



Anhydrite Weathering Zone with Hydration Caves at Dingwall (Nova Scotia, SE Canada) as a Potential Geosite and Geodiversity Site

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Abstract

The abandoned gypsum quarry at Dingwall, in Canada, is a unique place with a peculiar “living” landscape created by expansive hydration of anhydrite process actively operating in the weathering zone at the quarry bottom. It causes a rapid volume increase of the rocks and the formation of the unique domed and tepee-like hydration landforms (several meters in length and up to 2.09 m high) with internal hydration caves (swelling caves, German: *Quellungshöhlen*). The quarry also shows some rare evaporite minerals, sulphate karst, spheroidal weathering of anhydrite and the other phenomena. Several steps of geoconservation strategy are described to promote Dingwall quarry as a geosite and a geodiversity site: inventory, quantitative assessment, conservation, interpretation, promotion and monitoring. The performed inventory describes the elements of the geoheritage. The quantitative assessment of the site, made according to the method by Brilha (*Geoheritage* 8:119–134, 2016), was based on the four aspects: scientific value, potential educational use, potential tourist use and the rate of destruction. For showing the geological heritage, the plan of the site was prepared, with paths for visitors, attendant infrastructure, thematic interpretation panels and plates with QR codes. As a part of the promotion, application of the Internet with already operating sites (e.g. hydrationcave.com) is proposed. In turn, monitoring, with measurements of benchmarks and photographic and photogrammetric documentation, will ensure the proper functioning of the site after establishing it as a geosite and a geodiversity site.

Keywords Hydration caves · Hydration landforms · Anhydrite · Gypsification · Geoconservation · Sulphate karst

Introduction

The idea of geoconservation is supported by the worldwide non-profit organization ProGEO operating within the framework of the International Union of Geological Sciences

(IUGS) (Alexandrowicz and Kozłowski 1999; Prosser 2013). Geoheritage is a part of the United Nations Educational, Scientific and Cultural Organization (UNESCO) activity, which established a network of geoparks to protect and promote geological diversity.

The term geodiversity refers to diverse natural features including geological (rocks, minerals, fossils), geomorphological (landforms, topography), physical, soil and hydrological processes as well as their assemblage, structures, systems and contributions to landscape (Gray 2004). Geoheritage and geoconservation are a consequential element of geodiversity (Serrano and Ruiz-Flano 2007; Coratza et al. 2018; Reynard and Brilha 2018). Geoheritage is a specific designation of varied types of geodiversity occurring both in situ and ex situ with exceptional scientific value (Brilha 2016).

An anhydrite weathering zone at Dingwall quarry area in Canada represents geodiversity through its already known geological and geomorphological features (Goodman 1952, 1954, 1957; Stenson 1990; Reimann and Vladi 2003;

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Jarzyna et al. 2020a, 2022a, b). Due to the geoheritage elements identified, the site can be considered as a new geosite or/and a geodiversity site to geoconservation strategy and establishing reliable protection. A geosite is characterized by the occurrence of geodiversity elements in situ with important scientific values and geodiversity presence exemplified by other values like education and tourism (Brilha 2016, 2019).

In Nova Scotia, where the Dingwall quarry presented in this text is located (Fig. 1), geodiversity and geoheritage

are active subjects of interest to the Nova Scotia Department of Natural Resources and Renewables (NSDNR). In this province, there is an established list of the sites with significant natural or cultural/historical values grouped according to their geological features into mineralogical sites, fossil sites or geomorphological sites (Fig. S1; Calder and DeMont 2010). The sites are categorized according to their importance for the natural world as (1) sites of global uniqueness and described in peer-reviewed publications (GH1), (2) globally important sites with

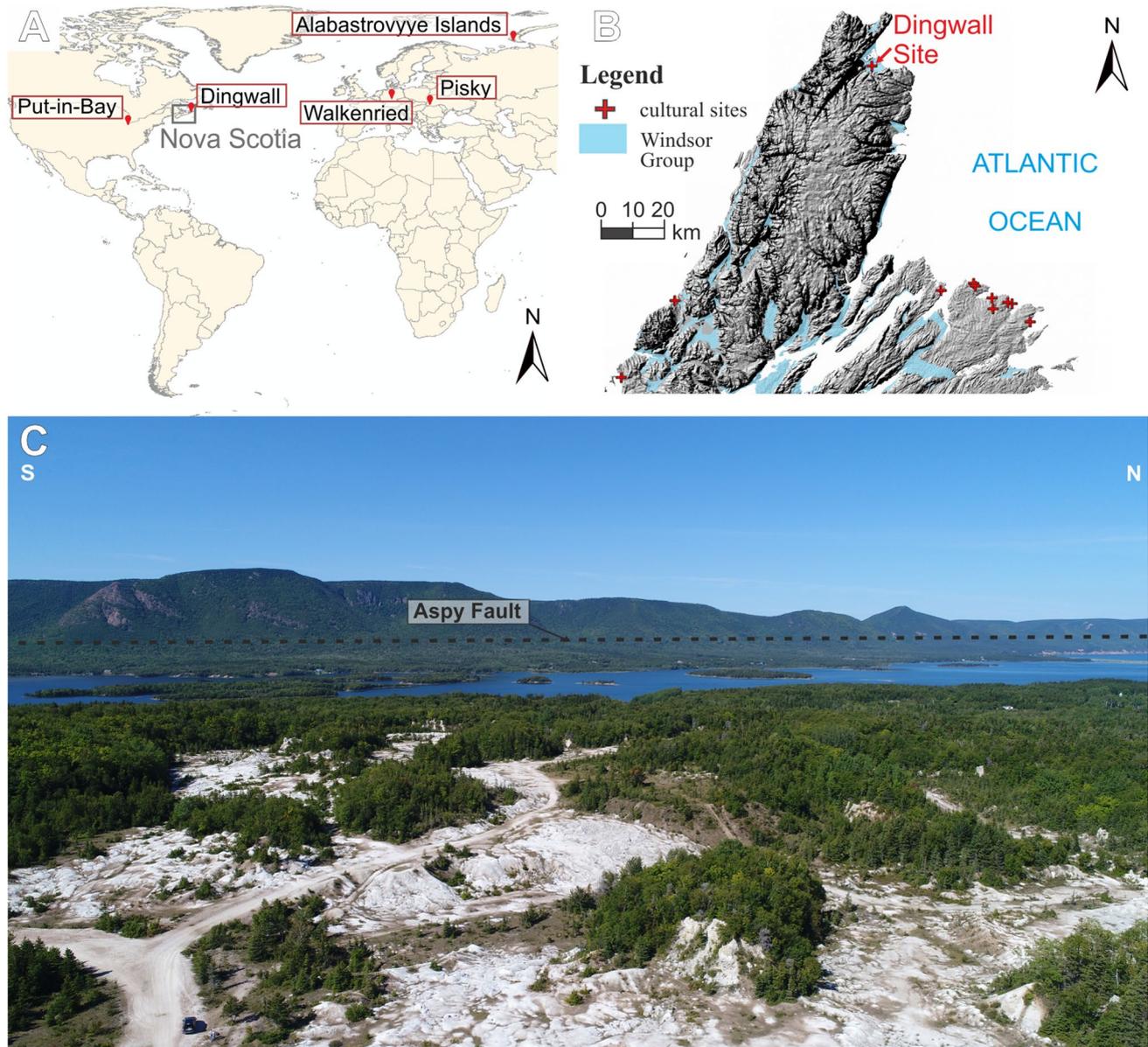


Fig. 1 General location and view of the Dingwall site. **A** Location in Nova Scotia Province and localities of the most significant hydration caves in the world. **B** Location of the cultural sites including Dingwall site in the northern part of Cape Breton Island on the basemap of hillshade and Windsor Group outcrops (for source, see Fig. S1). **C**

The landscape of the central part of the abandoned Dingwall gypsum quarry with the North Aspy River estuary and Cape Breton Highlands in the background separated by the Aspy Fault; photo made by A.J. on September 2018, using the unmanned aerial vehicle (DJI Phantom 4 Advanced)

determinable importance (GH2) and (3) sites with exceptional geological features but that may occur elsewhere (GH3).

Evaporite deposits (e.g. gypsum, anhydrite) of the Mississippian Windsor Group are widespread across Nova Scotia. Nova Scotia, in particular, is considered one of the largest areas of gypsum karst in the world (Klimchouk et al. 1996, p. 160; Moseley 2017). The Windsor Group has five natural-type sites located throughout the province, one of which is the abandoned Dingwall quarry, which is the largest outcrop of the Windsor Group anhydrite deposits on the northern edge of Cape Breton Island. The site was catalogued with the number 4409 in the Historic Quarries and Mining Area category (Fig. 1B). No other information has been published to showcase aspects of the geological heritage in this site (Calder and DeMont 2010; Calder 2014).

