EDITORIAL CSIC

Boletín Geológico y Minero
137 (1) January-April 2026, 006
ISSN-L: 0366-0176, eISSN: 2253-6167
https://doi.org/10.21701/bolgeomin/137.1/006

Artículo

Linking 12th century churches and marble quarries in Norway using C, O and Sr isotope ratios

Vinculación de iglesias del siglo XII y canteras de mármol en Noruega usando relaciones isotópicas de C, O y Sr

Tom Heldal
Geological Survey of Norway NGU
Corresponding author: tom.heldal@ngu.no, https://orcid.org/0000-0003-3613-568X

Per Storemyr
Fabrica Kulturminnetjenester
https://orcid.org/0009-0004-3146-8025

Magdalena Huyskens
Geological Survey of Norway
https://orcid.org/0000-0003-0546-320X

Trond Slagstad
Geological Survey of Norway NGU
https://orcid.org/0000-0002-8059-2426

Alf Tore Hommedal
University Museum in Bergen, Department of Cultural History
https://orcid.org/0000-0003-0319-7497

Gitte Hansen
University Museum in Bergen, Department of Cultural History
https://orcid.org/0000-0002-9361-1745

Abstract: Archaeological excavations have revealed the existence of a deserted medieval town and trading place named Borgund, near Ålesund, Norway. Borgund, now a greenfield site, boasted three or four churches in its heyday. Worked marble blocks at the excavation site, some with architectural details, and in the last remaining church suggest that some of the churches were built of marble ashlars, probably in the 12th century. The present investigation aims to identify the geological source of the marble ashlars from Borgund and compare the results with marble found in other medieval churches and church ruins in the Sunnmøre district. Samples were collected from 12 marble deposits and six churches/ruins. Since all the relevant marble deposits in the region are mineralogically and texturally similar, provenance sourcing could not be carried out visually or by petrographic examination alone. Moreover, modern quarrying of marble for lime mortar has eradicated traces of medieval marble extraction. Consequently, we studied the provenance of the marble using C, O and Sr isotopic analyses. The isotopic data provided evidence for a major source of marble for the Borgund Churches, most likely the nearest sizeable marble deposit. Other churches in the region displayed different isotopic signatures, indicating that several marble quarries were employed in the 12th century, showing a complex pattern of resource acquisition.

Keywords: marble; medieval; church; provenance

Key points:

White, coarse-grained marble was applied in construction of several medieval churches in the Møre and Romsdal county, west Norway.

The provenance of the marble is established through analyses of isotopic ratios ($δ_{13}C$ versus $δ_{18}O$ and $^{87}Sr/^{86}Sr$) in samples from churches and church ruins and a number of potential quarry sites.

The interpretation of results points to a diversity of quarries used, predominantly sizeable marble deposits in proximity to the church sites.

Resumen: Diversas excavaciones arqueológicas han revelado la existencia de una ciudad medieval y un lugar de comercio llamado Borgund, cerca de *Ålesund*, Noruega. Borgund, en la actualidad, un sitio en campo abierto, contaba con 3 o 4 iglesias en su apogeo. Bloques de mármol, algunos con detalles decorativos, encontrados en el lugar de la excavación y sillares pertenecientes a la *última* iglesia existente, sugieren que algunas iglesias fueron construidas con sillares de mármol, probablemente en el siglo XII. El objetivo de la presente investigación es identificar la procedencia geológica del mármol y comparar los resultados con el encontrado en otras iglesias y ruinas de iglesias medievales en la región. Se recogieron muestras de numerosos depósitos de mármol y de seis iglesias/ruinas. Dado que todos los afloramientos de mármol en la región son mineralógicamente y texturalmente similares, no se pudo llevar a cabo la determinación de la procedencia visualmente ni mediante composición petrográfica. Además, la explotación moderna de canteras de mármol para mortero de cal ha erradicado las huellas de las canteras de mármol medievales. En consecuencia, se estudió la procedencia del mármol mediante su composición isotópica (C, O y Sr). Del estudio comparativo con los afloramientos regionales se evidencia una procedencia mayor de mármol para las iglesias de Borgund, probablemente el afloramiento de mármol más cercano de gran tamaño. Otras iglesias en la región mostraron señales diferentes, lo que indica que se utilizaron varias canteras de mármol en el siglo XII, evidenciando un patrón complejo de adquisición de recursos.

Palabras clave: Mármol; Medieval; iglesia; procedencia

Puntos clave:

Se utilizó mármol blanco de grano grueso en la construcción de varias iglesias medievales en el condado de Møre y Romsdal, en el oeste de Noruega.

La procedencia del mármol se establece mediante la comparación de los análisis de proporciones isotópicas ($δ_{13}C$ versus $δ_{18}O$ and $^{87}Sr/^{86}Sr$) en muestras de iglesias y sus ruinas y las obtenidas en varios sitios potenciales de cantera.

La interpretación de los resultados apunta a que se utilizaron diversas canteras, predominantemente depósitos de mármol de gran tamaño localizados en las proximidades de las iglesias.

Recived: 29-05-2024 / **Accepted**: 06-05-2026 / **Published**: 17-07-2026

Citation: Heldal, T., Storemyr, P., Huyskens, M., Slagstad, T., Hommedal, A. T., Hansen, G. (2026). Linking 12th century churches and marble quarries in Norway using C, O and Sr isotope ratios. Boletín Geológico y Minero, 137(1), 006. http://dx.doi.org/10.21701/bolgeomin/137.1/006

Supplementary information ↓

1. INTRODUCTION

Archaeological excavations have revealed the existence of the deserted medieval town Borgund, near Ålesund, in the Sunnmøre district of the Møre and Romsdal county, Norway (Figure 1). Borgund was one of only 16 towns during the Middle Ages in Norway (Helle, 2006, p 42.). With the transition from the Viking Age to the Middle Ages (mid 10th century - early 12th century) Christianity was introduced and a central kingdom was established. Alongside these changes a new generation of towns also emerged in the country, which had so far been little urbanised (Helle, 2006). Borgund was one of the new towns. Our understanding of the driving forces and associated actors behind investments in smaller and medium-sized Norwegian towns, such as Borgund, remains limited. However, studies show that investments made by kings and institutions in churches and other monuments were fundamental for the establishment and upkeeping of the large, and still-existing, towns as centers of administration and hubs in trade networks (e.g., Hansen, 2005, Andersson *et al.*, 2008). According to written sources Borgund, now a greenfield site, boasted three or four churches during its peak period (Kloster, 1977). The presence of worked marble blocks at the Medieval Museum located at the excavation site (Hommedal, 1988; Haugene, 2020) and by the last remaining church suggests that at least three of these churches were constructed using marble ashlars, probably in the 12th century. The erection of several churches in the early years of Borgund's history indicates that influential individuals or powerful institutions had significant plans for the development and prosperity of the town. However, due to the scarcity of written sources in Norway, the identities of those behind the early investments in Borgund remain unknown. Geological provenancing of raw materials such as stone for millstones or soapstone used for churches in combination with studies of ownership to land and quarries has proven fruitful when addressing actors behind large initiatives/building projects in the Middle Ages (Baug, 2002, 2013, 2015; Berglund *et al.*, 2017; Hommedal, 2017). By identifying the sources of building materials used in the 12th century churches of Borgund and the surrounding region, we can gain new insights into the region's marble production and procurement networks and the town's connections to these networks. When combined with subsequent studies on quarry ownership, the new geological data may serve as a catalyst for a more comprehensive understanding of the actors – influential persons or institutions – involved in Borgund's early history, and the situatedness of these actors in the region.

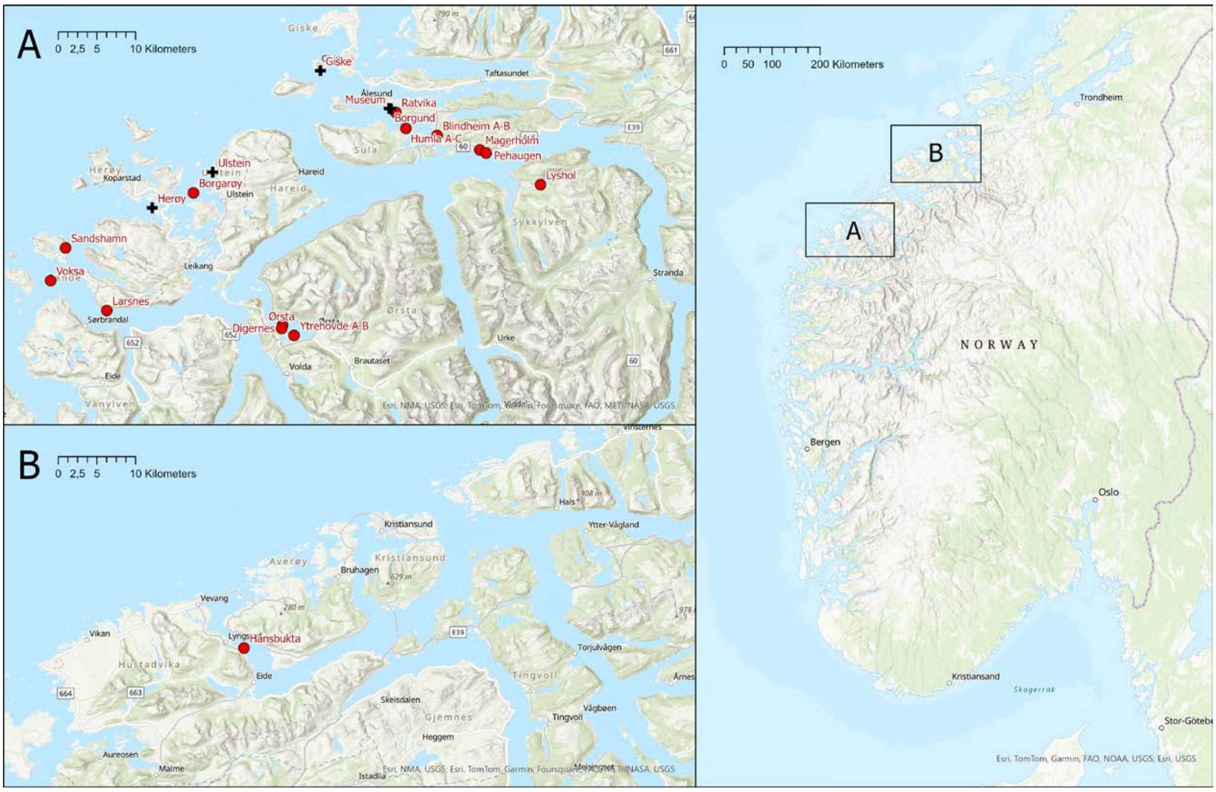


Figure 1. Map displaying sampled marble deposits/quarries (red dots) and churches (black crosses).

