

A holistic approach to diagnose
deterioration of rock-cut structures
in Lalibela, Ethiopia



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A thesis presented for the degree of
Doctor of Philosophy
in
Science and Engineering in Arts, Heritage and Archaeology
April 2022

Abstract

Rock-cut architecture is made through a subtractive process of removing material from rock outcrops or cliff faces to create spaces. Rock-cut sites are at the intersection of the natural and built environments, producing a unique semi-natural setting in which both naturally existing geological features and human activities contribute to their deterioration. This thesis develops a holistic approach to diagnosing deterioration of rock-cut structures by focusing on the rock-cut church complex at Lalibela, Ethiopia. The diversity of rock-cut church types in the UNESCO world heritage site of Lalibela makes it a suitable case study to investigate the factors that influence the deterioration of rock-cut structures.

In semi-natural settings, key drivers of weathering can be broadly classified into climate, lithology, architectural form and history of conservation. These drivers were investigated in Lalibela using field studies, laboratory-based experiments and archival resources to develop a comprehensive understanding of weathering of rock-cut sites.

Rock-cut sites share lithological characteristics; many of them tend to be built in low-strength rock outcrops. This inherent characteristic is correlated with the presence of secondary minerals such as swelling clays. The churches at Lalibela are carved from basaltic scoria that contains $> 30\%$ swelling clays. The climate at Lalibela is characterised by intense seasonal rainfall (main rains season) and high rock-surface temperature fluctuations (dry season). High, but fluctuating relative humidity (RH) and intense rainfall during the main rains season are favourable conditions for surface and deep-seated wetness and for frequent wetting-drying cycles to occur. To determine the impact of wetting-drying cycles on clay swelling/shrinkage and salt crystallisation/dissolution cycles, dilatation was measured in salt-free and salt-contaminated basaltic scoria samples in simulated wetting-drying cycles. Results showed that the introduction of salt (NaCl) to clay-rich basaltic scoria can substantially accelerate decay and that the range of RH fluctuations at Lalibela can cause significant dilatation.

The architectural form influences the degree of exposure of rock-cut structures to climatic variables such as rainfall and insolation. Moisture dynamics assessments done in the main rains and dry seasons demonstrated that the saturation state of the walls is influenced by exposure of the roofs to rainfall. Salt distribution assessments showed that the thickness of the walls (which lack foundations to retard the flow of moisture) influences salt loading. Conservation at Lalibela has mainly focused on protecting the exposed roofs from water ingress and has often been destructive or altered the cultural landscape. Revisiting traditional conservation techniques that mimic soft capping may present a new opportunity to preserve the sites in a manner that is in keeping with the intangible heritage values of the site.

A holistic methodology to understand the processes that lead to the deterioration of rock-cut architecture should be based on a semi-natural site framework, as has been attempted in this thesis. Two scales of approach are recommended to assess the state of and threats to the preservation of rock-cut structures: architectural form and landform. The architectural form will influence micro-climate, moisture dynamics and salt distribution, and overall, the post-exposure history of transformation and conservation of rock-cut sites. At the landform scale, inherited properties (pre-exposure history) such as topography and geological discontinuities can influence weathering.

By identifying and assessing the key drivers of weathering of rock-cut structures, this thesis lays the foundation for a scientific approach to understanding the deterioration of rock-cut architecture, which can be applied elsewhere beyond the seasonal tropical environments of northern Ethiopia.

Acknowledgement

I am very grateful to my supervisor, Professor Heather Viles, for her consistent support, encouragement and patience throughout this project. Working closely with her has been crucial in developing my research skills and has helped me to deepen my understanding of the scientific method. I feel grateful for having had her as a supervisor.

I have learned a lot from past and present members of the Oxford Resilient Buildings and Landscapes Lab (OxRBL). The thought-provoking discussion and presentations from a diverse group of researchers was the best part of being in the Geography department. Special thanks to Hong Zhang and Dr. Mona Edwards for their help in lab and fieldwork preparations.

I would like to thank the following organisations that have helped run this research smoothly: Lalibela Tourism Office, the Lalibela Church Administration and the Authority for Research and Conservation of Cultural Heritage (Ethiopia) for giving the permission that was required to conduct this research; the National Meteorological Agency (Ethiopia) for providing Meteorological data. A very special thanks to the priests and staff at Bete Amanuel and Bete Golgotha for graciously welcoming me, helping me collect samples and take measurements.

I would like to acknowledge the funding provided by the Science and Engineering in Arts, Heritage and Archaeology (SEAHA CDT) and the St Edmund Hall Pontingy Award.

To my friends and family in Oxford, thank you for making Oxford feel like home, especially in dark winter days. To my family, I am so grateful to you in ways words can't describe.

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Part I

Context and Framework

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Ten churches were built from one rock mass, when the time had come for them to be revealed God told Saint Lalibela to reveal the churches he had shown him.