The Dingwall quarry is a location of interest for establishing a geosite and a geodiversity site. An inventory of the Dingwall site is presented with a discussion of the most important elements of geological heritage. A quantitative assessment of the scientific, educational and tourist values is performed. Furthermore, the dynamic evolution of unique forms of relief is described in more detail as a key element of Dingwall's geological heritage, which requires special ways of investigations (monitoring), conservation and protection.

Geological Setting

Dingwall quarry is a location with anhydrite outcrops and preserved karstic topography; the evaporites at Dingwall quarry belong to the Mississippian (Viséan) Windsor Group, part of the late Paleozoic Maritimes Basin, that covers much the onshore Atlantic Canadian provinces (Bell 1929; Neale 1963b; Adams 1991; Davis and Browne 1996; MacNeil et al. 2018; Gibling et al. 2019). The anhydrite was likely deposited as gypsum in Viséan (344–330 Ma) when much of Atlantic Canada was under a vast shallow water marine basin (Schenk 1969; MacNeil et al. 2018). The gypsum was later, during burial, transformed (dehydrated) into the anhydrites, which in turn was subjected to hydration and gypsification in the weathering zone during exhumation (MacNeil et al. 2018; Jarzyna et al. 2022b). Just this secondary gypsum from the weathering zone covering the anhydrite bedrock with an approximately several meters thick layer was once exploited at Dingwall.

Maritimes Basin rocks were subject to significant tectonic deformation, including folding, faulting and salt tectonism (Waldron et al. 2015, 2022). For example, Dingwall lies near the contact between two tectonostratigraphic units: the Aspy terrane and the Blair River Complex (Neale 1963a, b; Barr and Raeside 1989; Gibling et al. 2019; Jarzyna et al. 2022a).

The picturesque Aspy Fault (Fig. 1C) runs nearby this border and marks the northern range of the Carboniferous deposits of the Aspy Bay (Grant 1990; Davis and Browne 1996).

In the Pleistocene, much of Eastern Canada, including the Dingwall area, was covered with ice, and during deglaciation sandy, silty and clayey tills with boulders were deposited directly on the Carboniferous anhydrite-gypsum substrate (Goodman 1954; Grant 1990). The evaporite rocks at Dingwall were exposed to weathering and karstification both before and after glaciations (Moseley 2017).

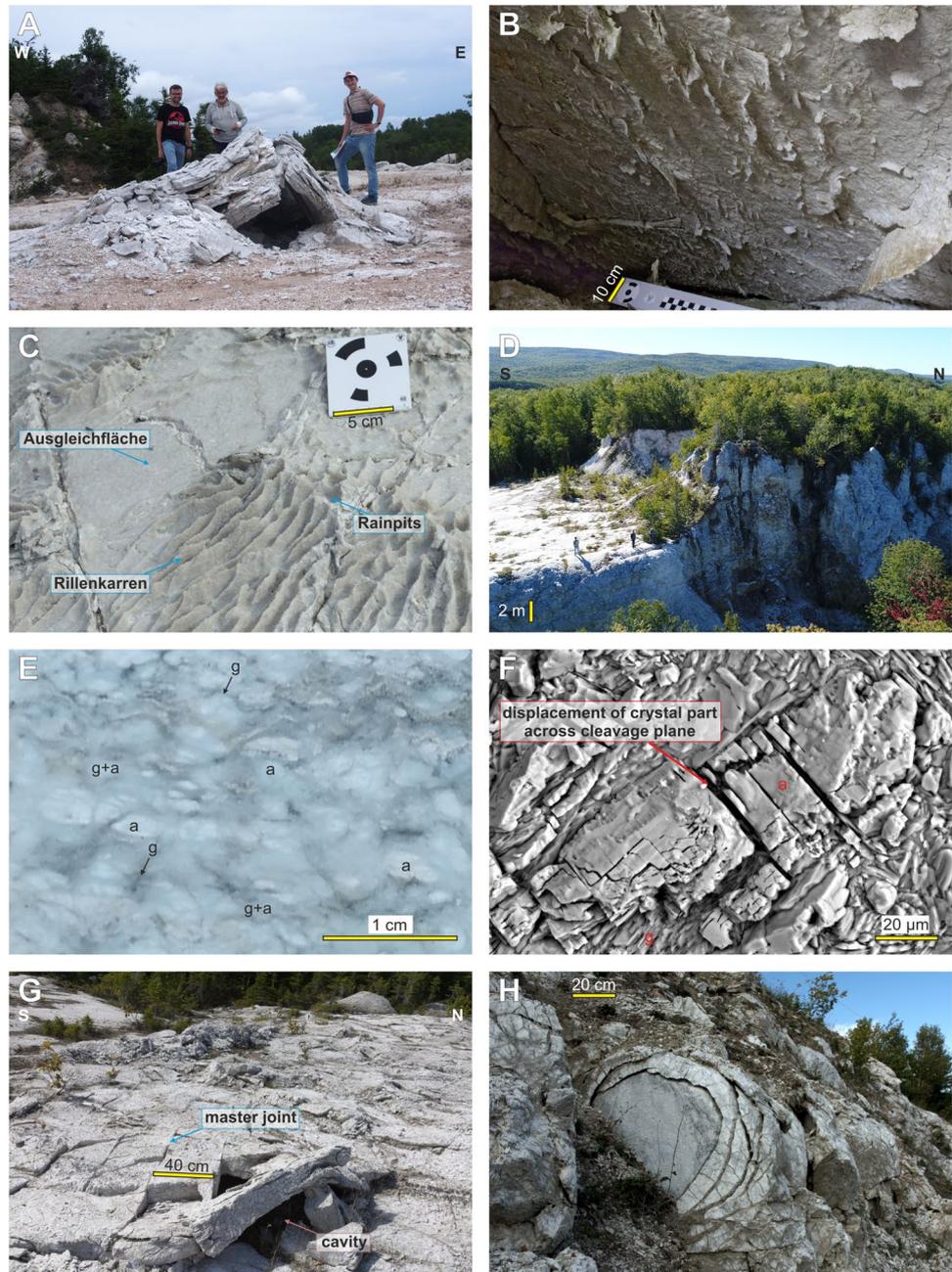
Geoheritage Values

The Dingwall quarry operated from 1933 to 1955 (Adams 1991). Gypsum was mined in the area of ca. 78 ha within four fields: the western, the central (Fig. 1C), the eastern and the southern field. The southern field is located above the Middle Aspy River valley and contains high gypsum cliffs with picturesque karst relief known as schlottenkarren (Fig. 2D; Goodman 1952; Adams 1991; Ford 1997; Jarzyna et al. 2020a). Schlottenkarren means “groups of densely-packed dissolutional funnels draining into vertical cylindrical shafts typically with connections to subsurface cavities (‘schlotten’) beneath” (Moseley 2017, p. 269). This relief occurs also in many other areas of Nova Scotia, but its accessibility is not as good as that at Dingwall (Moseley 2017).

The other fields of the quarry show spectacular weathering forms of relief described below. As in the other exposed areas of readily dissolved rocks (Ginés 2009; Madonia and Sauro 2009), surface dissolution led to the formation of extensive gypsum-anhydrite karren assemblages or karren landscapes throughout the area (Stenson 1990; Stenson and Ford 1993).

Due to the exploitation of the gypsum, the anhydrite bedrock was exposed on the quarry bottom. This action led to ongoing weathering, including anhydrite hydration under the influence of precipitation and also surface and subsurface water. In the weathering zone, the anhydrite hydration reaction ($\text{CaSO}_4 + 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) takes place in an open system—meteoric water is evidently supplied from the outside. Therefore, the hydration or gypsification of anhydrite is associated with volume increase, theoretically up to 62.6% (Mossop and Shearman 1973; Zambak and Arthur 1986). Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) crystallizing at the expense of anhydrite (CaSO_4) occupies a larger volume than anhydrite. The direct cause of the volume increase is the displacive crystallization of secondary gypsum exerting crystallization pressure on its surrounding (Jarzyna et al. 2022a). Expansive gypsification has caused significant deformation in the surface zone of the Dingwall quarry over most of the weathering zone. The most spectacular deformation effect is related to localized expansive hydration which resulted in

Fig. 2 Elements of geological heritage in the Dingwall site. **A** Hydration landform showing a tepee shape with internal cave called the Personal Grotto. **B** Interior of the Damian Cave. **C** Rillenkarren, Ausgleichfläshe and rainpits on anhydrite-gypsum rock. **D** Schlottenkarren relief exposed on the edge of the Middle Aspy River cliffs near the southern field of the quarry (Fig. 3). **E** Mosaic-nodular-wispy structure of the rock composed of anhydrite (a) and gypsum (g). **F** Anhydrite crystals showing gypsification along the cleavage planes and resulting displacement of crystal fragments; water-etched surface, scanning electron micrograph. **G** Part of the eastern field of the quarry showing master joints and cavity inside of the hydration form. **H** Spheroidal weathering of anhydrite bedrock



the local rising of the detached rock layer, creating domes and tepee-like forms, or elongated ridges (Fig. 2A, G). Domes are usually round, oval or variably elongated and resemble a loaf of bread in shape, whereas tepee-like forms are triangular in vertical cross-section normal to the crest (Jarzyna et al. 2022b). They can be treated as basic hydration landforms which together create a rare type of relief called hydration landscape (Jarzyna et al. 2022b). Fractures and rock displacements are very common.