Figura 1. Mapa de localización de los depósitos/canteras de mármol e iglesias estudiados.

2. MARBLE DEPOSITS IN THE MØRE AND ROMSDAL COUNTY

The bedrock geology of the Møre and Romsdal County is part of the Western Gneiss Region, predominantly composed of Proterozoic to Palaeozoic rocks that have undergone eclogite-facies metamorphism (Krogh, 1977, Dobrzhinetskaya *et al.*, 1995; Roberts, 2003; Hacker & Gans, 2005, see summary in Kylander-Clark *et al.*, 2009) during the late Silurian to Early Devonian Caledonian orogeny. Collision between the ancient continents Baltica and Laurentia caused continental subduction of the former beneath the latter. This caused deep burial of the Baltican margin causing eclogite formation, and subsequently post-orogenic uplift with several stages of retrograde metamorphic events.

The rocks can be subdivided into two distinct units: 1) late Palaeoproterozoic high-grade gneisses of varying composition, from granitic to gabbroic, including eclogite, and 2) Neoproterozoic to Palaeozoic supracrustal rocks including mica schist, amphibolite and calcite marble. The latter occurs as inlayers, strongly folded and sheared, in the former.

Krill (1980) correlated the supracrustal rocks with the Oppdal area further inland, and interpreted the whole unit as a nappe, named the Blåhø Nappe.

Thus, the marble occurrences (Figure 1), along with the other rock types in the region, suffered a complex metamorphic evolution, from ultra high-pressure conditions to various stages of retrogression during exhumation (Andersen, 1998; Walsh *et al.*, 2013). Consequently, all the marble samples from the medieval churches are medium- to coarse-grained calcite marble with no traces of sedimentary features, containing minor amounts of silicates such as quartz, white mica, biotite and very fine-grained aggregates of sericite and possibly zoisite. Studies of marble thin sections from the church remains and the potential quarry locations failed to provide significant indicators for provenance, in our view because of the total obliteration of primary features in the marble related to its long and extreme tectonometamorphic history (Figure 2). Likewise, differences in whole-rock geochemistry were considered to be non-conclusive, since variations within one deposit can be larger than systematic variations between different deposits. Thus, there was a need for other analytical methods illuminating aspects "surviving" the impact of the tectonometamorphic evolution and independent of the silicate content. Therefore, it was decided to try C, O and Sr isotope composition within the carbonate grains, which is supported by previous studies.

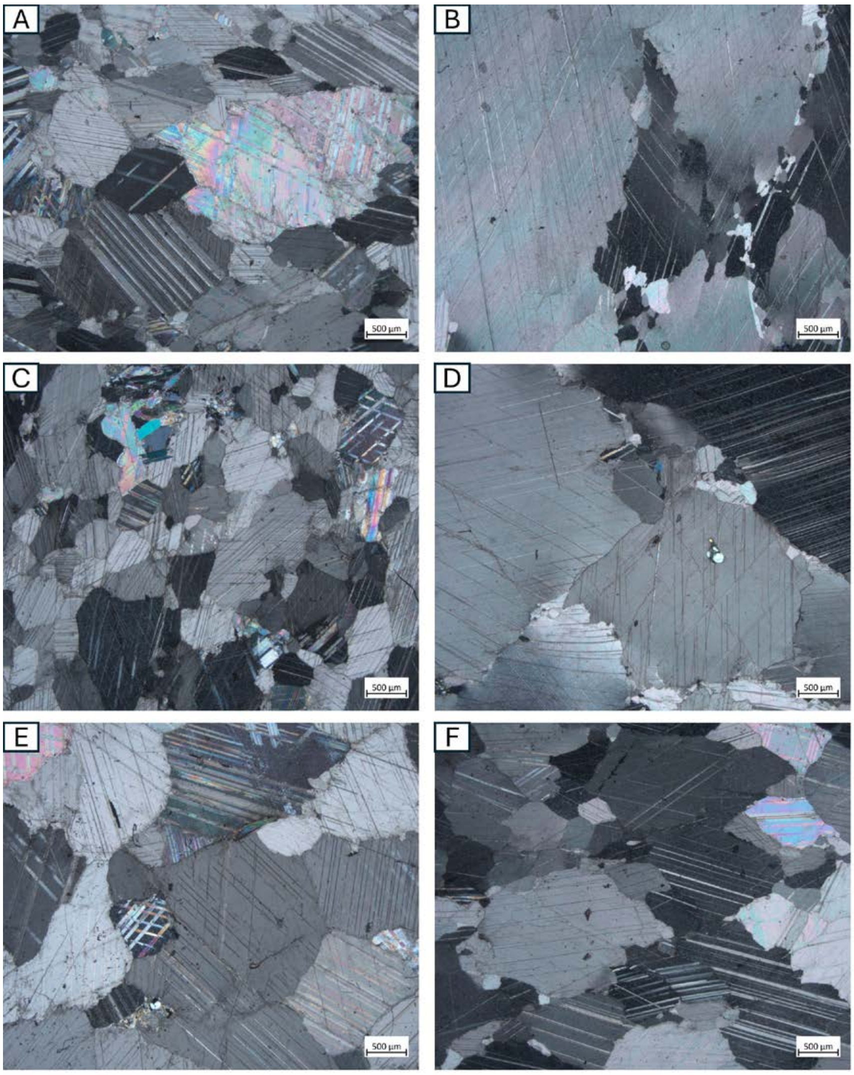
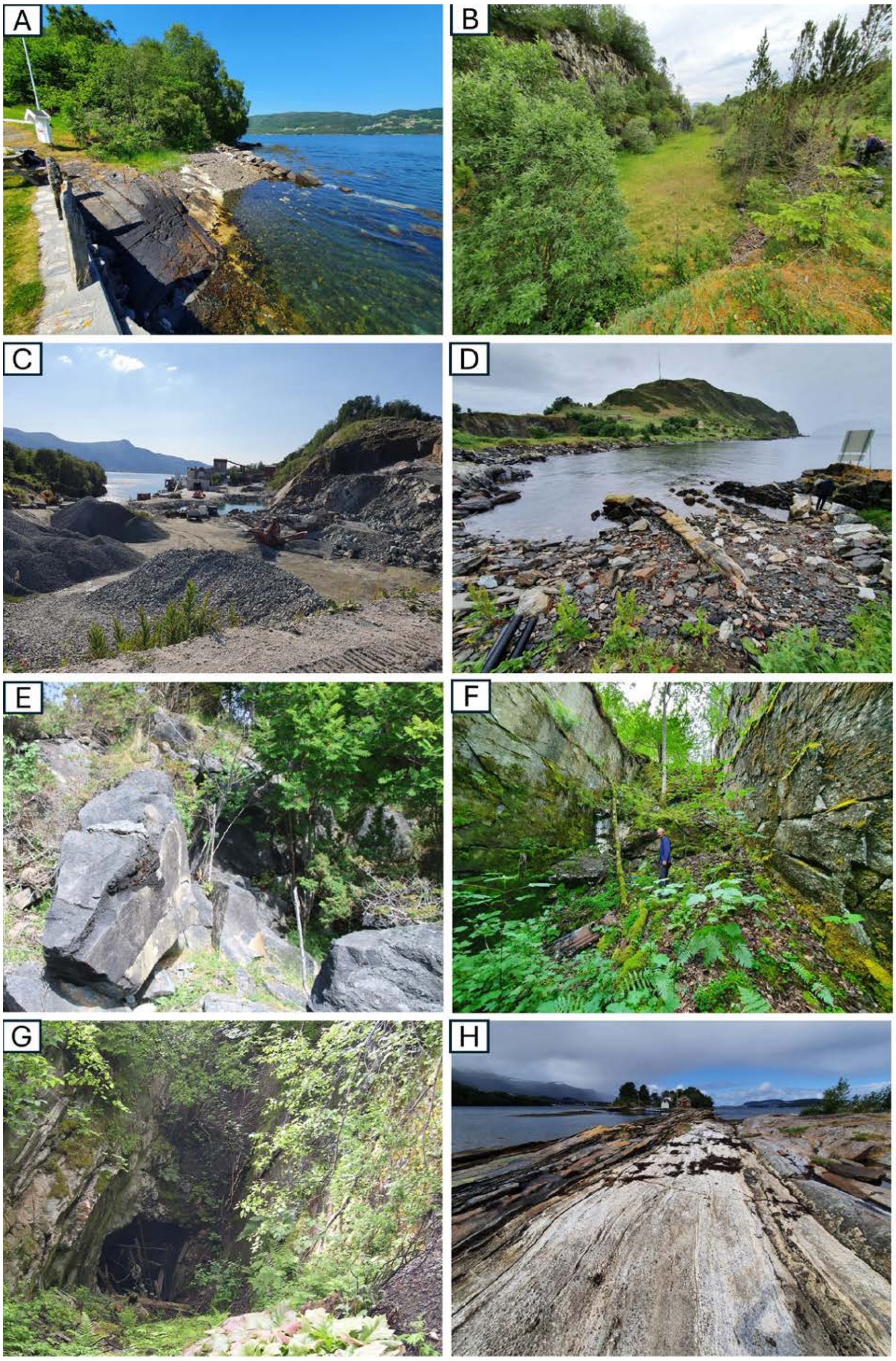


Figure 2. Examples of microscopis features in the marble, thin sections, crossed polars.
A-B) samples from Borgund churches, C-D) Humla quarries, E) Voksa quarry, F) Larsnes quarry.

