmensen, L.B. 1985. Desert sand plain and sabkha deposits from the Bunter Sandstone Formation (L. Triassic) at the northern margin of the German Basin. Geologische Rundschau 74, 519–536.

Frei, D., Gerdes, A., 2009. Precise and accurate in situ U-Pb dating of zircon with high sample throughput by automated LA-SF-ICP-MS. Chemical Geology 261, 261–270.

Hellström, J., Paton C., Woodhead J., Hergt J., 2008. Iolite: Software for spatially resolved LA- (quad and MC) ICPMS analysis. In: Sylvester, P. (Ed.) Laser Ablation ICP–MS in the Earth Sciences: Current Practices and Outstanding Issues, Mineral. Assoc. of Canada, Quebec, Canada, 343–348.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology 211, 47–69.

Michelsen, O., Clausen, O.R. 2002. Detailed stratigraphic subdivision and regional correlation of the southern Danish Triassic succession. Marine and Petroleum Geology 19, 563–587.

Michelsen, O., Nielsen, L.H., Johannessen, P.N., Andsbjerg, J., Surlyk, F. 2003. Jurassic lithostratigraphy and stratigraphic development onshore and offshore Denmark. In: Ineson, J.R. & Surlyk, F. (Eds.): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1, 147–216.

Nielsen, L.H., 2003. Late Triassic – Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. Geological Survey of Denmark and Greenland Bulletin 1, 459–526.

Olivarius, M., Nielsen, L.H., 2016. Triassic paleogeography of the greater eastern Norwegian-Danish Basin: Constraints from provenance analysis of the Skagerrak Formation. Marine and Petroleum Geology, 168–182.

Olivarius, M., Weibel, R., Friis, H., Boldrel, L.O., Keulen, N., Thomsen, T.B., 2017. Provenance of the Lower Triassic Bunter Sandstone Formation: implications for distribution and architecture of aeolian vs. fluvial reservoirs in the North German Basin. Basin Research 29, S1, 113–130.

Paton, C., Hellstrom, J.C., Paul, P., Woodhead, J.D., Hergt, J.M., 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. Journal of Analytical Atomic Spectrometry 26, 2508–2518.

Petrus, J.A., Kamber, B.S., 2012. VizualAge: A Novel Approach to Laser Ablation ICP-MS U-Pb Geochronology Data Reduction. Geostandards and Geoanalytical Research 36, 247–270.

Slama, J., Kosler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, N., Tubrett, M.N., Whitehouse, M.J., 2008. Plesovice zircon - a new natural reference material for U-Pb and Hf isotopic microanalysis. Chemical Geology 249, 1–2, 1–35.

Thomsen, T.B., Heijboer, T., Guarnieri, P., 2016. jAgeDisplay: software for evaluation of data distributions in U-Th-Pb geochronology. Geological Survey of Denmark and Greenland Bulletin 35, 103–106.

Vejbæk, O.V. 1997. Dybe strukturer i danske sedimentære bassiner. Geologisk Tidsskrift 4, 1–31.

Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., von Quadt, A., Roddick, J.C., Spiegel, W. 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards Newsletter 19, 1–23

Wiedenbeck M, Hanchar JM, Peck WH, Sylvester P, Valley J, Whitehouse M, Kronz A, Mor-ishita Y, Nasdala L, Fiebig J, Franchi I, Girard J-P, Greenwood RC, Hinton R, Kita N, Mason PRD, Norman M, Ogasawara M, Piccoli, PM , Rhede D, Satoh H, Schulz-Dobrick B, Skår Ø, Spicuzza MJ, Terada K, Tindle A, Togashi S, Vennemann T, Xie Q, Zheng Y-F, 2004. Further characterisation of the 91500 zircon crystal. Geostandards and Geoanalytical Research 28, 9–39.