The most striking feature of the anhydrite weathering zone at Dingwall is that it represents what can be called “a living landscape”. The expansive hydration and deformation

processes are still ongoing, and the hydration forms grow or undergo destruction at an easily noticeable rate. The domes and tepee-shaped forms can grow up to a height of over 2 m in the Dingwall quarry, and their typical feature is a cavity appearing under the detached, elevated rock layer. The cavity can be called a cave or, strictly, a proper cave (Jarzyna et al. submitted), when it can accommodate a human (Curl 1964, 1999; White and Culver 2019), particularly an adult human (Curl 1958; Panoš 2001; Poucher and Copeland 2006), and in this case, it is a rare type of cave called a hydration cave (Kraus 1905a) or a swelling cave (*Quellungshöhle* in

German; Biese 1931; Reinboth 1997; Reimann 1991; Reimann and Vladi 2003).

A large and rapid volume increase due to anhydrite gypsification is rarely observed. More commonly gypsified anhydrite rocks do not show any traces of volume changes (McWhae 1953; Ham 1962; Holliday 1970 and other references in Jarzyna et al. 2022a), and therefore, the Dingwall site is particularly unique and presents important geoheritage values (Jarzyna et al. 2020a).

Although high quantity and magnitude of anhydrite hydration features is the most distinctive process recorded at Dingwall, other natural aspects of the site can be considered “subtypes” of geoheritage (Serrano and Ruiz-Flano 2007; Brilha 2016) which are important to the site’s need for geoconservation. Subtypes of geoheritage at Dingwall include aspects as, firstly, dissolution of gypsum-anhydrite rocks, which led to the formation of karst relief (Moseley 2017; Vladi et al. 2022), specific petrographic features of the rocks recording diagenetic changes and weathering typical of the burial-exhumation cycle of Ca sulphate evaporite deposits (Mossop and Shearman 1973; Adams 1991; MacNeil et al. 2018; Babel et al. 2020; Jarzyna et al. 2022a), and structural features involving spheroidal weathering and fractures developed during the conversion of anhydrite to gypsum and weathering. Furthermore, in the quarry, several sets of master joints are visible which significantly shape the morphology of hydration forms (Jarzyna et al. 2022b).

Methods

Brilha (2016) describes in the most detail how the inventory and quantitative assessment are used to develop a work strategy and determine the best methodology of operation for establishing a geosite and a geodiversity site. This strategy was applied by many authors (e.g. Lahmidi et al. 2020; Jaya et al. 2022).

For establishing the Dingwall quarry as a geosite and a geodiversity site, several steps of geoconservation are required: (1) inventory, (2) quantitative assessment, (3) conservation, (4) interpretation, (5) promotion and (6) monitoring (Lima et al. 2010; Prosser 2013; Brilha 2016). These steps are described in detail in the following.

The purpose of an inventory is to provide appropriate documentation of noteworthy sites from the perspectives of science, culture and tourism. An inadequate inventory of a certain area can result in the omission of sites important to the geological heritage of the region (Brilha 2016). There are several key elements of Dingwall’s geological heritage that can be classified into one of the geoheritage subtype (Brilha 2016). This inventory is simplified because it involves only one site.

The assessment of the site is the basis for processing further actions to classify the study site as the geosite and geodiversity site (Brilha 2016). By comparing the Dingwall quarry to the other sites, the assessment can also reduce the impact of subjective view and determine if more work is needed in the field of geoconservation. A quantitative method based on established criteria, numerical values and their weights is used during the assessment of Dingwall’s site. We determined a scientific value (SV), a potential educational use (PEU) and potential tourism use (PTU), but also a degradation risk (DR; Brilha 2016). For the above-mentioned aspects of SV, PEU, PTU and DR assessment, several criteria were used with the possibility of scoring each of them from 0 to 4 points (parameters), except of SV scored 0, 1, 2 or 4 points. There is a weighting in % for each of the criteria, giving a total of 100%. The points available for each of the above aspects of assessment range from 0 to 400. As a part of the DR assessment, documentation of morphological changes in the hydration forms was taken on the basis of photographs, observations and benchmarks method.

We refer to conservation as ensuring that the site is protected against destruction by some people (Brilha 2005). During the description of the conservation activities, all dangerous elements and acts that are a threat to both visitors and heritage elements were taken into account.

The interpretation is an explanation to non-geologist visitors in a simple, transparent manner, without difficult specialized words and, preferably, with the use of pictures and skillfully targeting the emotions of the person (Tilden 1957; Macadam 2018; Beraaouz et al. 2019). Further, engaged steps include promotion informing the local and international community about the site through brochures, leaflets, road signs and media, as well as through conferences or symposia (Ryanard et al. 2009).

Monitoring is associated with the risk of the site’s degradation over time and taking steps to ensure not only the safety of visitors but also the constant monitoring of the protected features like hydration forms (JNCC 2004; Moura et al. 2021).

The design of conservation, interpretation and promotion activities was based on observations of geoheritage features and data collected in the form of photographs, ground and aerial photogrammetry, collected samples and performed analyses. All graphic works were done in CorelDRAW computer program, and those requiring geographic and geological data in ArcGIS program.

Inventory of Geoheritage Values

There are several aspects of geological heritage in the Dingwall quarry (Fig. 2) related to various processes that have affected gypsum-anhydrite rocks from Carboniferous to

present. Currently, anhydrite hydration is being observed, as well as the well-preserved hydration landforms and the hydration caves that were formed within those deposits. Other valuable aspects for geological heritage include karst relief, mineralogical-petrographic features and structural features.

Mineralogy and Petrography

Rocks at Dingwall quarry are composed of gypsum and anhydrite (ca. 98–100 wt% of the content), and celestine, quartz and calcite constitute less than 2% of the rock (Jarzyna et al. 2022a). Rare limestone beds and calcite nodules are present (Goodman 1952). In the northern part of the quarry, two rare borate minerals were documented by Goodman (1952, 1954, 1957): ulexite ($\text{NaCaB}_5\text{O}_6(\text{OH})_6 \cdot 5\text{H}_2\text{O}$) within joints and howlite ($\text{Ca}_2\text{B}_5\text{SiO}_9(\text{OH})_5$) as nodules up to over 15 cm in diameter intercalated in gypsum. Howlite was a mineral first discovered in Nova Scotia by Henry How (1868) and named after the discoverer by James Dwight Dana (1868, p. 598) (Papezik and Fong 1975). Native sulphur, dolomite and epsomite were also noted at Dingwall (Goodman 1952, 1957; Grantham 1985).

The gypsum-anhydrite rock contains rare poorly visible sedimentary structures of the primary bottom-grown gypsum in the form of anhydrite pseudomorphoses after the grass-like gypsum (selenite) crystals or ghosts of such crystals. The massive anhydrite is evidence of dehydration of the originally deposited gypsum and transition to pure anhydrite during burial under the influence of increase in temperature and pressure. The petrographic record of the gypsum-anhydrite rock shows the weathering change of a massive anhydrite rock with tightly packed crystals into a mosaic and nodular gypsum-anhydrite rock (Fig. 2E) characterized by greater porosity. The rock entirely composed of gypsum has even more porous fabric (Jarzyna et al. 2022a). In addition to the changes manifested in the rock structure, the fabric also changes, where predominantly euhedral anhydrite crystals dissolve and are replaced/displaced by mostly anhedral gypsum. A gypsum-anhydrite rock also exhibits distortion in the form of reoriented fractured crystals, as well as distortion of the orientation of the anhydrite crystals (Fig. 2F).

Morphology

Crystallization pressure of the secondary gypsum leads to volume increase that is best visible on a macroscopic scale as convex hydration landforms (Jarzyna et al. 2022a). Based on the documentation carried out in 2018 and 2019, 77 anhydrite hydration landforms with lengths from 1.86 up to 23.05 m and relative heights from 0.33 up to 2.09 m were recognized (Fig. 3; see also hydrationcaves.com). Besides

these 77 hydration forms, there are more than one hundred similar undocumented forms on the quarry bottom, most of them are small in size (Vladi et al. 2022).