(Acts of Lalibela, [2018](#), p. 199)

1. Introduction

1.1 Context

1.1.1 Rock-cut architecture

Carved, hewn and excavated rock structures represent some of the world's most wondrous heritage sites across the globe (Fig 1.1). The earliest known examples of this building technique at a monumental scale are the rock-cut tombs in Egypt in the 13th century BCE, the best example of which is Ramesses II's temple at Abu Simbel. This building style evolved over centuries and was used to carve theatres, temples, tombs and dwellings in Petra, Jordan, between 312 BCE to 106 CE. Between the end of the 1st millennium BCE and the late 1st millennium CE, large Buddhist and Hindu cave temples and grottoes that were adorned with intricate details were carved in China and India. Historic monuments were built using this technique elsewhere in the middle east (Saudi Arabia, Iran and Turkey) and Afghanistan. In the 12th to 13th century CE, rock-cut churches were carved in the northern Ethiopian highlands at a town called Lalibela. Contrary to what Ching et al. (2017, p. 434) refers to as a 'sudden appearance of this form of building in Ethiopia', there is widespread evidence of this style of architecture in the northern highlands of Ethiopia dating back to the

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6th century CE (Asrat, 2002; Rickerby et al., 2017). This unique building tradition continues to be used in Ethiopia up to the present day, where several churches have been carved in the regions of Wello, Shoa and Adigrat.

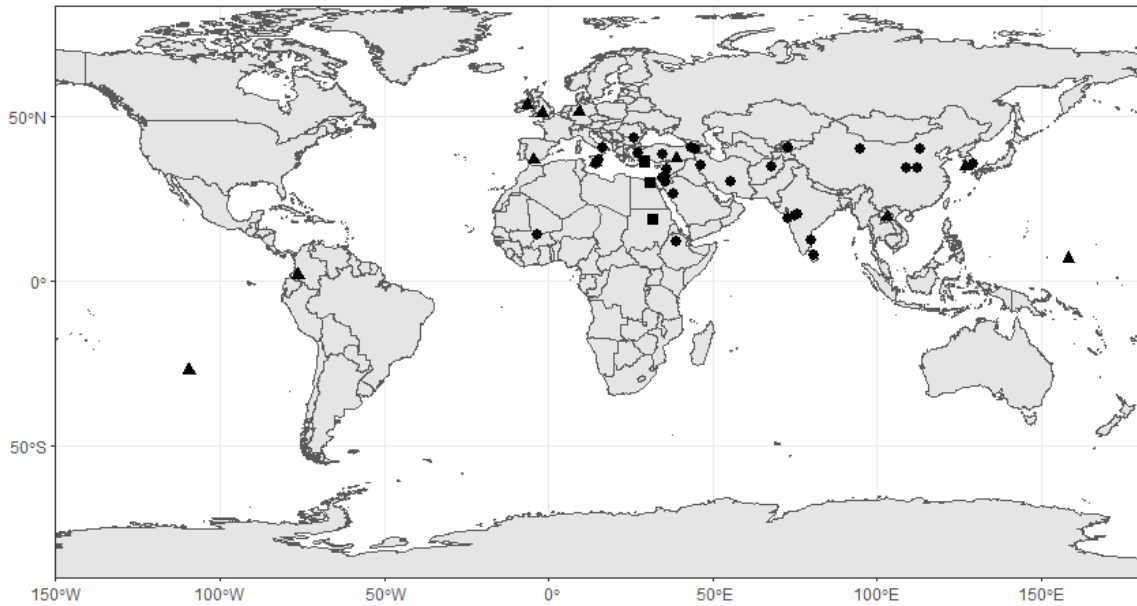


Figure 1.1: Rock-cut and cave/grotto temples (circles), megalithic sites (triangles) and rock-cut tombs (squares) listed as UNESCO World Heritage Sites. Data source: UNESCO World Heritage List Statistics. Map created by author using ggplot2 in R.

Carved rock structures have been referred to with many names, such as cave, grottoes, rupestrian, rock-hewn, rock-cut, hypogeum, underground built heritage and troglodytic structures. These names stem from the diversity of architectural styles and the evolution of these structures from naturally existing caves. Cave and grotto are often used to refer to Buddhist temples in China and India. Using the word ‘cave’ to describe these structures can be misleading as they are a constructed form of architecture (Ching et al., 2017). Rupestrian is sometimes used interchangeably

with the term ‘rock-cut’ when referring to large carved structures such as those found in Cappadocia (Carpiceci et al., 2015) and Vardzia (Frodella et al., 2020). In archaeological studies this term has also been used to refer to rock-art (Fioretti et al., 2021; La Russa et al., 2016; Rovella et al., 2016) and rock engravings (Defrasne, 2014). Carved rock structures have also been referred to as troglodytic architecture (Ashton, 1927; Finneran, 2012) primarily by art historians focusing on the cultural context these structures were carved. Heritage managers also use underground built heritage and hypogeum to describe cave architecture and underground dwellings (Genovese et al., 2019; Sauter, 1963). Again, the words ‘built’ and ‘underground’ can be misleading in describing structures made by a subtractive process and often found above ground or on the side of steep cliffs. Rock-cut and rock-hewn are better terms to describe this building technique because it encompasses all forms of architecture that are made by shaping a rock outcrop. For clarity, the term rock-cut will be used to describe this building technique in this thesis.