Figura 2. Ejemplos de características microscópicas en el mármol, secciones delgadas, polares cruzados.
A-B) muestras de iglesias de Borgund, C-D) canteras de Humla, E) cantera de Voksa, F) cantera de Larsnes.

^{13}C - ^{18}O isotope analyses have for a long time been applied to marble provenance. Craig & Craig (1972) were the first who applied the method on classical marble artefacts. Over the years, several archives of isotope data of Mediterranean marble deposits were created (e.g. Herz, 1987) and a database has been made available (Prochaska & Attanasio, 2022). The method was also well described in Herz & Waelkens (1988). Over the years a significant archive of analytical data has been created.

Herz *et al.* (1982) initiated the use of ^{87}Sr/^{86}Sr ratios as a "discriminant for classical marble provenance". Later studies on a growing pool of samples around the Mediterranean concluded that ^{87}Sr/^{86}Sr ratios alone were not satisfactory for marble provenance, but that "the strontium isotope ratios could give a valuable contribution to solving particular cases of discrimination when combined with other methodologies" (Castorina *et al.*, 1997). Later studies have confirmed this and contributed to a growing database of strontium ratios (Brilli *et al.*, 2005).



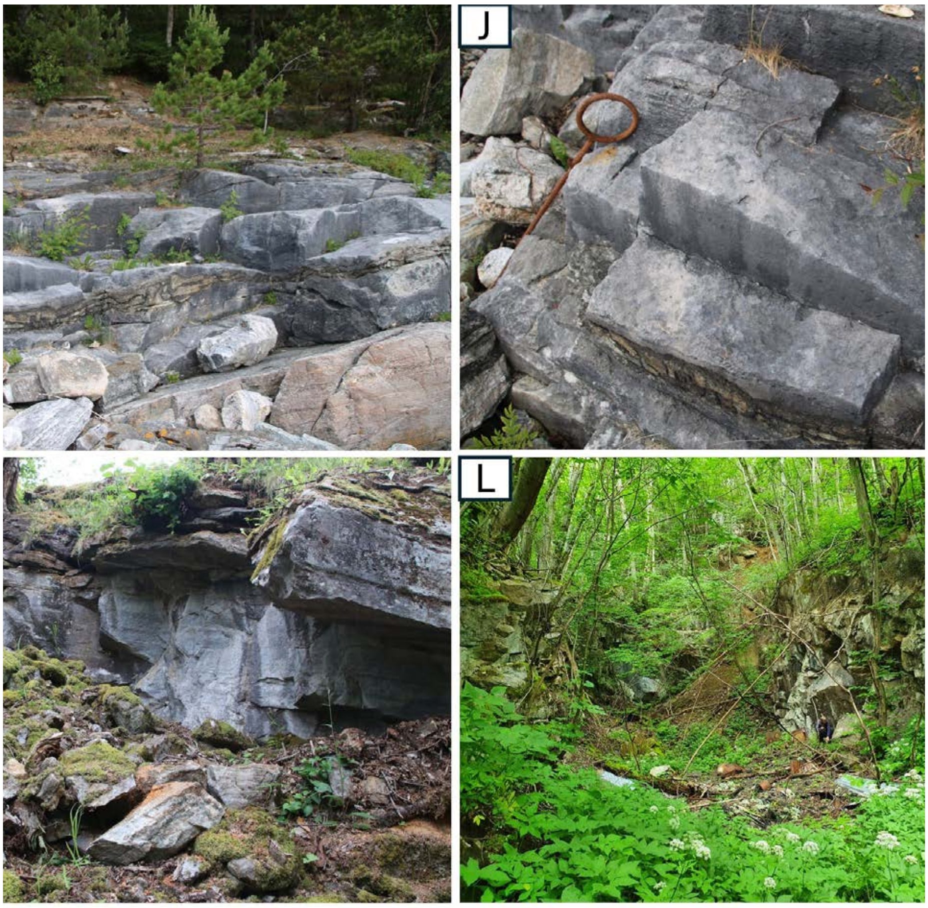


Figure 3. Photos from selected marble deposit sites: A) Hansbukta, B) Voksa, C) Larsnes, D) Sandshamn, E) Borgarøy, F) Ytrehovde, G) Digernes, H) Humla, I) Pehaugen, J) Pehaugen possible wedge marks, K) Magerholm, L) Lyshol. See Table 1 for further information.

Figura 3. Imágenes de los depósitos de mármol seleccionados: A) Hansbukta, B) Voksa, C) Larsnes, D) Sandshamn, E) Borgarøy, F) Ytrehovde, G) Digernes, H) Humla, I) Pehaugen, J) Pehaugen posibles marcas de cuña, K) Magerholm, L) Lyshol. Consulte la Tabla 1 para obtener más información.

3. METHODS

3.1. Fieldwork and sampling

3.1.1. Marble deposits and quarries

In the medieval period, marble was exploited in the county for both natural building stone and most likely for lime mortar employed in the same constructions. Later on (peaking in the 19th and 20th century), numerous quarries were exploited for lime burning, feeding kilns in the district and across Norway (Heltzen, 1996). At present, there are three active marble quarries in the county, producing marble powder for agricultural and industrial uses (NGU, https://www.ngu.no/).

The massive exploitation of marble after the medieval period has most likely obliterated any trace of primary production of masonry units for the medieval churches. At least, we have not yet found any such traces, with a possible exception at Pehaugen (see below). Thus, the sampling aimed at covering all marble deposits that lie close to the sea in the county. This choice was made assuming that the medieval builders had a strong preference for the easy logistics (boat transport) near-sea deposits would provide.

From this criterium, we selected 12 marble deposits (Figure 1, Figure 3, Table 1, Annex 1). Between four and 15 samples were obtained from each site. In total, 86 samples were collected from marble deposits.

Figure 4. Selection of church sites sampled. A) Giske church with marble ashlars, probably 1960-70s (photo: Directorate for Cultural Heritage). B) Detail of marble ashlars at Giske church 1971 (Photo: H.-E. Lidén, Directorate for Cultural Heritage). The church is presently plastered. C) Borgund Kaupang site, Medieval Museum, marble blocks on exterior display (samples Museum 1-5). D) Ulstein site, stone enclosing wall with reused marble from the medieval church, now a faint ruin inside the wall. E) Herøy site, foundation walls of 19th century church with reused marble from the now vanished medieval church nearby. F) Detail of reused marble ashlars at the Herøy site. G and H) Examples of chipped off marble fragments for analyses; samples Museum 2 (left) and Borgund 4, cf. Table 2.

Figura 4. Selección de los lugares de las iglesias muestreadas. A) Iglesia de Giske con sillares de mármol, probablemente de los años 1960-70 (foto: Dirección de Patrimonio Cultural). B) Detalle de sillares de mármol de la iglesia de Giske 1971 (Foto: H.-E. Lidén, Dirección de Patrimonio Cultural). La iglesia actualmente está revocada. C) Sitio de Borgund Kaupang, Museo Medieval, bloques de mármol expuestos al exterior (pruebas del Museo 1-5). D) Sitio de Ulstein, muro de piedra con mármol reutilizado de la iglesia medieval, ahora prevalece una escasa ruina dentro del muro. E) Sitio de Herøy, muros de cimentación de una iglesia del siglo XIX con mármol reutilizado de la cercana iglesia medieval ya desaparecida. F) Detalle de sillares de mármol reutilizados en el yacimiento de Herøy. G y H) Ejemplos de fragmentos de mármol desprendidos para análisis; pruebas Museo 2 (izquierda) y Borgund 4, cf. Tabla 2.

Table 1. Overview of marble deposit/quarries sampled in this study.
See Figure 1 for location and Appendix 1 for detailed sample list.

Tabla 1. Descripción general de los depósitos/canteras de mármol muestreados en este estudio. Consulte la Figura 1 para conocer la ubicación y el Apéndice 1 para obtener una lista de muestras detallada.