Speleology

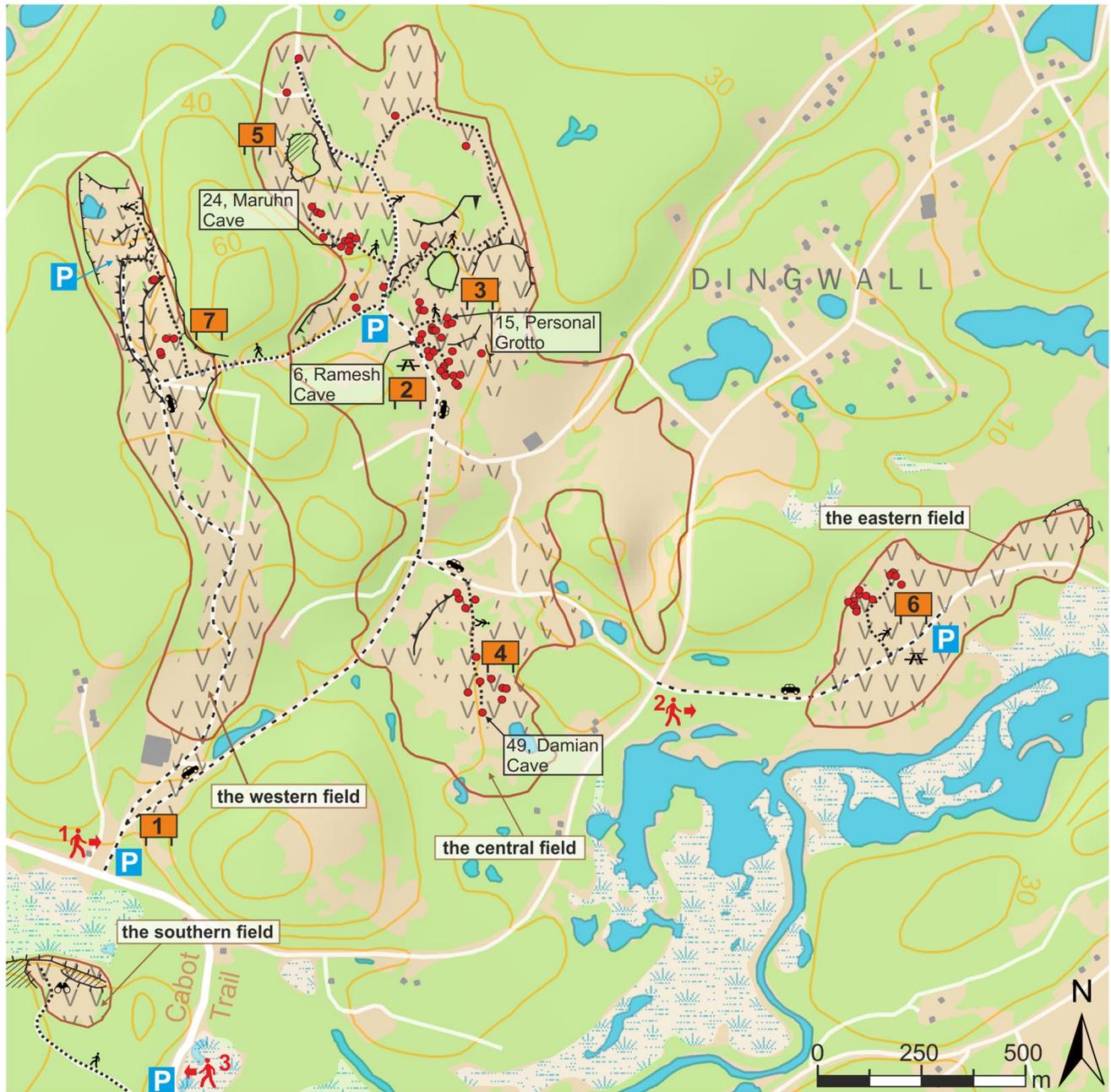
In many places of the quarry bottom, detached rock layers grow up forming the particular hydration caves. The rock layers range in thickness from 0.06 to 0.46 m (0.21 m on average) and form a cavity below with a generally domed shape, but also triangular in vertical cross-section. The internal space as a rule reflects the outer shape of the landform. The rock surfaces of the cavities are usually without speleothems, smooth and fractured. Hanging thin, folded rock fragments can be found on the ceiling surface as a typical feature of the anhydrite caves (Fig. 2B). These folded forms apparently originated due to expansive hydration of anhydrite (e.g. Forti 2017), although their origin may be more complex (White and White 2003). The floor is covered with debris and some remains of plants and leaves.

The cavities vary in degrees of accessibility, size and shape. Those which fit the definition of a proper cave or a cave (Curl 1964, 1999; Panoš 2001; Poucher and Copeland 2006; White and Culver 2019) and show a “minimum size of about 0.3 m diameter” (Gillieson 1996, p. 3) were classified as hydration caves. The cavities identified within 77 described hydration forms are 43 caves with a proper entrance that an adult can crawl into (Fig. 2A, B; Jarzyna et al. submitted).

The longest and the highest hydration cave according to the measurements in 2018 is the Ramesh Cave having planar dimensions of 8.87×2.97 m and 1.35 m in height (as observed in 2022, almost entirely destroyed). However, the largest according to the size of the floor surface is the Damian Cave with the area of 29.4 m^2 (Fig. 2B). It is 8.80 m long and 5.10 m wide but attains only 0.88 m in height (measured in 2018).

Karst Relief

Sulphate karst which developed in gypsum, gypsum-anhydrite and anhydrite rocks is the dominant type of relief at Dingwall quarry (Stenson 1990; Stenson and Ford 1993). The bare karst originated due to direct dissolution of the exposed rock by water and is expressed as many forms of presently formed karren. Of them, gypsum rillenkarrren were analysed by Stenson and Ford (1993) who proved that they differ in some morphometric details from rillenkarrren developed on carbonate rocks (Fig. 2C). Other common karren include well-developed planar solution surfaces (*Ausgleichsfläche*) and rainpits (Stenson 1990; Stenson and Ford 1993; Jarzyna et al. 2020a).



Legend

- the hydration forms documented in the quarry
- extent of the quarry
- gypsum-anhydrite rocks visible on the satellite map
- contours lines, interval 10 m
- roads
- flora
- waters
- other area
- view point
- slope
- cliffs
- picnic place
- car route
- walk route
- buildings
- P road parking
- 2 interpretation panel and its number mentioned in the interpretation chapter
- schlotenkarren
- ➔ entrance and its number

Fig. 3 Map of the Dingwall quarry showing the location of hydration landforms and other important elements of the geological heritage, as well as proposals for their conservation, interpretation elements and accompanying infrastructure

Unexploited parts of the quarry area and its surroundings show schlottenkarren relief with sinkholes of about 2–3 m wide and a few meters deep (Fig. 2D). Schlottenkarren are very active rainwater drainage zones. Throughout the quarry, schlottenkarren are usually found in the uppermost part of the rocks and the best place to see them is on the south field (Figs. 2D and 3). In some places of the quarry bottom, the remnants of these sinkholes up to 1 m deep are observed. According to Goodman (1952), they can be up to 20 m deep. This type of karst occurs only in gypsum and gypsum-anhydrite rocks of the weathering zone (Goodman 1952, p. 50) and does not penetrate deeper into massive anhydrite bedrock.

Structural Features

Structural elements in the quarry can be divided into 3 characteristic types: master joints presumably connected with some tectonic event, fractures connected with spheroidal weathering and the other fractures including those formed during the expansive gypsification.

The master joints are regularly arranged and form a system composed of five (from A to E) vertical and subvertical sets slightly rotated in some parts of the quarry (Fig. 2G; Jarzyna et al. 2022b). According to analysis in ArcGIS, the apparent angle between the two dominant joint sets (A (east orientation) and B (southeast orientation)) is acute and varies from 25 to 39°. The system of joints directly influences the morphology of the weathering anhydrite zone. The shape of many hydration landforms is clearly dependent on the orientation of the master joints.

The fractures related to spheroidal weathering create regular parallel and semi-parallel arcs with radii ranging from ca. 30 cm to ca. 200 cm (Fig. 2H). They commonly develop within the anhydrite blocks separated by master joints and other fractures in the manner typical of the spheroidal weathering, and their origin has been interpreted by Webb (2010) to be a result of expansive hydration. The more advanced forms of such weathering, anhydrite cores surrounded by an exfoliated gypsum crust, are known as cannonball structures from the nearby New Brunswick Province (Webb 2010). They represent a unique type of spheroidal weathering of anhydrite bedrock connected with expansive hydration. The appearance of these fractures have changed remarkably from 1996 (first visit in the quarry) to 2019 (Babel and Vladi 2020; Vladi et al. 2022).