1.1.2 Weathering of rock-cut architecture

Weathering is the ‘combined action of all processes whereby rocks at or near the Earth’s surface are weakened and prepared for removal’ (Shroder, 2013, p. 12). Similar to rock outcrops, weathering on rock-cut structures leads to loss of surface material and structural disintegration. Rock-cut architecture is more intimately connected with the natural environment than historic masonry structures. Unlike quarrying stone for use in masonry construction, there is very little room for error

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in carving rock-cut structures, as there is no opportunity to discard material that is not suited for the purpose. In this way, rock-cut sites are made by negotiation with what the natural environment can offer; to an extent where the carvers happen to find a bedrock that is harder to carve into, they will alter the design to accommodate these features (Fauvelle-Aymar et al., 2010). Studies at the Sheikh Abd el-Qurna tomb in Egypt showed that the carvers were accustomed to adapting rock masses unfavourable to carving into the form of the structure (Ziegler et al., 2019). The nature of the rock outcrop, that is, its suitability for carving, dictates the architectural form rock-cut structures take. In architecture, architectural form is the point of contact between mass and space (Stellingwerff and Verbeke, 2004); in the context of weathering at rock-cut sites, it can be understood as the point of contact between rock mass and the environment. At rock-cut heritage sites, the architectural form determines the extent of exposure to the environment and, thereby, the nature and rate of weathering.

The geological setting, rock type, rock hardness and joint spacing determine the durability of rock-cut architecture. Asrat (2002) studied rock-cut churches across the Tigray region in Ethiopia and observed that the rock masses chosen for carving are usually compact but soft enough to be easily incised using ancient tools. Motterhead et al. (2008) also noted that the cart ruts found in Malta were carved in soft limestone. Margottini et al.(2016) studied rock-cut cultural heritage sites in Georgia and found that the stones were mechanically weak. The compressive strength of the rocks used to carve these structures was below 25 MPa. Kaşmer et al. (2013)

and Topal and Doyuran (1998) noted the influence of jointing and weakness of the rock and its influence on the shape of the rock-cut structures at Cappadocia, Turkey. Shtober-Zisu and Zissu (2018) from their study of the distribution of rock-cut tombs in Jerusalem's necropolis, found that there was a strong correlation between rock type, location and tomb frequency. They found that most of the tombs were located in areas with a softer limestone substrate. The inherent lithological property of rock-cut structures demonstrably contributes to their vulnerability to weathering.

Due to their cultural and spiritual significance, deteriorated rock-cut structures are often restored to conserve their functional and aesthetic values. These conservation works alter the form and composition of the structures. The complexity of weathering of rock-cut architectures increases by varying rates of human activity (conservation, restoration and use) across centuries.

In this thesis, a new approach to diagnosing weathering of rock-cut structures is developed. This approach goes beyond exploring the interaction between rock mass and climate at rock-cut sites and identifies the role played by architectural form and history of conservation in controlling this interaction. Figure 1.2 presents a conceptual diagram of the interaction between rock mass and climate at rock-cut sites and how this interaction is influenced by the architectural form and history of carving and conservation.

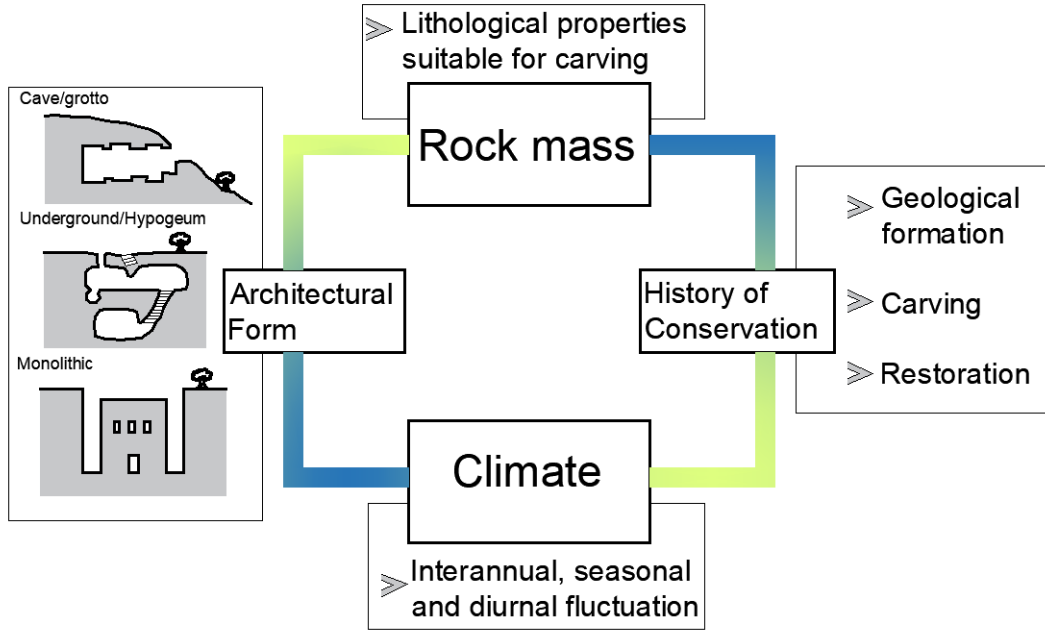


Figure 1.2: Conceptual diagram of the interaction between rock-mass and climate at rock-cut sites and the influence of various aspects of architectural form and history of conservation.