Quarry/deposit	**Texture**	**Size/features**
Hansbukta	Coarse-grained	Small deposit by the sea, large operating quarry 1 km inland
Ratvika	Coarse-grained	Few outcrops in residential area
Humla	Coarse-grained	Large deposit, distinct marble layer 6 m, abandoned marble mine
Blindheim	Coarse-grained	Unknown size, few remaining outcrops
Magerholm	Coarse-grained	Abandoned marble quarry, small
Pehaugen	Coarse-grained	Abandoned quarry by the shore, evidence of ashlar block extraction,
Borgarøy	Coarse-grained	Two very small extraction sites, possible ashlar
Sandshamn	Coarse-grained	5-6 m marble vein, small extraction site
Voksa	Coarse-grained	Large deposit and large abandoned marble quarry
Larsnes	Coarse-grained	Large deposit and operating marble quarry
Digernes-Ørsta	Fine-grained	<10 m marble vein, two abandoned marble mines
Ytrehovde	Coarse-grained	c. 10 m marble vein, abandoned marble quarry
Lyshol	Coarse-grained	c. 10 m marble vein, abandoned marble quarry

3.1.2. Sampling marble at the Borgund site and other medieval church sites

There were at least seven mainly Romanesque stone churches in the area covered by the Sunnmøre district (Ekroll, 1997; Brendalsmo & Eriksson, 2016). Other than the three or four situated in Borgund (Kloster, 1977), churches were located at Åheim, Herøy, Ulstein and Giske. Three churches are still standing: these are the almost entirely reconstructed St Jetmund's in Åheim, as well as the relatively authentic Giske church, while in Borgund one of the medieval churches, probably St Peter's (hereafter St Peter's) is incorporated in the still standing parish church. The other churches are now faint ruins, with marble stones reused/preserved in on-site, later stone walls (Herøy and Ulstein) or as part of museum collections (Borgund; from St Mary's/St Margareth's and/or St Mattew's and/or a possible Christ's church), see description of stones in Hommedal (1988) and Haugene (2020). There are also some reused marble stones in the cemetery walls by St Peter's in Borgund and by the Giske church. The reason why relatively few marble stones are left at the Borgund site is, presumably, their later use as available raw material for lime burning. Lime burning was important in the region not only for building the medieval churches, but also in later periods (Heltzen, 1996).

Except for the original St Peter's church in Borgund, which seems to have been built with gneiss rubble masonry and with quoins of soapstone (Kloster, 1977), all the churches may to a significant extent have been built from white to greyish white, medium to coarse-grained calcite marble. This includes not only decorative elements like bases, quoins, portals and windows, but also ashlar masonry (Ekroll, 1997; Kloster, 1977). However, interior and some exterior walls may have featured lime-plastered rubble, exemplified today at the reconstructed St Jetmund's church, which is not lime plastered in the interior. The still standing Giske church is entirely built from marble ashlars in exterior masonry, whereas it is difficult to assess its lime-plastered interior. The masonry probably mainly consists of rubble (see Kloster, 1977).

With very few exceptions, marble was not used as building stone to the south of the Sunnmøre district in the Middle Ages, but lime mortars at nearby Selja Monastery were burnt from marble, possibly from Sunnmøre (Storemyr, 2023). North of Sunnmøre, with Tingvoll church in the Nordmøre district (Bryhni, 2006) as the closest, marble for decoration and, sometimes, coursed rubble walls, occurs in medieval churches, not least in Trøndelag county. However, regular marble ashlar masonry is very rare, a feature which makes the Sunnmøre churches exceptional. Generally, the use of marble is closely connected to the occurrence of marble deposits, and commonly also to the absence of major soapstone deposits. Soapstone was the other important stone used for ashlar and decoration along the Norwegian west coast (Ekroll, 1997; Storemyr, 2015; Hansen, 2017).

In this study, marble from five of the church sites were sampled (Figure 4, Table 2, Annex 1): Giske church, loose blocks from the Medieval Museum at the Borgund site, as well as loose blocks in walls surrounding the St Peter's church and the faint ruins of Herøy and Ulstein churches. St Jetmund's church was omitted, mainly due to its reconstruction history and thus difficulties in finding and dating suitable marble blocks for sampling.

The loose blocks at the Medieval Museum have been recovered over several years (see archaeological excavation by Fischer, 1912; Hommedal, 1988) and may belong to any of the churches in general identified as St Mary's/St Margareth's, St Matthew's and Christ's churches. St Peter's church was heavily rebuilt in the 17th century, seemingly with marble stones from St Mary's/St Margareth's church (Kloster, 1977); it is thus not unlikely that remains in the cemetery walls around St Peter's could stem from St Mary's/St Margareth's. Herøy church was demolished in 1859 (Ekroll, 1997), its marble stones reused in the foundations of a new, wooden church nearby. This church was demolished in 1916, but the foundations are still standing. Ulstein church was demolished in 1848 (Ekroll, 1997), but the marble stones were reused, together with other stones, in the wall surrounding the site/cemetery.

After extensive reconnaissance and by permission from heritage authorities, samples of the generally white, coarse-grained crystalline marbles were mainly collected using hammer and chisel to chip off small fragments without damaging decorative parts or other historically important remains (tool marks, inscriptions etc.) (see details in Table 1).

Table 2. List of marble sample locations at church sites. Coordinates are approximate (within c. +/-1 m). Samples are either fragments chipped from blocks with hammer and chisel to leave minimal damage, outside of decorative parts, or entirely loose, small fragments without decoration. Sample size is normally c. 5-10 x 5-10 x 2-5 cm. Permission for sampling was granted by Møre og Romsdal fylkeskommune in letter of 20.10.2020, ref. no. 2020/13893 - 134206/2020). Samples and photos are stored at the Geological Survey of Norway. Notes: (1) Marble stones likely taken from Giske church during previous restorations. (2) Marble stones likely from St. Margareth's church, St. Matthew's and Christ's churches (description of stones in Hommedal 1998 and Haugene 2020). (3) Marble stones perhaps from St. Margareth's church during restorations works in the 17th century (cf. Kloster, 1997).

Tabla 2. Lista de ubicaciones de pruebas de mármol en sitios de iglesias. Las coordenadas son aproximadas (dentro de c. +/-1 m). Las pruebas son fragmentos astillados de bloques con martillo y cincel para dejar un daño mínimo, fuera de las partes decorativas, o fragmentos pequeños completamente sueltos sin decoración. El tamaño de la pruebas es normalmente de c. 5-10 x 5-10 x 2-5 cm. Se concedió permiso para tomar pruebas por Møre og Romsdal fylkeskommune en la carta del 20.10.2020, ref. no. 2020/13893 - 134206/2020). Las pruebas y las fotos se almacenan en el Servicio Geológico de Noruega. Notas: (1) Piedras de mármol probablemente tomadas de la iglesia de Giske durante restauraciones anteriores. (2) Piedras de mármol probablemente de la iglesia de Santa Margarita, las iglesias de San Mateo y Cristo (descripción de las piedras en Hommedal 1998 y Haugene 2020). (3) Piedras de mármol quizás de la iglesia de Santa Margarita durante los trabajos de restauración en el siglo XVII (cf. Kloster, 1997).

<table>
<tr><th>Sample no.</th><th>Sampling date</th><th>Coordinates (UTM 33)</th><th>Photo no.</th><th>Description of location/samples</th></tr>
<tr><td colspan="5">Giske church site. ID 84245-1</td></tr>
<tr><td>Giske 1 and 2</td><td rowspan="5">09.06.2021</td><td>6961679 N, 39985 E</td><td>9455-58</td><td>Fragment of loose blocks by stone wall and modern rest rooms 10 m due S of the church nave (1)</td></tr>
<tr><td>Giske 3</td><td>6961688 N, 39987 E</td><td>9459</td><td>Fragment of base block at the SW corner of the nave</td></tr>
<tr><td>Giske 4</td><td>6961686 N, 40003 E</td><td>9460</td><td>Fragment of base block at the S side of the choir</td></tr>
<tr><td>Giske 5</td><td>6961685 N, 39953 E</td><td>9461</td><td>Loose piece in cemetery wall, W of the church (1)</td></tr>
<tr><td>Giske 6</td><td>6961702 N, 39953 E</td><td>9462</td><td>Fragment of loose block in cemetery wall, W of the church (1)</td></tr>
<tr><td colspan="5">Borgund Kaupang site, Medieval Museum, marble blocks on exterior display. ID 91851-1</td></tr>
<tr><td>Museum 1</td><td rowspan="5">09.06.2021</td><td rowspan="5">6956755 N, 49134 E</td><td>9464-65</td><td rowspan="5">Fragments of loose blocks retrieved during past archaeological excavations of church ruins at Borgund Kaupang, now located E of the entrance to the museum (2).</td></tr>
<tr><td>Museum 2</td><td>9466-67</td></tr>
<tr><td>Museum 3</td><td>9469-69</td></tr>
<tr><td>Museum 4</td><td>9470-71</td></tr>
<tr><td>Museum 5</td><td>9472-73</td></tr>
</table>

Borgund church site (St. Peter's church). ID 83932-1				
Borgund 1	09.06.2021	6956783 N, 48880 E	9474-76	Loose piece in cemetery wall, SW of the church (3)
Borgund 2		6956793 N, 48886 E	9477-78	Loose piece by large marble ashlar in cemetery wall, W of the church (3)
Borgund 3		6956805 N, 48913 E	9479-80	Loose piece on the ground by the E transept, S side
Borgund 4		6956790 N, 48872 E	9481-84	Fragment of loose stone in cemetery wall, WSW of the church
Herøy church site. ID 84565-1				
Herøy 1	10.06.2021	6943944 N, 18271 E	9497	Loose piece in foundation wall, S side of choir
Herøy 2		6943944 N, 18270 E	9498	Loose piece of ashlar in foundation wall, S side of choir
Herøy 3		6943945 N, 18274 E	9499-9501	Loose piece in the staircase, S side of choir
Ulstein church site. ID 115114-1				
Ulstein 1	10.06.2021	6948556 N, 26108 E	9502-04	Fragment of loose block by stone wall, SE corner
Ulstein 2		6948564 N, 26036 E	9505-06	Fragment of loose block in stone wall, W side
Ulstein 3		6948577 N, 26064 E	9507	Fragment of loose block in stone wall, N side
Ulstein 4		6948569 N, 26111 E	9508-09	Fragment of loose block in stone wall, E side

3.2. Carbon and oxygen stable isotopic analyses

For carbon and oxygen isotopic analyses, powder from samples were collected with fine drilling equipment, sealed in small plastic sample containers at the Geological Survey of Norway, and shipped to the University of Tartu, Estonia. Stable isotope analyses were conducted using a GasBench II sample preparation device coupled to a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer (IRMS). Samples were dissolved in >99% phosphoric acid with a reaction time of >8 hours to ensure complete dissolution of carbonate minerals. Analyses were calibrated against the standard reference materials NBS 18, IAEA 603, LSVEC, and IAEA 611, with 1σ uncertainties smaller than ± 0.2‰.