In the process of anhydrite weathering and its transformation into gypsum, fractures develop on the surfaces of the hydration forms as well as within the remaining quarry bottom. These fractures are characterized by variable orientation.

Assessment

The assessment of the Dingwall site for each of the four aspects (SV, PEU, PTU and DR) is presented below with points (parameters) from 0 to 4 in brackets for each criterion. Each criterion has a description, the number of points conferred (Fig. 4) and the total number of points is used to determine whether Dingwall is a geosite and a geodiversity site.

Scientific Value

- *Representativeness (4 pts)*: Dingwall is one of only a few places in the world where hydration landforms and internal hydration caves are actively forming due to anhydrite weathering. Other significant hydration landforms occur at Pisky (Lviv Oblast, Ukraine), between Walkenried and Bad Sachsa (Niedersachsen, Germany), on the Alabastrovyye Islands (Novaya Zemlya, Russia; Reimann 1991; Yushkin 1979, 1994; Reimann 1991; Reimann and Vladi 2003; Babel et al. 2020; Jarzyna et al. 2020a, b) (Fig. 1A). At present, among them, the Dingwall site is the most completely documented and contains all the characteristic features present in the other sites (Stenson 1990; Reimann and Vladi 2003; Jarzyna et al. 2019, 2020a, 2022a, b; Vladi and Babel 2020; Vladi et al. 2022). This location has the greatest amount of hydration landforms and caves at various stages of development, along with other important elements of geoheritage. The site is the ideal location to observe sulphate karst processes and spheroidal weathering of anhydrite.
- *Key Locality (2 pts)*: The Dingwall site is not yet recognized by national and international institutions as a place of geological, speleological or morphological importance. However, this area has been the subject of research which highlights the site's uniqueness (Stenson 1990; Reimann and Vladi 2003; Vladi and Babel 2020; Jarzyna et al. 2020a, 2022a, b; Vladi et al. 2022).
- *Scientific Knowledge (4 pts)*: The study area has been described in several scientific articles in English (Goodman 1952; Jarzyna et al. 2020a, 2022a, b and submitted; Vladi and Babel 2020), Polish (Jarzyna et al. 2019) and German (Reimann and Vladi 2003; Vladi et al. 2022). The papers focused on problems of expansive anhydrite hydration recorded at Dingwall, but also mention the phenomena of master joints and spheroidal weathering, as well as karst features.
- *Integrity (4 pts)*: All the elements of great importance in the geological heritage, such as hydration forms and hydration caves, karst relief, petrographic and mineral-

Fig. 4 Criteria, weights and calculated points of the quantitative geoheritage assessment of the Dingwall site based on a method by Brilha (2016)

Scientific Value (SV)	
Criteria	Weight [%] × Parameter = Points for Dingwall
Representativeness	30 × 4 = 120
Key locality	20 × 2 = 40
Scientific knowledge	5 × 4 = 20
Integrity	15 × 4 = 60
Geological diversity	5 × 4 = 20
Rarity	15 × 4 = 60
Use limitations	10 × 4 = 40
Total weights multiply by maximum parameter value/ total points for Dingwall	100 × 4 = 400/360

Potential Touristic Use (PTU)	
Criteria	Weight [%] × Parameter = Points for Dingwall
Vulnerability	10 × 2 = 20
Accessibility	10 × 3 = 30
Use limitations	5 × 4 = 20
Safety	10 × 3 = 30
Logistics	5 × 4 = 20
Density of population	5 × 1 = 5
Association with other values	5 × 4 = 20
Scenery	15 × 4 = 60
Uniqueness	10 × 4 = 40
Observation conditions	5 × 4 = 20
Interpretative potential	10 × 2 = 20
Economic level	5 × 1 = 5
Proximity of recreational areas	5 × 4 = 20
Total weights multiply by maximum parameter value/ total points for Dingwall	100 × 4 = 400/310

Potential Educational Use (PEU)	
Criteria	Weight [%] × Parameter = Points for Dingwall
Vulnerability	10 × 2 = 20
Accessibility	10 × 3 = 30
Use limitations	5 × 4 = 20
Safety	10 × 3 = 30
Logistics	5 × 4 = 20
Density of population	5 × 1 = 5
Association with other values	5 × 4 = 20
Scenery	5 × 4 = 20
Uniqueness	5 × 4 = 20
Observation conditions	10 × 4 = 40
Didactic potential	20 × 1 = 20
Geological diversity	10 × 3 = 30
Total weights multiply by maximum parameter value/ total points for Dingwall	100 × 4 = 400/275

Degradation Risk (DR)	
Criteria	Weight [%] × Parameter = Points for Dingwall
Detorioration of geological elements	35 × 3 = 105
Proximity to area/ activities with potential to cause degradation	20 × 0 = 0
Legal protection	20 × 4 = 80
Accessibility	15 × 3 = 45
Density of population	10 × 1 = 10
Total weights multiply by maximum parameter value/ total points for Dingwall	100 × 4 = 400/240

ogical features and also structural fractures are now well preserved.

- *Geological Diversity (4 pts)*: As mentioned above, the Dingwall site possesses more than three aspects connected with various geological processes and their effects, like hydration caves, hydration forms, schlottenkarren and common karren (rillenkarren, rainpits, *Ausgleichsfläche* and others); petrography (structure and fabric) of the Windsor Group rocks; master joints; spheroidal weathering; and fractures created due to expansive anhydrite hydration.

- *Rarity (4 pts)*: The Dingwall site representing the expansive anhydrite hydration process leading to formation of the hydration landscape with so many hydration landforms and hydration caves along with the other geological features (bare sulphate karst, spheroidal weathering of anhydrite-gypsum rocks) is so far the only one in the world. The other three sites in Germany, Ukraine and Russia are not so representative. Furthermore, the site at

Ukraine is 50% destroyed (Jarzyna et al. 2020a, b), and this in arctic Russia is in the desolate area of radioactive fallout (Matzko 1993) which makes it practically inaccessible. Hydration caves are particularly rare. Moseley (1996, p. 6) stated that “All the known caves in the Maritimes are dissolution (‘solution’) caves. Quellungshöhlen (‘bulge caves’), a rare type of cave described by Biese (1931), have not been found”. Dingwall is apparently the first place with hydration caves recognized in Canada (Stenton 1990; Reimann and Vladi 2003), and at present, it contains the largest known existing hydration caves.

- *Use Limitations (4 pts)*: Access to the site is provided by a gravel road, several hundred meters long, that is connected with the well-known Cabot Trail (Fig. 3). The terrain is owned by several people, but its accessibility is not hindered. Minor fieldwork can be carried out at this site, including sampling, measurements, photogrammetry and installation of benchmarks. However, it is strongly advised not to destroy the unique hydration and karst relief of this area.

Potential Educational and Touristic Values

The following criteria apply to both PEU and PTU:

- *Vulnerability (2 pts)*: Hydration caves and hydration forms, as well as karren, are the most fragile elements of the Dingwall site, and their destruction can be caused by improper human activity, such as tourists’ trekking on the delicate surface of the karren and above roofs of the caves.
- *Accessibility (3 pts)*: The distance of the site from the paved Cabot Trail road is ca. 300 m (Fig. 3).
- *Use limitations (4 pts)*: The site can be easily accessed by bike or off-road car using the gravel road network. It is also possible to get there by bus; however, the bus should be parked right next to the entrance to the site in an unmarked parking space (Fig. 3) or in marked parking next to the store located at a distance of 650 m west from the mentioned entrance. Almost all year round, the site is easily accessible. In winter, the rocky relief is almost invisible due to the snow cover. And during the high snow cover, the terrain may be inaccessible due to road problems. Also, accommodation in wintertime is reduced.
- *Safety (3 pts)*: The site does not have the infrastructure that facilitates visiting, such as handrails, barriers and benches. Alternatively, the coverage of the mobile network is satisfactory and enables telephone contact and Internet access. The drive to the nearest emergency department, approximately 17 km away, takes 15 min by car.
- *Logistics (4 pts)*: At a distance of less than 15 km from the site, there are about 10 restaurants and 11 lodgings, enough to accommodate 50 people. The largest place to stay is the Markland Coastal Beach Cottages on the shores of the Atlantic Ocean. It should be noted that these places are closed in wintertime.
- *Density of population (1 pt)*: The site is located on the edge of a small coastal community at Dingwall with approximately 600 residents living in an area of at least 200 ha and is close to another small community at Cape North (with comparable number of inhabitants) located from the west site.
- *Association with other values (4 pts)*: To the south, the quarry is bounded by the Middle Aspy and South Aspy River valley and to the north by the Atlantic waters of the North Harbour bay. North Highlands Community Museum is located 1.2 km west of the site, while 1.5 km north, there is the St. Paul Island Museum and Lighthouse. Within 5 km from the site, there are three religious temples: Aspy Bay United Church, St. Joseph’s Catholic Parish Church and North Highlands Pastoral Charge (presently used by the local community for organizations of some events). Furthermore, Dingwall is a home to a harbour used for recreation, tourism and fishing. Cabot Landing Provincial Park, a recreation and leisure area a few kilometres north of the site on the coast of the Atlantic Ocean, is one of the most attractive areas rich in the natural beauty. The other even more attractive area, Cape Breton Highlands National Park, is located to the south. It is inhabited with numerous mammals, such as moose, bobcat, coyote, bear, lynx and American marten (Bush and Baldo 2019), and within the Aspy Bay, there are habitats of eagle and heron (Davis and Browne 1996). Gypsum terrain around Dingwall represents one of the most unique ecosystems in Nova Scotia (Neily et al. 2017). The forest growing on the gypsum substrate contains such species as sugar maple, yellow birch, beech and hemlock but also rare plants like boreal northern holly fern (*Polystichum lonchitis*) (Neily et al. 2017) or yellow lady’s slipper (*Cypripedium parviflorum*) (Vladi and Babel 2020).
- *Scenery (4 pts)*: The site has a remarkable picturesque landscape, including the North, Middle and South Aspy River valleys; the Aspy Bay filled with waters from the Atlantic Ocean; and Cape Breton Highlands (Davis and Browne 1996; Neily et al. 2017). The quarry also offers a view of the Aspy Fault at the edge of the Highlands (Fig. 1C).
- *Uniqueness (4 pts)*: Actively forming hydration caves of such a great number, variety and quantity seen at Dingwall are the only such objects so far recognized. In the USA, there are only some singular examples of hydration forms created due to anhydrite gypsifi-

cation process (e.g. Myers 1969; Breisch and Wefer 1981). The hydration caves on the South Bass Island (and its vicinity) on the Lake Erie in Ohio (Put-in-Bay in Fig. 1A), with the Perry's Cave open for visitors, are incomparable to the Dingwall caves. They have a more complex (and controversial) origin being shaped by dissolution of expansive evaporitic rocks (Verber and Stansbury 1953; Kraus 1905b; Hobbs III 2009; Waffen et al. 2010). Moreover, they are in a static state of development.

- *Observation conditions (4 pts)*: Hydration landscape with hydration domes is visible in almost every part of the site. Depending on the place in the quarry, we are able to see the other elements of the geological heritage (e.g. spheroidal weathering of anhydrite-gypsum rocks). Only the karst relief in the form of schlotenkarren requires climbing a few meters higher in some cases, which may be difficult for some tourists. Also, petrographic aspects are impossible to see and this issue should be shown on special informational panels.

The following criteria apply only to PEU:

- *Didactic potential (1 pt)*: This place has a good didactic potential to present first of all processes of weathering of anhydrite-gypsum rocks, karst phenomena and structural features. This potential, however, is limited to those educated at the university level due to its thematic scope.
- *Geological diversity (3 pts)*: Educational potential of the site refers to various phenomena and processes. The site is significant from the point of view of palaeogeography, historical and physical geology, as well as sedimentology and mineralogy. In the quarry, there are Carboniferous evaporite rocks deposited in the Maritimes Basin once existing in this part of Canada. They underwent progressive diagenetic dehydration during burial and hydration during exhumation and weathering in the way typical of many ancient Ca sulphate deposits (Goodman 1952; Stenson 1990; MacNeil et al. 2018; Jarzyna et al. 2020a). The master joints cut the rocks, documenting some tectonic forces acting on them in the past. During the last Wisconsinan glaciation (from 75 or 65 to 11–10 ka; Grant 1994; Moseley 2017), till was deposited above the eroded anhydrite-gypsum substrate. Gravels of crystalline rocks from Cape Breton Highlands found scattered on the quarry bottom derive just from this till. Schlottenkarren document long-lasting Quaternary karst solution of the gypsum-anhydrite rocks. Small-scale karren on the surface of the rocks illustrate a rapid present-day solution. However, expansive hydration of anhydrite associated with weathering leading to creation of a unique hydration landscape is the key process acting in the quarry.

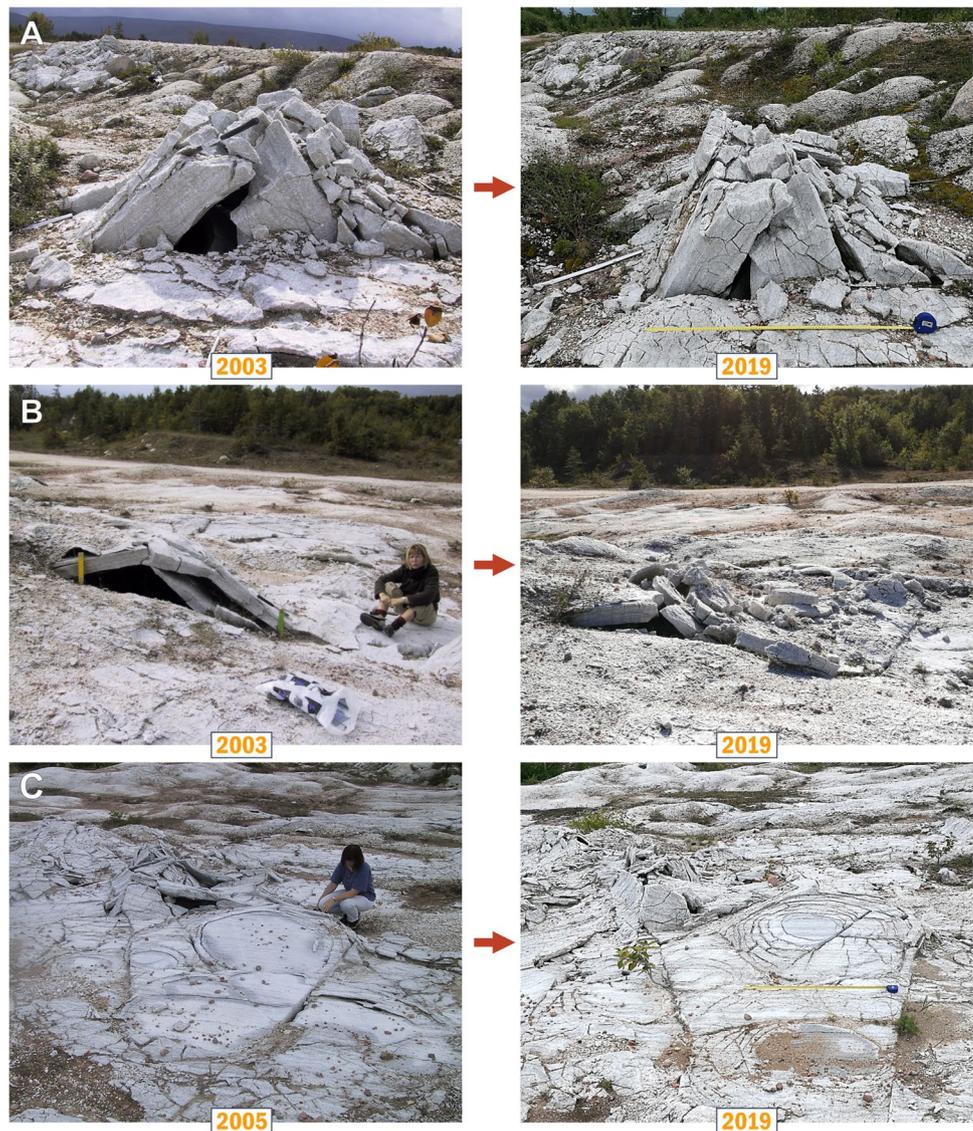
The following criteria apply only to PTU:

- *Interpretive potential (2 pts)*: Understanding the processes responsible for the formation of hydration caves and landforms, joints, schlotenkarren and karren requires some basic knowledge of geology, sometimes not familiar to common tourists. However, more difficult and complicated processes can be explained in a graphic way.
- *Economic level (1 pt)*: As the family in Nova Scotia, potential visitors of the quarry, has a lower income of 78,920 CAD (data from 2018), the third lowest in Canada, the potential benefits from the entrance tickets to site are low (<https://www.statista.com/statistics/467078/median-annual-family-income-in-canada-by-province/>).
- *Proximity of recreational areas (4 pts)*: Numerous places to rest and many tourist attractions, like beautiful beaches at Cabot Landing Provincial Park, South Harbour Beach and Middle Harbour Beach, are in the radius of 5 km from the site. In the Atlantic Ocean, it is possible to practice water sports, sailing, fishing and kayaking (e.g. canoe and kayak renting service at South Harbour). During winter, there is the possibility of skiing in the resort of North Highlands Nordic Ski Club. Numerous cultural attractions like churches and museums are near site.