1.1.3 Churches at Lalibela

The rock-cut churches that make up the UNESCO world heritage site of Lalibela are located in the northern Ethiopian Highlands in a small rural town that shares the same name. The churches are found carved below the ground level in three separate groups in an area that covers approximately 0.25 km². Hagiographical evidence attributes the building of the churches to Saint and King Lalibela, who reigned from 1133 to 1173 CE (Hable Selassie, 1972). Saint Lalibela was one of the kings of the short-lived Zagwe dynasty. There is very little archaeological and historical evidence of the Zagwe dynasty that remains to the present day. The churches that were built by Saint Lalibela are one of the few monuments built in the medieval period in Ethiopia. Beyond their religious significance, the rock-cut churches at Lalibela are

also important historical evidence as one of the least understood periods in medieval Ethiopian history.

The scale and diversity of the eleven rock-cut churches at Lalibela make it a suitable location for investigating weathering of rock-cut architecture. The number of churches and the different rock-cut typologies allow for an in-depth assessment of the various factors that influence weathering of rock-cut structures. Previous research on Lalibela has thus far taken a stone conservation approach and has mainly focused on rock properties (Asrat, 2002; Delmonaco et al., 2005; Kiros et al., 2013; Renzulli et al., 2011; Sani, 2012; Schiavon et al., 2013). There is a need for a holistic approach that investigates the climatic conditions, lithological properties, architectural form and history of conservation and their complex inter-linkages.

1.2 Outline

1.2.1 Aims and objectives

This thesis aims to develop a holistic approach to understanding weathering of rock-cut architecture by focusing on the rock-cut churches at Lalibela as a case study. Identifying the key drivers of change at rock-cut sites and their complex synergistic relationship is crucial for developing a methodology that addresses the vulnerability of rock-cut sites to degradation. The main research objectives are:

- **Objective 1:** to characterise the ambient and micro **climatic** trends at Lalibela and their implications for weathering

- **Objective 2:** to assess the role played by **lithology** on weathering at Lalibela
- **Objective 3:** to determine the role of **architectural form** on moisture dynamics and localised deterioration at Lalibela
- **Objective 4:** to conduct archival research on the **history** of conservation at Lalibela and assess the efficacy of traditional conservation techniques.

Together, these objectives address multi-scale challenges to preserving rock-cut architecture, contribute to a broader understanding of deterioration of rock-cut sites and lay the foundation for a holistic approach to studying rock-cut sites. Although the focus of the research is the rock-cut churches of Lalibela, the approach and many of the findings are relevant to wider populations of rock-cut structures.

1.2.2 Thesis structure

The thesis is structured into three parts. Part I sets the framework for this research and the paper route approach it follows. Part I is composed of Chapter 1 to 3 and includes this introductory chapter. Chapter 2, literature review, covers a survey of research studies and methodologies in relevant scientific fields including the identification of key methods and gaps in research. It also reviews the history of the churches at Lalibela and scientific studies that focused on Lalibela. Chapter 3 offers an overview of the methodology used in the thesis and an in-depth description of various aspects of the study site. Part II comprises four chapters that address the four objectives outlined in section 1.2.1. The four chapters are presented as five

papers as follows:

Chapter 4

Paper I : Implications of climatic variability for the nature and rate of weathering of rock-cut churches in northern Ethiopia

Submitted to Earth Surface Processes and Landforms on 03 March 2022

Chapter 5

Paper II : Influence of salts in hydric and hygric dilatation of clay-rich rocks

Submitted to Journal of Cultural Heritage on 14 February 2022

Chapter 6

Paper III : Seasonality in moisture dynamics in the walls of rock-cut churches in Lalibela, Ethiopia: Implications for weathering

Submitted to International Journal of Architectural Heritage on 04 April 2022

Paper IV : Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-cut bas-reliefs at Bete Golgotha, Lalibela (Ethiopia)

Published as: Taye-Gemeda, B, Viles, H., Giorghis, F. and Sifir, F. (2019) Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-hewn bas-reliefs in Bete Golgotha, Lalibela (Ethiopia) In, Hyslop, E., Gerdwilker, C. and Gonzales., V (Eds). Monuments in Monuments. Historic Environment Scotland. (pp. 43-52).