3.3. Sr isotope analyses

Samples cast in epoxy were analysed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for Sr isotopes in the Mimac lab (Mineral and Materials Characterisation) at the Geological Survey of Norway. The samples were ablated with a Teledyne-Cetac Analyte Excite 193 nm excimer laser equipped with a HelEx II two-volume cell. Ablations were carried out in a He atmosphere, and the sample aerosol was transported to a Nu Plasma 3 for Sr isotope analyses. Additional Ar was added to the sample-He mixture in a glass mixing bulb before the plasma torch. Samples were ablated as spots with a diameter of 85 µm. The ablations were performed with a frequency of 10 Hz and an energy of 4 J/cm2. All masses from 82-88 were measured on Faraday cups coupled to 1011 Ω amplifiers including half masses for interference corrections. As a primary reference material, a mollusk with presumed modern-day ocean Sr isotope composition ($^{87}Sr/^{86}Sr$ = 0.70918, McArthur *et al.*, 2001) was used. Data reduction was carried out in Iolite 4. The DRS "Sr isotopes universal" (Mulder *et al.*, 2023) was chosen using the marine mollusk as the primary reference material. Baselines were measured on peak and are subtracted from all masses, which includes krypton interferences. The mass bias for Sr is calculated based on the Kr-corrected $^{86}Sr/^{88}Sr$ ratio for the primary reference material. The interference of ^{87}Rb on ^{87}Sr is corrected based on the measured 85Rb and calculating the fractionation factor of Rb in the fused reference glass BCR-2G. For both fractionation corrections, an exponential law was assumed. No subtraction of REE interferences or CaAr or CaCa dimers was performed as these are low. We monitored two in-house reference calcite materials and one basaltic glass to monitor the efficacy of the Rb interference correction. A marine foraminifera assumed to reflect modern seawater composition gave $^{87}Sr/^{86}Sr$ value of 0.709188 ± 0.000017 (MSWD = 0.26, n = 54, reference value of 0.70718), a chalk gave a value of 0.707878 ± 0.000028 (/MSWD = 0.41, n = 54, reference value of 0.70786, Thomsen & Andreasen (2019)). The basaltic glass BHVO-2G gave $^{87}Sr/^{86}Sr$ value of 0.70363 ± 0.00014 (MSWD = 0.16, n = 54, reference value of 0.703487 (Weiss *et al.*, 2006)). Additional explanations about analytical conditions are summarised in Annex 3, analyses in Annex 4.

4. RESULTS

The carbon and oxygen isotope data are shown in figures 5 and 6. Annex 2 shows the values. The Sr isotope results are summarised in Figure 7 and values are displayed in Annex 4.

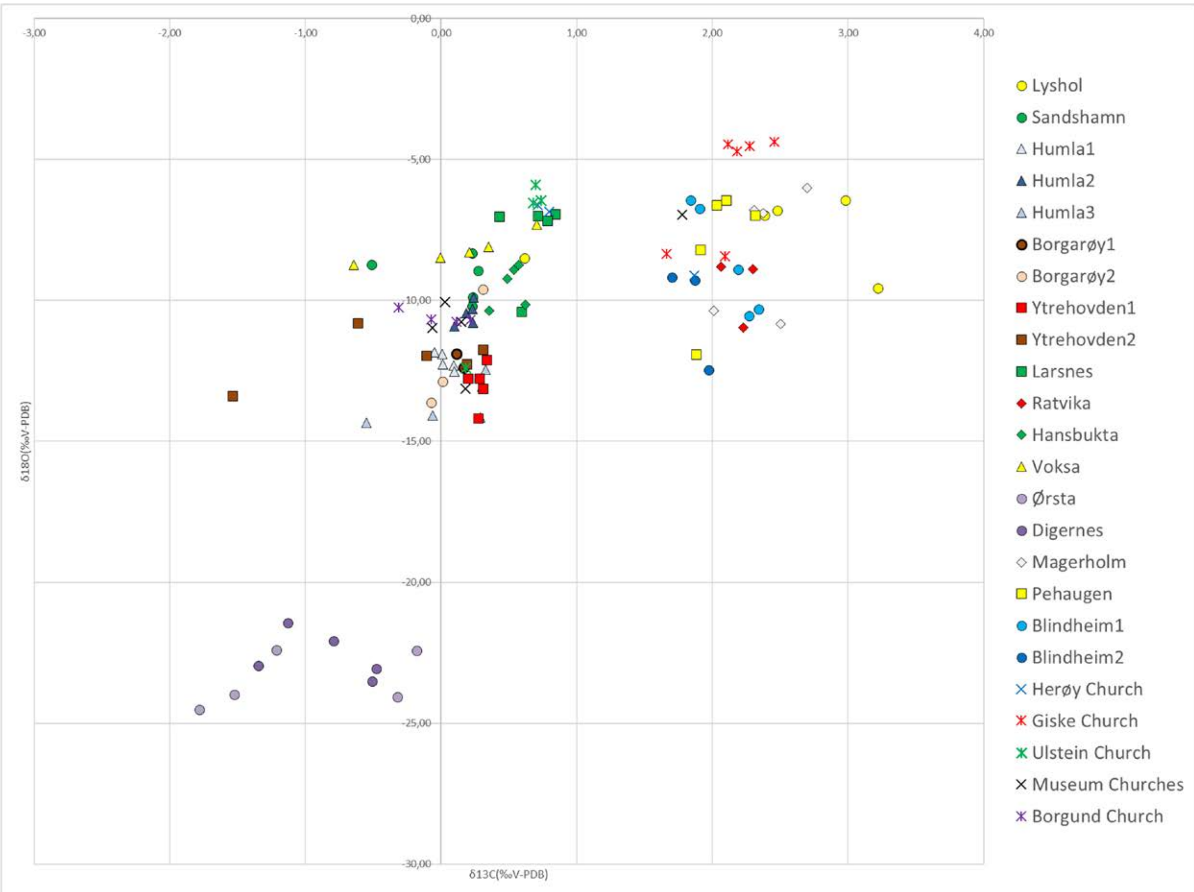


Figure 5. δ_{13}C versus δ_{18}O diagram of marble samples from quarries and churches.

Figura 5. δ_{13}C versus δ_{18}O diagrama de muestras de mármol de canteras e iglesias.

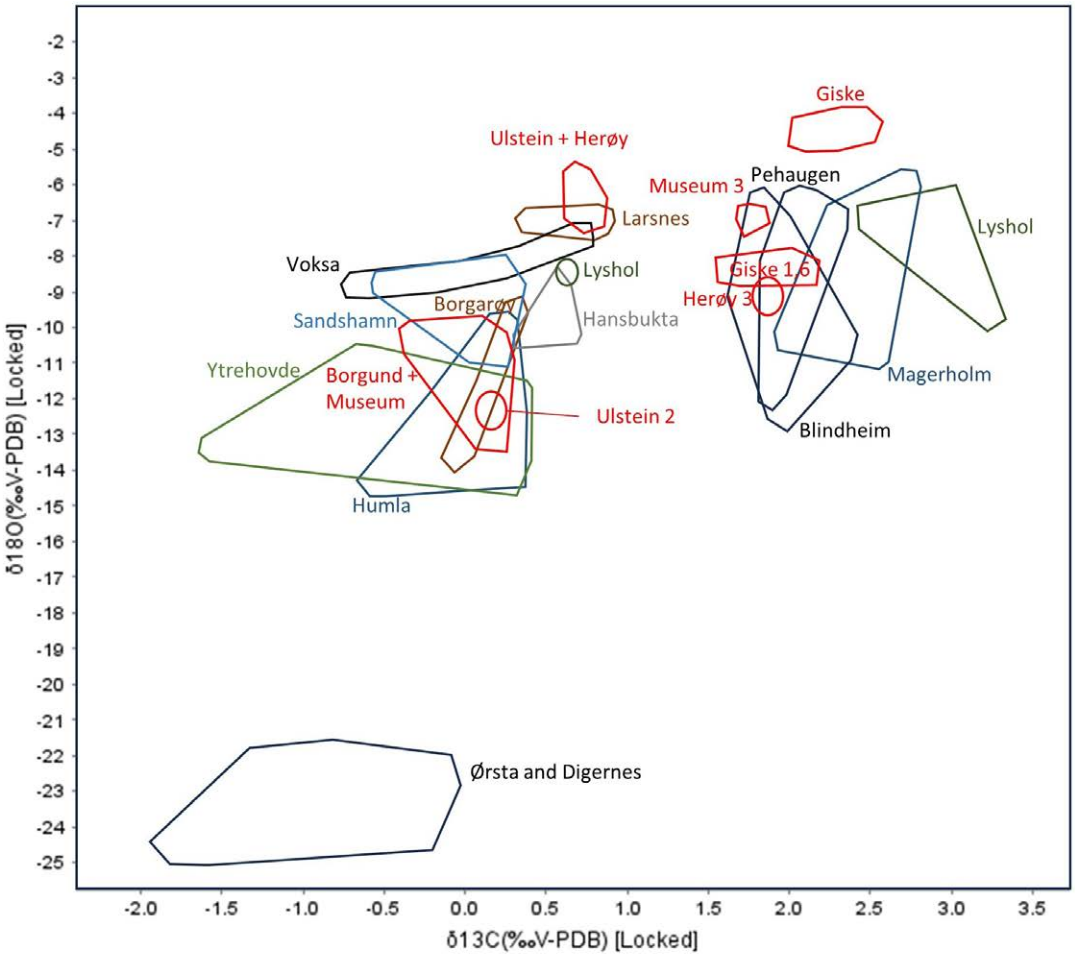


Figure 6. Delineated isotopic fields ($\delta_{13}C$ versus $\delta_{18}O$) of samples from quarries and churches (red lines and text).
Figura 6. Campos isotópicos delineados ($\delta_{13}C$ versus $\delta_{18}O$) con las muestras de canteras e iglesias (líneas y texto rojos).