Destruction Rate and Evolution of Relief

Many natural landscapes and landforms are seemingly static, but in reality, they are in a state of dynamic development (Reynard and Giusti 2019). The relief changes generated by the hydration process at Dingwall are very rapid in terms of the geological time, and changes in the flat rock surface into domes and pressure ridges appear over months and years (Fig. 5). Assuming that the hydration started after the closure of the quarry in 1955, there have been measurable changes at the quarry for nearly seven decades. The morphological development of hydration forms can be divided into five stages of evolution: initial, youth, mature, senile and destruction (Reimann 1991; Jarzyna et al. 2020b). Currently, the majority of the forms exposed at Dingwall quarry are in the mature stage of development. The changes are particularly well seen, comparing photographs taken at different times in 2003, 2005 and 2019 (e.g. Figure 5). During 26 years of observation, the morphology of the quarry showed noticeable changes like the local increase in height (Fig. 5A), movements and rotations of rock slabs, fall of rocks (Fig. 5B) and development of fracture networks (Fig. 5C). The Ramesh Cave, recognized in 2006, showed an increase in the height of the inner cavity accompanied with a decrease in the horizontal extent which was documented by the measurements in 2008 ($10.7 \times 6.6 \times 1.1$ m), 2017 ($9.95 \times 4.10 \times 1.32$ m) and 2018 ($8.87 \times 2.97 \times 1.35$ m). In 2003, the Maruhn Cave was

Fig. 5 Development of hydration forms of relief at Dingwall over 14–16 years of observations. **A** Horizontal movement of rock layers of tepee-like form. **B** Destruction of dome-like form. **C** Development of spheroidal weathering during progressing gypsification (Susanne Maruhn-Vladi is a person photographed as a scale)



the largest cave at Dingwall ($9.5 \times 4.5 \times 1.0$ m; Vladi and Babel 2020), but due to the collapse of the roof right at the entrance (Vladi and Babel 2020), the interior, measured in 2018, was shorter, measuring 6.90 m, and the height was 0.8 m. Moreover, the measurements of benchmarks during several years of documentation showed an average rate of displacement of ca. 2 cm/year (Vladi and Babel 2020).

A number of other aspects of the site were not thoroughly investigated in terms of the rate of changes, which is not so relevant due to the greater significance of the hydration process as it pertains to the geological heritage of the site.

The rate of destruction based on the following parameters primarily relates to the least durable hydration forms and hydration caves:

- *Deterioration of geological elements (3 pts)*: The destruction of hydration forms and caves can occur over time

(years or decades) as a natural result of the landscape exposed here. Also, if site maintenance measures are not provided and visiting routes are not set, the destruction may be the result of human recklessness.

- *Proximity to areas/activities with potential to cause degradation (0 pt)*: Apart from a playground for the local youth with motorbikes, hunters and also animals, the site is not near any potentially damaging areas or activities.
- *Legal protection (4 pts)*: Currently, the site is located within a several plots of land owned by private owners. The province did not provide yet protection for this site, and only a specific geological site of cultural importance due to the former quarry operation is designated there.
- *Accessibility (3 pts)*: As mentioned in the evaluation of SV, PEU and PTU, the site is located close to the paved road and therefore exposed to the influence of unwise

activity of some people destructive for the natural beauty of the site.

- *Density of population (1 pt)*: The site is located in the area with a small number of communities, as already mentioned above. Furthermore, in winter, the population is even smaller due to more difficult living conditions, such as long journeys to larger cities and unemployment.

The DR value of 240 points (Fig. 4) is rated moderate (Moura et al. 2021), which, of course, influences the subsequent fate of the site management policy, including the use of conservational elements to protect the most important heritage elements, and the safe delineation of visitors paths to avoid entanglement with natural objects.

Proposition of Geosite and Geodiversity Site at Dingwall

The above assessment of individual criteria for SV, PEU and PTU showed the following results: 360 pts, 275 pts and 310 pts, respectively, out of 400 pts possible (Fig. 4). It is noticeable that the SV score is highest which proves that the scientific potential is the most important for the Dingwall site, followed by the educational potential and then tourism. This is a clear indication of the direction in which further work related to the conservation, interpretation, promotion and monitoring of the site should proceed. Dingwall requires further geoconservation work in order to create not only a geosite but also a geodiversity site.

Following the guidelines by Brilha (2016), the proposed geosite (also geodiversity site) at Dingwall is characterized as follows:

- *Name of the geosite*: hydration caves at Dingwall
- *Geographical location*: Dingwall area is located within the range of 60°29' 31.32" W–60°28' 5.76" W and 46°53' 7.147" N–46°53' 52.216" N, in the northern part of the Cape Breton Island of Nova Scotia, in the vicinity of bay of the three rivers: North Aspy River, Middle Aspy River and South Aspy River right at their influx to the Atlantic Ocean. The quarry is situated in the Victoria Lowlands ecodestrict between the mountainous Cape Breton Highlands and Atlantic Ocean (Neily et al. 2017).
- *Owner*: Site is located on several private plots of land divided by public and private roads.
- *Legal protection*: The site is devoid of any means of state protection.
- *Accessibility*: Access from the mainland part of the province requires a driving distance of 210 to 700 km, depending on the departure point, while the road from Halifax International Airport is 436 km. The roads are of good quality, paved and passable, and the road pass-

ing Dingwall is the Cabot Trail (Fig. 3), which stretches across the central and northern parts of the Island and joins the shores of the Gulf of St. Lawrence and the Atlantic Ocean.

- *Fragility and vulnerability*: The main subtype of geological heritage like hydration forms and caves is susceptible to damage, mainly by the collapse of the cave ceilings, not only by stepping on the rock surfaces by humans but also due to natural evolution. Other subtypes of geological heritage, except of some karren and fractures, are slightly less susceptible to human destruction.
- *Geological description*: The site at Dingwall lies within Carboniferous anhydrite-gypsum rocks of the Windsor Group, formed as a result of the evaporitic and clastic deposition in the Maritimes Basin in the early Viséan age. The quarry is located within the Aspy terrane close to the Blair River Inlier Complex.
- *Most remarkable geological features which justify the need to consider the occurrence as a geosite*: Anhydrite hydration forms and hydration caves are the most important part of geological heritage at Dingwall.
- *Eventual limitations to its scientific use*: It is imperative that the site should be sampled with care and consideration, especially where fragile and vulnerable hydration forms are concerned. It is suggested to collect rock samples from the bottom of the quarry without any important heritage value and from the least vulnerable morphological forms. In addition, during field observations, it is suggested not to walk on the most fragile rocks.

Dingwall geosite could be extended as a foregoing cultural site but, first of all, should be developed as a site with a significant natural value of a global uniqueness (GH1), represented by only eight places in Nova Scotia (Fig. S1). In the case that Dingwall's proposal as a geosite and geodiversity site does not meet the criteria typical of all those present in Nova Scotia Province, then a list of less significant local geological sites of Nova Scotia can be created according to the rules of the UK. There are 4400 of such sites scattered almost all over UK (Prosser 2013). Also, the site could be a part of the Canadian Geoparks Network or Global Geoparks Network supported by the UNESCO (Zouros 2016) and/or an extension of the Cape Breton Highlands National Park. The idea to create a geosite and a geodiversity site is supported by the fact that gypsum deposits are exhausted in the quarry, so there will be no conflict with the modern gypsum industry. The greatest difficulty in creating a geosite and a geoheritage site is certainly an element of quarry ownership by many entities; moreover, geoconservation activities require some amount of money as well as the involvement of local (like North Highland Community Museum) and provincial authorities and people directly related to the site.



Fig. 6 Warning signs

Conservation

In order to protect Dingwall against intentional and unintentional destruction, visitors should be informed of the possibility of site degradation and follow the appropriate visiting paths. It is necessary to explain how hydration relief and other elements in the site could be destroyed on the interpretation panels (Fig. 3). In addition, it is necessary to install small warning signs about the danger to the visitor and the risk of damaging the geological heritage (Fig. 6).

The proposed routes leading through the entire site, 6 km in length, show the most important elements of the geological and geomorphological features (Fig. 3). They should be marked in the field on trees or small signs stuck into the rock or in the ground. In the paths, all elements of the site are shown in the most effective and safe way, without any obligation to stay on the path, but emphasizing heeding warning signs and prudent sightseeing.