Chapter 7

Paper V : Efficacy of traditional conservation methods for the protection of rock-cut heritage sites: Lessons from Lalibela, Ethiopia

Published as: Taye-Gemeda, B, Fusade, L. and Viles, H. (2020) Efficacy of traditional conservation methods for the protection of rock-hewn heritage sites: Lessons from Lalibela, Ethiopia. In, Siegesmund, S. and Middendorf,

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B. (Eds.). 14th International congress on the deterioration and conservation of stone (pp. 687-692).

Finally, Part III addresses the research gaps identified in Part I, synthesises the implications of the findings in Part II, and lays the foundation for a novel methodology to characterise weathering of rock-cut architecture. Chapter 8 draws broader implications from the study of the churches at Lalibela that can be generally applied to an improved management and preservation strategy of rock-cut architecture. Chapter 9 summarises the findings and implications of the research and concludes the thesis with recommendations for future work.

2. Literature Review

2.1 Overview

This chapter discusses the prevailing themes and methods in the study of rock-cut architecture at Lalibela and elsewhere. Researchers in multiple disciplines have studied rock-cut architecture. The uniqueness of the architectural style has attracted a lot of scholarly attention from art historians, historians and archaeologists. The scale and complexity of weathering of rock-cut structures have necessitated the expertise of stone conservators and rock mechanics experts. The first section of this chapter will discuss recent studies on weathering of rock-cut structures in Ethiopia, China, Turkey, Iran and Jordan. Major themes in the scientific study of weathering of rock-cut structures will be discussed, and areas that need further study will also be identified. The second part of this chapter will cover the environmental, geological and historical setting at Lalibela and explore the different theories regarding who the builders of Lalibela were, when, how and why these churches were built.

While there are numerous publications that deal with various aspects of weathering of rock-cut architecture, thus far, there has not been an attempt to review these works with the aim of developing a framework to holistically characterise weathering

of rock-cut architecture. Commonalities and differences in weathering of rock-cut sites driven by typology, scale, and morphology of rock-cut structures will be discussed. Underpinning the scientific research carried out thus far, the final part of this section will discuss how to approach and frame the study of weathering of rock-cut architecture.

2.2 Weathering in a semi-natural context

Weathering in the historic environment is understood as a complex process in which two major variables, material and climate, interact at various temporal and spatial scales (Prikryl and Smith, 2007; Torraca, 2009). Recent studies on weathering of historic structures have veered towards a new approach that emphasises material characteristics and the important interrelationships between climatic, material and historical variables (Doehne and Price, 2010). A physical geography approach to stone conservation has emphasised the important role decay agents like pollution and salts (Brimblecombe, 2014; Charola, 2013) play and has linked micro and macro decay processes (Viles, 2001; Viles and Goudie, 2013). Similar to stone conservation research, studies on rock-cut architecture have taken an interdisciplinary approach. Rock-cut architecture has been of particular interest to geomorphologists because it offers the opportunity to study the rate of weathering from a known baseline (Pope et al., 2002). The benefit of studying rock-cut architecture to understand weathering in the natural environment go beyond determining the rate of weathering. Rock-cut

structures are carved rock masses; they are more comparable to rock outcrops than masonry walls that are composed of various significantly altered materials extracted from the natural environment. The scale of rock-climate interaction and the vulnerability of rock-cut sites to rock mass failure such as rockfall has drawn researchers from rock mechanics to study rock-cut sites. Given the characteristics of rock-cut architecture that resemble both the built and natural environments, it is essential to study rock-cut sites through a framework that acknowledges the context of rock-cut architecture. Wang et al. (2018) have suggested a geo-environmental approach to study rock-cut sites, and Germinario et al. (2020) have also noted that these sites are semi-natural and do not behave in a similar way to masonry structures. Due to their similarity to sites in the built and natural environment, rock-cut architecture belongs at the intersection of the built and natural environment (Fig 2.1). In biodiversity conservation, ecosystems with most of their processes intact, but altered by human activity relative to the natural state are called semi-natural habitats (IPBES, 2022). The study of rock-cut architecture would benefit from a similar categorisation of sites that belong at the intersection of the natural and built environments as semi-natural sites. This framing is useful to effectively address both human and natural forces that contribute to weathering of semi-natural sites.

2.2.1 Rock properties

Characterising the behaviour and inherent property of dimension stones, mortars and rocks in the historic built environment is normally the first step in both