The $\delta_{13}C$ - $\delta_{18}O$ analyses clearly show patterns where both quarries and churches form clusters, indicating that the dataset is valid for marble provenance.

The $^{87}Sr/^{86}Sr$ values range from 0.70737 to 0.71159, and churches define rather narrow ranges with considerable overlap, and we also consider these data as valid allowing them to be used in conjunction with $\delta_{13}C$ - $\delta_{18}O$.

The $\delta_{13}C$ - $\delta_{18}O$ isotope data defines three separate clusters (figures 5 and 6) that roughly reflect the geographical position of the marble deposits: one eastern cluster, one western and one southern. The southern cluster (fine-grained varieties of marble included for testing the discrimination of quarry data) does not fit any of the isotope ratios from the churches and will not be considered further.

Most of the Medieval Museum samples and the samples of blocks in walls surrounding the St. Peter's church display $\delta_{13}C$ - $\delta_{18}O$ isotope compositions similar to several quarries: Humla, Sandshamn, Ytrehovde and Borgarøy, where Humla is the best fit. $^{87}Sr/^{86}Sr$ values exclude Borgarøy; hence, although the Humla deposit seems to be the one with the best fit for all the church samples (excluding sample Museum 3, see below), we cannot exclude Sandshamn and Ytrehovde.

One sample from the Medieval Museum (Museum 3) displays deviating $\delta_{13}C$ - $\delta_{18}O$ values, plotting in the Blindheim field and close to the Pehaugen and Ratvika field. $^{87}Sr/^{86}Sr$ values exclude Pehaugen, leaving Blindheim and Ratvika as the most likely provenance.

The samples from Giske church define two distinct groups. Four samples (Giske 2, 3, 4, 5) plot above the fields defined by quarry analyses, and two samples (Giske 1, 6) plot within the overlapping fields of Magerholm, Ratvika, Blindheim and Pehaugen. A similar clustering is found in plots including $^{87}Sr/^{86}Sr$. Giske 2, 3, 4, 5 plot close to the same four quarries, whilst Giske 1 and 6 only plot near Magerholm. Given that all Giske samples plot within or near the Magerholm cluster in Figure 7, we consider it likely that the Magerholm quarry could have been the source for all Giske samples.

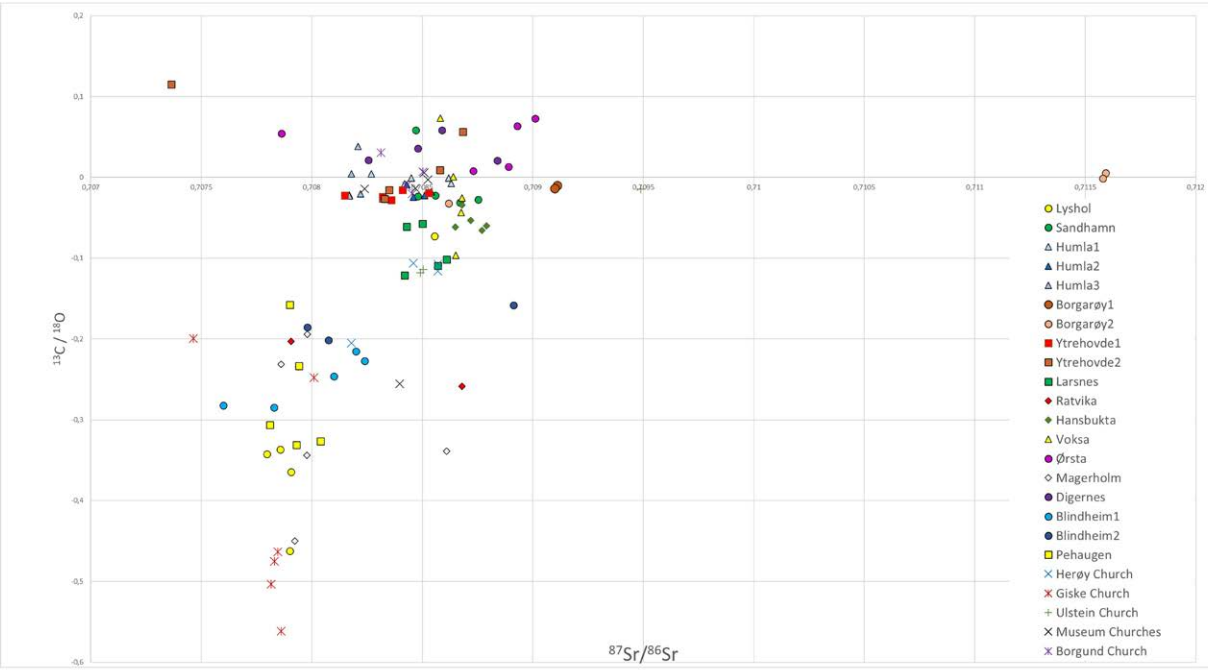


Figure 7. ^{13}C / ^{18}O - $^{87}Sr/^{86}Sr$ plot of marble from quarries and churches.
Figura 7. ^{13}C / ^{18}O - $^{87}Sr/^{86}Sr$ de las muestras de mármol de canteras e iglesias.

The majority of samples from the Ulstein and Herøy churches plot tightly together in or close to the Larsnes field. A weaker possibility is Voksa. Thus, we suggest Larsnes to be an important source of ashlar to both these churches.

One stone from Ulstein church (Ulstein 2) plots in or near the $\delta_{13}C$ - $\delta_{18}O$ fields for Humla, Ytrehovde and Borgarøy. $^{87}Sr/^{86}Sr$ values do, however, exclude it from all these sources except Borgarøy. Thus, we think that at least one stone from Borgarøy was used in Ulstein Church.

One stone from Herøy church (Herøy 3) plots close to the two isolated Giske samples in the ^{13}C - ^{18}O diagram, within the overlapping fields of the Blindheim, Ratvika, Magerholm and Pehaugen quarries. However, $^{87}Sr/^{86}Sr$ also suggest Blindheim as the strongest link, Thus, we conclude that Blindheim is a second source to Herøy church but cannot exclude the other candidates.

The most likely source(s) of marble for the different churches are illustrated on the map in Figure 8.

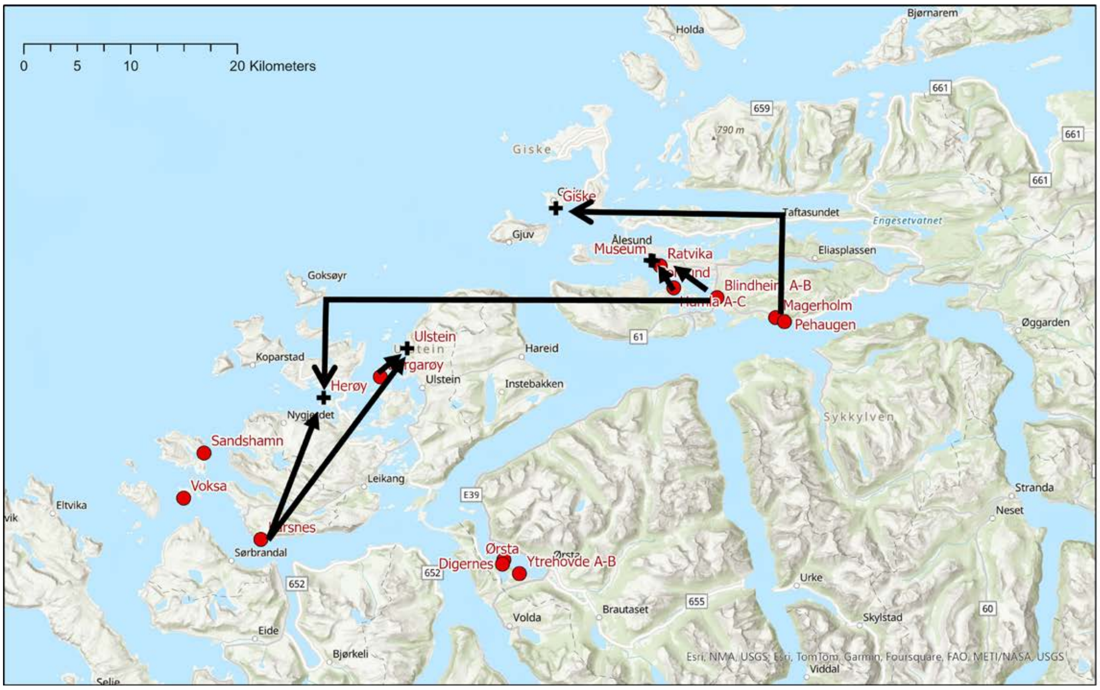


Figure 8. Map showing most likely sources of marble (red circle) to the churches (black cross).
Figura 8. Mapa que muestra el origen más probable del mármol (círculo rojo) para las iglesias (cruz negra).