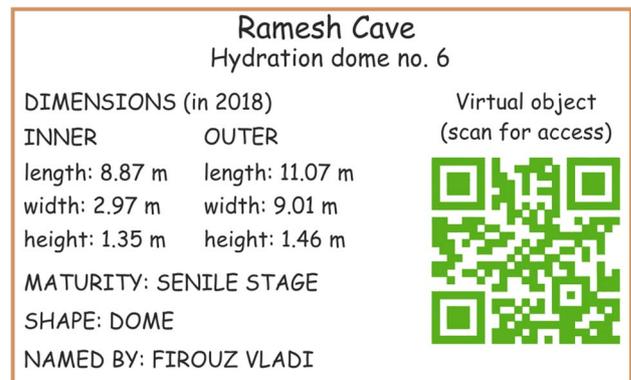


Fig. 7 Exemplary plate informing visitors about hydration caves through access to the Internet

Interpretation

The basis for showing the geological and geomorphological heritage will be the installation of interpretation panels and small plates with quick response (QR) codes showing in a clear and simple way any necessary information (Macadam 2018; Beraaouz et al. 2019). Their content should be based on data collected in a scientific manner, but presented in a way that contains as little complicated definitions as possible, barely known to most of the public. Interpretation panels should be adapted to the average human age and preferably contain those elements of the environment that are known and close to him. Analogies and comparisons should be used to explain difficult terms, and the visual presentation of information should be colourful and emotional (Tilden 1957).

The optimal number of interpretation panels is 7 (numbered in Fig. 3). The first will show the geological cross-section of the Aspy River valley, introducing the basic geological history of the area. The second one will present exploration of gypsum in the quarry by National Gypsum Company. The third panel should present the process of anhydrite hydration (gypsification) and the volume increase due to expansive gypsum crystallization. The third panel will also provide information on the evolution of hydration forms that progresses with anhydrite hydration. The fourth panel will focus on a single hydration form and cave forming inside detailing its dimensions, evolution, parameters and features with a graphic showing the results of benchmarks measurements. The fifth panel will show karst dissolution and the resulting common karren and the schlottenkarren relief. The sixth panel will present the fractures both in the form of master joints and those created by spheroidal weathering and anhydrite hydration including karst hydrology, with particular emphasis of what process is responsible for each type of fracture and what is their time relation. The seventh panel will show

the petrographic features of the rock at the bottom of the quarry, highlighting the origin of the volume increase and its impact on the deformation.

The second element of the interpretation will be the fitting of small plates to each of the most unique forms of hydration studied by the authors (Fig. 7). Each of the plates would contain the name of the form, its number, basic information, cross-section and QR code sending the reader to a website containing virtual form objects and caves inside them, including 3D photogrammetric models (Fig. 8, Fig. S2; Mariotto and Bonali 2021). Access to a virtual facility would require the visitor to have a smartphone with a camera, good processor and RAM, and access to the Internet.

What is particularly important, a visit to the quarry may be associated with the active participation of visitors with the promotion and monitoring of the site. The possibility of taking photos and making them available to those people responsible for the site will be mentioned on the appropriate panels. In addition, visitors will be encouraged to safely measure the distance between the selected benchmark pairs, save the results and send them to the appropriate e-mail address (a ruler will be mounted with a chain). The results will be published on the website hydrationcaves.com and will enable visitors to better understand the anhydrite gypsumification phenomenon, as well as to participate in its study.

Promotion

The creation and functioning of geosite and geodiversity sites requires, first of all, an appropriate promotion by many institutions, both public and private ones. Dissemination of information is an important part of every geosite

and geodiversity site (Beraaouz et al. 2019) and demands a proper way of communication. These include communication via Internet media, but also roadside advertisements, leaflets, brochures and newspaper articles. The main place for publishing promotional materials is the website hydrationcaves.com, also the [youtube.com](https://www.youtube.com) channel and the hydration caves profile on [facebook.com](https://www.facebook.com) and [instagram.com](https://www.instagram.com). Moreover, the geocaching community will continue to encourage people to come and actively visit the site (link: <https://linkd.pl/padez>). Communication through the above-mentioned media is almost free and has a global reach.

Among the traditional methods of promotion, it is important to mount informational signs, e.g. “Dingwall—the world of hydration caves”. Regardless of their number, it is important that they stand ahead of drivers and inform them about the geological heritage of this area. Leaflets and brochures should be designed in such a way as to encourage visitors to visit Dingwall in an interesting way. Free entry is a good way to encourage people to come. Information about the site could be promoted by thematic newspapers connected with geoheritage and nature, as well as in some materials in nearby places visited by tourists, museums and information centres such as Cape Breton Highlands National Park Visitor Center.

Monitoring

We propose episodic (e.g. every 6 months), quality inspections of the installed interpretation and maintenance infrastructure at Dingwall. During quality inspections, the presence and condition of all plates and panels will be checked. Monitoring will also help in the assessment of the development of anhydrite hydration, the most influential process at the bottom of the quarry. As a part of this task, photogrammetric documentation as well as photographic documentation and measurement of displacements using benchmarks

Fig. 8 Exemplary 3D photogrammetric model of the Deep Cave (for another 3D models, check the Supplementary Materials)



will be commissioned every few years. State of the knowledge about evolution of this phenomenon contributes to a better understanding of the origins of hydration caves and updating the promotion techniques.

Future of the Dingwall Site

The expansive gypsification at Dingwall quarry will continue until all anhydrite present in the weathering zone is dissolved and replaced by the secondary gypsum. Then, the hydration processes will finish, the accretion of the forms will stop and the relief will be shaped mainly by the processes of karst dissolution of the gypsum substrate. It is difficult to foresee when this phase of morphological evolution will be achieved, and it will be in a historical not a geological time scale. Knowledge of this future and of the fact that the present hydration forms and hydration caves sooner or later will collapse and disappear is important for proper management of the site. Keeping current documentation is therefore particularly important for recording the unique history of this place.

Conclusions and Final Remarks

The active anhydrite hydration process and its effects in the form of domes, tepee-shaped forms and ridges as well as the hydration caves beneath them are so far a little-known rare natural phenomenon that may prove very attractive for tourists and nature lovers. Hydration forms are rarely documented (Myers 1969; Breisch and Wefer 1981; Stenson 1990; Reimann 1991; Yushkin 1979, 1994; Reimann and Vladi 2003; Babel et al. 2007; Jarzyna et al. 2020a and submitted, Vladi and Babel 2020; Vladi et al. 2022), and only hydration caves in the vicinity of Walkenried are protected and accessible as touristic objects. There are more than 20 hydration caves and cavities located in the forests of Sachsenstein and Höllstein between Walkenried and Bad Sachsa in the southern Harz (Reinboth 1997). Similar protection and promotion on the American continent at the Dingwall quarry could be invaluable in attracting attention to the important problem of expansive anhydrite hydration. The authors have already seen the interest in the Ramesh Cave since 2018 being a geocaching point named “Dwarf holes are bubble caves” (<https://linkd.pl/padez>) and in the hydration caves shown on the website hydrationcaves.com, [youtube.com channel-named hydration caves](http://youtube.com/channel-named-hydration-caves), and on the facebook.com and instagram.com with the profiles called hydration caves.

The abandoned Carboniferous gypsum quarry at Dingwall in Nova Scotia is a good candidate for creation of the geosite and the geoheritage site. The reason for this is the presence of several unique subtypes of geological heritage in this site, such

as hydration landforms, hydration caves, sulphate karst in the form of various karren and schlottenkarren, spheroidal weathering of anhydrite and others. The site of weathering gypsum-anhydrite rocks at Dingwall is distinguished primarily by the anhydrite gypsification and the accompanying volume increase of the rock. The Dingwall quarry is the place with the largest existing and actively forming hydration caves in the world, exceptionally numerous and varied. Other geological elements in the site are also important and, together with the vegetation and the surrounding scenery, constitute an important destination for tourists and enthusiasts of the abiotic nature.

The quantitative assessment indicated a high scientific value of 360 pts (out of 400 maximum) for Dingwall quarry, showing how important this place is from the geological point of view, and it is undoubtedly worth taking steps to create the geosite here. On the other hand, the high rating of PEU and PTU is the reason to promote Dingwall quarry as a geodiversity site as well.

For the proposed site, we prepared plans of car and walk routes, appropriate safety signs and places of recreation. The site would be supplemented with interpretative panels to make people aware of what is the subject of the visit and what is the origin and current state of the discussed subtypes of geological heritage. Conservation, interpretation and promotion actions will help make people aware of the destruction risk of geoheritage elements. The site with proper promotion in the form of signs, information in the Internet and other media as well as with the assistance of other institutions would give Dingwall the appropriate recognition. The authors believe that this plan supplemented by appropriate agreements with the plot owners would make it possible to protect the uniqueness of this place.

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Declarations

Competing Interests The authors declare no competing interests.

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