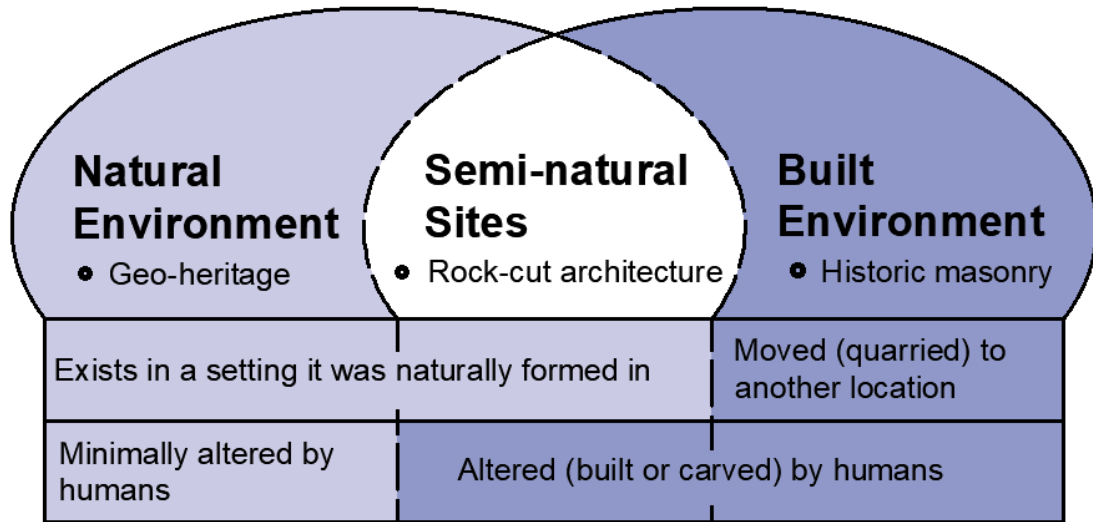


Figure 2.1: Conceptual diagram showing key difference and commonalities between semi-natural sites and sites found in the built and natural environments. *Source: Author's original diagram.*

understanding their deterioration and developing a preservation strategy (Doehne and Price, 2010; Odgers and Henry, 2012; Prikryl and Smith, 2007). Geology, in the sense of the availability of natural resources and the morphology of the landscape, heavily influences the built environment (Margottini et al., 2016). The availability of suitable material for building is associated with the flourishing of urban landscapes. Similarly, rock-cut structures tend to be built in areas where there are outcrops suitable for carving. Shtober-Zisu and Zissu (2018), from their study of the distribution of rock-cut tombs in Jerusalem's necropolis, found that most of the tombs were located in areas where there was softer limestone. Chen et al. (2019) credit the carving of the Bingling Temple Grottoes in China to the unique geomorphic conditions of the Danxia landforms, which have high vertical sandstone cliffs. The Nabateans who built Petra took advantage of the availability of building materi-

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als, location, topography, and geomorphological features to carve their structures (Rababeh et al., 2010). Other researchers have characterised the mechanical properties of rock-cut sites and noted that the carvers took advantage of an outcropping of soft rocks (Asrat, 2002; Margottini et al., 2016; Mottershead et al., 2008; Topal & Doyuran, 1998). Table 2.1 lists notable lithological properties from studies of rock-cut architecture globally. Soft (low strength) limestones, sandstones and tuffs are the most common rock types at rock-cut sites. The examples listed in table 2.1 indicate that low strength and low resistance to weathering are common characteristics of rock-cut structures.

Table 2.1: Lithological properties of a range of important rock-cut sites from around the world. UCS: Uniaxial Compressive Strength.

Location	Type of heritage	Rock type and property	Citations
Japan	Taya caves (hypogeum)	Extremely soft siltstone	Germinario et al., 2020
China	Tongtianyan Grottoes	Argillaceous sandstone, low strength, high porosity and good water permeability	Wang et al., 2018
India	Monolithic and cave type temples at Masrur, Himdal Pradesh	alternate sequence of sandstone, siltstone, claystone. Rocks are generally un cemented soft, weak and prone to erosion and weathering	Sharma et al., 2013
Iran	Cave type structure in Marāgha and Sulṭāniyya,	Soft limestone	Azad, 2016
Iran	Cave type dwellings in Kandovan	Pyroclastic rocks with low resistance to weathering	Asghari Kaljahi and Amini Birami, 2015
Iran	Meymand rock-cut village	pyroclastic rock is a lithic tuff of a low degree of welding that has very weak strength and low durability	Hashemi et al., 2018
Jordan	Cave type structures in Petra	25 lithotypes of the sandstone and siltstone type	Heinrichs, 2008
Georgia	Grotto churches in Vardizia	Mechanically weak compressive strength (25 Mpa)	Margottini et al., 2016

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Turkey	Cave and fairy chimney structures Cappadocia	Based on UCS - moderately weak to very weak	Aydan and Ulusay, 2003
Israel	Rock-cut tombs Jerusalem	Strong correlation between frequency of rock-cut tombs and material property of limestone	Shtober-Zisu and Zissu, 2018
Ethiopia	Cliff cave type churches in Tigray	Soft rocks chosen for carving rock-cut churches	Asrat, 2002
Ethiopia	Abraha-Atsibha	Mesozoic Adigrat sandstone, low to medium UCS	Abay et al. 2017
Ethiopia	Debre Aron cave-type in Tigray	Soft tuff rock	Demissie, 2020
Ethiopia	Monolithic and cave-type structures in Lalibela	Hydrothermally weathered, porous basaltic scoria with smectite and zeolite	Renzulli et al., 2011
Malta	Cart ruts	Soft limestone	Mottershead et al., 2008
France	Cave type (with masonry) and monolithic structure	Soft limestone	Vouve et al., 1997
USA	Bandelier cavate (cave type) structures	Soft tuff	Toll, 1995