5. DISCUSSION

5.1. Data interpretation

The present study is the first scientific attempt to use ^{13}C - ^{18}O and $^{87}Sr/^{86}Sr$ ratios for discriminating between Norwegian marble artefacts. Since the relevant marble deposits have undergone high-grade metamorphism and thus appear similar in hand specimens and thin sections, it was our hope that isotope ratios could provide a basis for correlating church building materials with possible source quarries.

This study concludes that C and O isotopes provide satisfactory discrimination between samples from deposits and churches, because deposits and churches form clearly identifiable clusters, although partly overlapping each other. $^{87}Sr/^{86}Sr$ ratios show more overlap, in line with previous studies mentioned above, and thus provide an additional test of the information gleaned by $\delta_{13}C$ - $\delta_{18}O$ data. The study also confirms that LA-ICP-MS is a valid method for Sr isotope analyses on calcite grains.

5.2. Multiple sources of marble and varying distance between quarry and consumer sites

Some immediate cultural historical conclusions drawn from the present study are very interesting. One is that the medieval marble churches in the Sunnmøre district were built from a diversity of marble sources, not one central quarry provided stone for them all. Another is the distance between quarries and consumer sites: The marble in the churches at Borgund seems predominantly to originate from one source, most likely the nearest sizeable one, Humla. But at least one sample has a different origin. Both Herøy and Ulstein churches also hold marble from nearby, sizeable deposits (Larsnes). However, they both contain additional stones from other sources, in the Ulstein case, from the nearest source, which is a very small deposit. It may be that these scarce stones represent stages of repairs, rebuilding or extensions at these two church sites. Regarding Giske, the pattern of raw material supply is different since the identifiable marble seems to originate from some more distant source (Blindheim/Magerholm/Pehaugen).

Thus, there is no strict one-to-one relationship between geographical distance between quarries and consumer sites (nearest possible), nor is there evidence of a central quarry site supplying all the churches. Our study does show that several quarries were employed for the marble churches. This may reflect changes of marble sources over time, issues related to ownership, or a combination of those. There may also have been other considerations at play beyond the more practical ones when procuring the building stone, such as yet unknown social relations.

It seems clear, though, that the marble analyses have succeeded in establishing a likely pattern of the stone acquisition system in medieval church building in the Sunnmøre district. This provides data for further research on the social dimension of quarrying and medieval church building at the Norwegian west coast.

5.3. There is marble – and marble

Marble is, in our modern world, often considered to be a prestigious material, reflecting an excess use of resources for displaying power and wealth. When interpreting the medieval period in Norway, we see a more practical approach to stone types. Where soapstone is readily available, it is used for construction, most likely due to it being a soft rock that is easy to carve. In the Sunnmøre district, there are no sizeable soapstone deposits, and marble remains the softest rock available. The anomaly (in Norwegian context) of building with marble thus may simply relate to the fact that it was the most workable stone available in the area.

6. CONCLUSIONS

The present study has shown that high-grade marble was used in the construction of medieval churches in the Sunnmøre district in the Møre and Romsdal county during the 12th century.

Analyses of the isotopic composition (^{13}C - ^{18}O and $^{87}Sr/^{86}Sr$) of marble from the churches and a range of marble deposits/quarries revealed that several sources of marble were used, in some cases the most proximal sources of sizeable deposits of marble to the individual church sites were used, while in other cases an input of more remote marble sources were observed.

It seems that most of the stone from the three or four churches in the deserted town Borgund had their marble originating from one deposit, most likely the Humla deposit.

The present study has contributed to a better knowledge of the geological environment and probable provenance of marble used for building churches in Borgund and the Sunnmøre district. As often is the case when obtaining deeper knowledge of cultural history, the past is not simple. The picture of connections between places of production and consumption of marble for churches is thus many-facetted. The step forward involving ownership of the quarries and the relationship between actors involved in stone exploitation and those who invested in the erection of churches, in Borgund and subsequently in the prosperity of the new town should be exciting.

Table 3. Interpretation of the diagrams in figures 5 and 6. Most likely candidate quarry in bold.

Tabla 3. Interpretación de los diagramas de las figuras 5 y 6. Cantera candidata más probable en negrita.

Church	^{13}C - ^{18}O	$^{87}Sr/^{86}Sr$	Best fit conclusion
Museum 1, 2,4,5	**Humla**, Sandshamn, Ytrehovde, Borgarøy	**Humla**, Sandshamn, Ytrehovde	**Humla**, Sandshamn, Ytrehovde
Museum 3	**Blindheim**, Pehaugen, Ratvika, Magerholm	**Ratvika**, Magerholm, Blindheim	**Non conclusive**
Borgund 1,2,3,4	**Humla**, Sandshamn, Ytrehovde, Borgarøy	**Humla**, Sandshamn, Ytrehovde	**Humla**, Sandshamn, Ytrehovde
Giske 2,3,4,5	Unknown, Blindheim, Pehaugen, Magerholm	**Blindheim**, Ratvika, Pehaugen, Magerholm	**Blindheim**, Ratvika, Pehaugen, Magerholm
Giske 1,6	**Blindheim**, Pehaugen, Magerholm	**Blindheim**, Ratvika, Pehaugen, Magerholm	Blindheim?
Herøy 1, 2	**Larsnes**, Voksa	**Larsnes**, Voksa	**Larsnes**
Herøy 3	**Blindheim**, **Pehaugen**, Ratvika, Magerholm	**Blindheim**, **Ratvika**, Magerholm Pehaugen	**Blindheim**
Ulstein 1, 3, 4	**Larsnes**, Voksa	**Larsnes**, Voksa	**Larsnes**
Ulstein 2	Humla, Ytrehovde, Borgarøy	**Borgarøy**	**Borgarøy**

Supplementary information ↑

Funding sources

Not applicable.

Supplementary material

Not applicable.

Data availability

Not applicable.

Acknowledgements

The present study is part of the multidisciplinary Borgund Kaupang Project (BKP) which re-assesses the available legacy sources from the Borgund site. Within the BKP economic and cultural prerequisites of Borgund from emergence to abandonment are addressed in sub-studies of a broad specter of datasets including the remains of marble from churches. https://www.uib.no/en/rg/borgund-kaupang.

The study is supported financially by a grant from The Research Council of Norway (NFR 288392). The Norwegian Laboratory for Mineral and Materials Characterisation, MiMaC is supported by the Norwegian research council project number 269842/F50. Thanks also to Aivo Lepland at NGU for help in organising ^{13}C - ^{18}O analyses, and to the University of Tartu, Estonia, for conducting them.

Authorship contribution statement

Tom Heldal: Conceptualization, Formal analysis, Funding acquisition, Investigation, Resources, Writing – original draft, Writing – review & editing.

Per Storemyr: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Magdalena Huyskens: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Trond Slagstad: Formal analysis, Investigation, Methodology, Writing – review & editing.

Alf Tore Hommedal: Writing – original draft, Writing – review & editing.

Gitte Hansen: Funding acquisition, Writing – original draft, Writing – review & editing.

Competing interests

The authors of this article declare that they have no financial, professional, or personal conflicts of interest that could have inappropriately influenced this work.

Statement on the use of Artificial Intelligence

Not applicable.

REFERENCES

Andersen, T. B. (1998). Extensional tectonics in the Caledonides of southern Norway, an overview. Tectonophysics 285, 333-351. https://doi.org/10.1016/S0040-1951(97)00277-1

Andersson, H., Hansen, G. & Øye, I. (2008) (eds.). De første 200 årene - nytt blikk på 27 skandinaviske middelalderbyer. UBAS vol. 5, University of Bergen Archaeological Series. Bergen: University Museum of Bergen & Institute for Archaeology, History, Culture Studies and Religion AHKR, University of Bergen, Norway, pp. 419. https://www.uib.no/ahkr/96654/ubas-nordisk-5-2008

Austrheim, H., Corfu, F., Bryhni, I. & Andersen, T. B. (2003). The Proterozoic Hustad igneous complex: a low strain enclave with a key to the history of the Western Gneiss Region of Norway. Precambrian Research, 120(1-2), 149-175.

Baug, I. (2002). Kvernsteinsbrota i Hyllestad. Arkeologiske punktundersøkingar i steinbrotområdet i Hyllestad i Sogn og Fjordane. Kongsberg: Norsk Bergverksmuseum.

Baug, I. (2013). Quarrying in Western Norway: an archaeological study of production and distribution in the Viking period and the Middle Ages. Bergen: University of Bergen.

Baug, I. (2015). Actors in quarrying. Production and distribution of quernstones and bakestones during the Viking Age and the Middle Ages. In: Hansen, G., Ashby, S. P., Baug, I., (eds.). Everyday products in the Middle Ages Crafts Consumption and the Individual in Northern Europe c. AD 800-1600. Oxford & Philadelphia: Oxbow; 2015. pp. 229-50. DOI.org/10.2307/j.ctvh1dtfs.18

Berglund, B., Heldal, T. & Grenne, T. (2017). From Soapstone Quarries to Churches: Control, Ownership and Transport Along the Helgeland Coast in North Norway. In: Hansen, G., Storemyr, P., (eds.). Soapstone in the North Quarries, Products and People 7000 BC - AD 1700. UBAS University of Bergen Archaeological Series. Bergen: University Museum of Bergen & Institute for Archaeology, History, Culture Studies and Religion AHKR, University of Bergen, Norway. pp. 329-58.