2.2.2 Rock mass properties

Rock-cut structures are often carved on the side of vertical cliffs (e.g., Petra, Bamiyan, Vardzia) and are characterised by joints and discontinuities (Margottini and Spizzichino, 2022), which makes them more vulnerable to structural failures than most built heritage sites. Geomechanical properties of the landscape in which rock-cut sites are carved have received a lot of attention in the literature. This approach has been essential to assessing the risk of rock mass failure. Fractured

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rock slopes, discontinuities and rockfall have been identified as a hazard in the Siq of Petra, Jordan (Cesaro et al., 2017), Abraha-Atsibha, Ethiopia, (Abay et al., 2017), Vardizia, Georgia (Spizzichino et al., 2017), Cappadocia, Turkey (Dinçer et al., 2016) and Ellora, India (Ansari, 2014). Research on rock-cut sites from a rock mechanics approach has viewed the sites as rock masses or part of the rock outcrops. At Lalibela, for example, Asrat and Ayallew (2011) used Bieniawski's (1989) Rock Mass Rating (RMR) system and rated the risk of structural failure of the churches by considering each church as a rock mass. According to their rating, the rock mass strength of the churches was medium to high strength. They also noted several fractures, discontinuities and deep weathering of the churches. Aydan and Ulusay (2003) used RMR to assess the geotechnical properties of the rock-cut structures at Cappadocia, Turkey, and concluded that while the rock mass as a whole is of good quality, the presence of discontinuities will reduce the strength of the intact rock. The RMR method is very useful in identifying the risk posed by large discontinuities and fractures in solid rock masses, but it is not a good method to assess hollow structures with several openings (Migoń, 2013) such as rock-cut architecture. Another shortcoming of the RMR method is the influence of operator variability (Hencher, 2013). This may lead to varying interpretations of the strength of the rock mass. As such, this method is not ideally suited for determining the mechanical properties of rock-cut sites.

Methods that are more sophisticated than the RMR have been used at Lalibela to assess the structural integrity of the churches. Sani et al.(2012) used 2D finite

element analysis modelling and fracture gauges to determine the risk of structural failure at Bete Gabriel-Rufael and concluded that the building system is not at immediate risk of damage. But they warned that horizontal forces like earthquakes can cause serious damage to the churches. Lalibela is located 70 - 80 km away from an area where seismic activity is concentrated, i.e., the Afar Rift System, and is graded 2 (on a 0 - 4 scale) of earthquake risks (see appendix 1). Another study at Bete Aba Libanos by Delmonaco et al. (2005) used slope structure stability model to assess the stability of two lateral walls of the church where discontinuities are causing a planar slide of the front facade and roof. In their investigation, Delmonaco et al. (2005) found that the upper part of the structure is statically sustained by the sides of the tunnel walls, most likely created due to the arch effect.

Studies of rock mechanical properties at rock-cut sites have focused largely on the geological background (genesis and alteration) and not on the impact of excavation of the structures, such as unloading. A semi-natural sites framework that acknowledges both the natural and human factors that contribute to the transformation of these sites is essential for a comprehensive understanding of the role rock mechanics plays in this unique setting.

2.2.3 Differential weathering

Research on weathering of rock-cut architecture has approached the characterisation of properties in two ways: the rock mechanics approach that deals with geotechnical and geological aspects of rock-cut structures and the material proper-

ties approach that examines the petrophysical properties and rock strength. The complex inter-linkages between rock properties (mineral, texture, composition, etc.) and rock mechanics (discontinuities, slope, etc.) lead to differential weathering that influences the mechanical properties of a rock mass. Rock-cut structures that are hewn into layered outcrops exhibit spatial variability in weathering (Dinçer et al., 2016; Sharma, 2013). Weathering is dynamic and non-linear and it is linked complexly to the evolution of rock slopes (Viles, 2013). It also plays an important role in the formation of hillslopes and can contribute to slope-driven rock mass failures (Migoñ, 2013). Rockfall hazard assessments near the Tatlarin Underground City in Cappadocia showed that instabilities are mainly controlled by different durability of tuffs and basalt layers (Dinçer et al., 2016). At monolithic rock-cut temples in Masrur, India, differential weathering has led to variation in mechanical properties of the rock mass (Sharma, 2013). Variation of petrophysical properties, such as the amount of cementing material in different bedding layers, has resulted in differential weathering patterns at Abraha-Atsibha rock-cut church which is carved into a Mesozoic Adigrat sandstone (Abay et al., 2017). Based on field observations, Asrat and Ayallew (2011) have noted that the bedrock that lies beneath the churches is a harder and less permeable layer, while the churches are porous substrates that will allow water to reside longer.