Brendalsmo, J. & Eriksson, J. -E. G. (2016). Kildegjennomgang. Middelalderske kirkesteder i Møre og Romsdal fylke. Report, Riksantikvaren/Directorate for Cultural Heritage, Oslo.

Brilli, M., Cavazzini, G. & Turi, B. (2005). New data of 87Sr/86Sr ratio in classical marble: an initial database for marble provenance determination. Journal of Archaeological Science, 32(10), 1543-1551, https://doi.org/10.1016/j.jas.2005.04.007.

Brueckner, H. K. (1977). A structural, stratigraphic and petrologic study of anorthosites, eclogites and ultramafic rocks and their country rocks, Tafjord area, western South Norway, NGU 332, 1-53 + pl

Bryhni, I. (1989). Status of the supracrustal rocks in the Western Gneiss Region, Gayer, R. A. (ed.). The Caledonide geology of Scandinavia, 221-28.

Bryhni, I. (2006). Bygningssteinen. In M. Stige & Spurkland, T. (eds.) Tingvoll kyrkje. Gåta Gunnar gjorde. Senter for middelalderstudier, Skrifter, 21. Trondheim: Tapir, 129-147.

Castorina, F., Preite Martinez, M. & Turi, B. (1997). Provenance determination of classical marbles by the combined use of oxygen, carbon, and strontium isotopes: a preliminary study. Science and Technology for Cultural Heritage, 6, 145-150.

Craig, H. & Craig, V. (1972). Greek marbles: determination of provenance by isotopic analysis. Science, 176(4033), 401-403.

Dobrzhinetskaya, L. F., Eide, E. A., Larsen, R. B., Sturt, B. A., Trønnes, R., Smith, D. C., Taylor, W. R. & Posukhova, T. V. (1995). Microdiamond in high-grade metamorphic rocks of the Western Gneiss Region, Norway. Geology, 7, 597-600.

Ekroll, Ø. (1997). Med kleber og kalk. Oslo: Samlaget.

Fischer, G. (1912). Fra Borgund gamle kjøpstad. Indberetning om undersøkelse og utgravning av «St. Mariæ kirkegaard». Fortidsminneforeningens årbok, 126-129

Fischer, G. (1912). Indberetning om undersökelse og utgravning av St Mariæ Kirkegård i Borgund. Topografisk arkiv, Gnr 43 bnr.1, Ålesund kommune, Møre Romsdal fylke, Universitetsmuseet i Bergen: University of Bergen, Norway, 4 p.

Gee, D. G. (1980). Basement-cover relationships in the central Scandinavian Caledonides. Förhandlingar, 102(4), 455-474.

Hacker, B. R. & Gans, P. B. (2005). Continental collisions and the creation of ultrahigh pressure terranes: petrology and thermochronology of nappes in the central Scandinavian Caledonides. Geological Society of America Bulletin, 117, 117-134.

Hansen, G. (2005). Bergen c 800-c 1170, The Emergence of a town. The Bryggen Papers Main Series, vol. 6, Bergen, Fagbokforlaget, 298p. DOI: 10.15845/bryggen v60

Hansen, G. (2017). Domestic and exotic materials in early medieval Norwegian towns: an archaeological perspective on production, procurement and consumption. In A. Z. T. Glørstad & K. Loftsgarden (Eds.), Viking-Age Transformations: Trade, Craft and Resources in Western Scandinavia, pp. 59-94. Oxon & New York: Routledge.

Haugene, H. A. (2020). Marmorstein på Borgundkaupangen 2020. Dokumentasjon av marmorstein liggende utenfor middelaldermuseet på Borgund, inne i utstillingen samt i kirkemuren ved Borgundkirke våren 2020. Unpublished report, Sunnmøre museum.

Heldal, T. (2005). Marmor til Borgund-kirkene. Tidsskriftet Gavlen, 12-14.

Helle, K. (2006). Fra opphavet til omkring 1500. In: Norsk byhistorie. Urbanisering gjennom 1300 år. Knut Helle, Finn-Einar Eliassen, Jan Eivind Myhre and Ola Svein Stugu (eds.), Pax Forlag A/S, Oslo.

Heltzen, A. M. (1996). Bergverksdrift på Sunnmøre i gammel og ny tid. Skrift, 10. Kongsberg: Norsk Bergverksmuseum.

Herz, N., Mose, D. G. & Wenner, D. B. (1982). 87Sr/86Sr ratios: a possible discriminant for classical marble provenance, Geol. Soc. Am. Abstracts (with programs) 14, p. 514.

Herz, N. (1987). Carbon and oxygen isotopic ratios: a data base for classical Greek and Roman marble. Archaeometry, 29(1), 35-43.

Herz, N. & Waelkens, M. (eds.) (1988). Classical marble: geochemistry, technology, trade (Vol. 153). Brill Archive.

Hommedal, A. T. (1988). A-321, Borgund-kaupangen, Ålesund kommune. Synfaring av kyrkjetufter og bygningssteinar. Unpublished report to the Directorate for Cultural Heritage.

Hommedal A. T. (2017). Cistercian Soapstone. Production and Delivery of Building Material from Lyse Abbey to Bergen in the 13th century. In: Hansen G., Storemyr P., (eds.) Soapstone in the North Quarries, Products and People 7000 BC - AD 1700. UBAS University of Bergen Archaeological Series. Bergen: University Museum of Bergen & Institute for Archaeology, History, Culture Studies and Religion AHKR, University of Bergen, Norway. pp. 391-403. https://hdl.handle.net/1956/16584.

Kloster, R. (1977). Kirkene i Borgundkaupangen og Giske kapell. Ålesund: Borgundkaupangens venner.

Krill, A. G. (1980). Tectonics of the Oppdal area, central Norway. Förhandlingar / GFF Meeting Proceedings, 102(4), 523-530.

Krogh, E. J. (1977). Evidence of Precambrian continent–continent collision in Western Norway. Nature, 267(5606), 17-19.

Kylander-Clark, A. R. C., Hacker, B. R., Johnson, C. M., Beard, B. L. & Mahlen, N. J. (2009). Slow subduction of a thick ultrahigh-pressure terrane. Tectonics, 28, TC2003. http://dx.doi.org/10.1029/2007TC002251.

McArthur, J. M., Howarth, R. & Bailey, T. (2001). Strontium isotope stratigraphy: LOWESS version 3: best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. The Journal of Geology, 109, 155-170.

Mulder, J., Hagen-Peter, G., Ubide, T., Andreasen, R., Kooijman, E., Kielman-Schmitt, M., Feng, Y. X., Paul, B., Karlsson, A., Tegner, C. & Lesher, C. (2023). New reference materials, analytical procedures and data reduction strategies for Sr isotope measurements in geological materials by LA-MC-ICP-MS. Geostandards and Geoanalytical Research, 47(2), 311-336.

NGU, URL https://geo.ngu.no/kart/common_mobil/?_/kart/mineralressurser_mobil/__lang=nor::extent=-127853.84399615091,6875975.690086393,344692.1560038491,7075352.190086393::map=18

Prochaska, W. & Attanasio, D. (2022). The challenge of a successful discrimination of ancient marbles (part III): A databank for Aphrodisias, Carrara, Dokimeion, Göktepe, Hymettos, Parian Lychnites and Pentelikon. Journal of Archaeological Science: Reports, 45. https://doi.org/10.1016/j.jasrep.2022.103582.

Roberts, D. (2003). The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. Tectonophysics, 365, 283-299.

Robinson, P. (1995). Extension of Trollheimen tectono-stratigraphic sequence in deep synclines near Molde and Brattvåg, Western Gneiss Region, southern Norway. Norsk geologisk tidsskrift, 75(4), 181-198.

Schuster, W. & Thomson, T. J. (1991). Description of the natural factors affecting the environmental conditions in the side of Llandose (Illinois). International Journal of Environmental Sciences, 5(3), 112-134.

Storemyr, P. (2015). Nidarosdomens grunnfjell. En reise i steinbryternes fotspor fra Det gamle Egypt til Europas nordligste katedral. Trondheim: Nidaros Domkirkes Restaureringsarbeiders Forlag.

Storemyr, P. (2023). Sandstein, kleber og kalk til Kinn kirke i middelalderen. In: M. Stige, Hauglid, K. and Nybø, K. (eds.) Kinnakyrkja – lengst vest i havet. Florø: Flora historielag og Instituttet for sammenlignende kulturforskning, 183-203.

Thomsen, E. & Andreasen, R. (2019). Agricultural lime disturbs natural strontium isotope variations: Implications for provenance and migration studies. Science advances, 5(3), eaav8083.

Walsh, E. O., Hacker, B. R., Gans, P. B., Wong, M. S. & Andersen, T. B. (2013). Crustal exhumation of the Western Gneiss Region UHP terrane, Norway: 40Ar/39Ar thermochronology and fault-slip analysis. Tectonophysics, 608, 1159-1179. https://doi.org/10.1016/j.jasrep.2020.102777.

Walsh, E. O., Hacker, B. R., Gans, P. B., Grove, M., Gehrels, G. (2007). Protolith ages and exhumation histories of (ultra)high-pressure rocks across the Western Gneiss Region, Norway. Geological Society of America Bulletin, 119, 289-301. https://doi.org/10.1130/B25817.1.

Weis, D., Kieffer, B., Maerschalk, C., Barling, J., De Jong, J., Williams, G.A., Hanano, D., Pretorius, W., Mattielli, N., Scoates, J. S. & Goolaerts, A. (2006). High-precision isotopic characterization of USGS reference materials by TIMS and MC-ICP-MS. Geochemistry, Geophysics, Geosystems, 7(8), Q08006.