Localised deterioration is a phrase used to describe uneven deterioration usually caused by spatial variability in micro-climate, moisture presence and rock properties. Differential weathering and localised deterioration are similar in the sense that they

are primarily driven by spatial variability in environmental or lithological factors. Differential weathering is often used in the context of the natural environment to describe rock mass scale phenomenon (see examples above), while localised deterioration is used to describe decay features on historic structures (e.g., Rodrigues, 2015; Steiger et al., 2011, Warke et al., 1996). In the context of a semi-natural site like Petra, for instance, north and south facing monolithic blocks can exhibit contrasting rates of deterioration (Paradise, 2000). Spatial variability in rock decay at rock mass and rock surface scales can be a good indication of environmental and lithological controls of rock decay.

2.2.4 Rock-climate interaction

Climatic variables like temperature, rainfall, wind and relative humidity exert a wide range of pressures on building stones (Brimblecombe, 2014). Studies on weathering of rock-cut structures have focused primarily on material characterisation and rock mass behaviour. Climatic variables act synergistically in causing weathering, ‘various water related weathering processes are caused by water but triggered by temperature’ (Camuffo, 1998, p.14), namely moisture evaporation, internal salt migration and salt efflorescence. The environment-material interaction of structures at rock-cut sites is very different from that encountered in built heritage. Germinario et al.(2020) argue the challenge of conservation of rock-cut sites represents that of a natural or semi-natural setting entailing a variety of environment-material interactions. Rock-cut architecture, unlike built structures, is wholly embedded in the

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setting it was formed in. Table 2.2 lists some of the common climate-related issues that are a result of the semi-natural setting of rock-cut architecture. The external walls of rock-cut structures are often large cliff faces or roofs directly exposed to rainfall and insolation. Infiltration of rainfall through fissures and joints are the primary routes of water infiltration in grotto temples in China and other rock-cut structures (Table 2.1). Flash floods and surface runoff have affected Petra, Theban tombs and Cappadocia. The thick load-bearing walls and columns of rock-cut sites facilitate the transport of groundwater because they do not have semi-impermeable foundations to retard the flow of moisture by capillary absorption. The thickness of walls in direct contact with the ground is associated with the rate of absorption of moisture and the height of rise (Hall and Hoff, 2003; Massari and Massari, 1985; Torres and Freitas, 2010). Aspects of the architectural form of semi-natural sites such as thick permeable walls, exposed roofs and cliff faces pose a substantial risk to moisture-driven weathering processes like salt weathering and wetting-drying cycles.

Moisture-related damage from infiltration of rain, surface runoff, flooding and high humidity has been observed by several studies on rock-cut architecture (2.2). However, the role of groundwater uptake in moisture-related damage has not been investigated in detail thus far. Capillary rise of groundwater in the lower parts of masonry structures and rock-cut structures can cause significant damage (Heinrichs, 2008; Massari & Massari, 1985). Without foundations to slow down the capillary uptake of water, rock-cut architecture is likely to have high rates of capillary uptake of moisture. The increased flow of moisture can considerably increase vulnerability

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to damage (Hall, 2011). Therefore, it is essential to characterise moisture dynamics in rock-cut architecture to gain insights into moisture-driven decay processes such as salt weathering.

Table 2.2: Examples of the main processes of moisture-driven weathering at a range of rock-cut sites.

Location	Summary	Citation
Yoshimi Hundred caves, JAPAN	<ul style="list-style-type: none"> • Infiltration of large volume of water • High humidity • Freeze-thawing 	Germinario and Oguchi, 2021
Bingling Grottoes, CHINA	<ul style="list-style-type: none"> • Direct infiltration of rainfall through densely fractured cliffs • Groundwater uptake • Freeze-thawing 	Chen et al., 2019
Tongtanyan Grottoes, CHINA	<ul style="list-style-type: none"> • Rain infiltrates through joints 	Wang et al. 2018
Mogao grottoes, CHINA	<ul style="list-style-type: none"> • Rain erosion • Flood scouring 	Guo et al., 2009
Yungang Grottoes, CHINA	<ul style="list-style-type: none"> • Infiltration of rainwater 	Huang, 2007
Petra, JORDAN	<ul style="list-style-type: none"> • Relative humidity and T fluctuation • Flash floods 	El-Gohary, 2017; Heinrichs, 2008; Paradise, 2002

Theban tombs, EGYPT	<ul style="list-style-type: none"> • Infiltration of water along steeply dipping open fractures • High humidity • Periodic flooding 	Ángel Molinero Polo and Soler Javaloyes, 2019 ; Ziegler et al., 2019
Cappadocia, TURKEY	<ul style="list-style-type: none"> • Fractures enhance rate of infiltration • Surface runoff promotes active erosion conditions • Groundwater seepage • Freeze-thawing 	Ulusay et al., 2006 Dinger et al., 2016 Topal and Doyuran, 1998
St Emillion, FRANCE	<ul style="list-style-type: none"> • Severe infiltration of rainfall • Groundwater uptake 	Vouvé et al., 1997

2.2.5 Rock decay processes

A broad review of studies on rock-cut sites demonstrates that the focus of research on rock decay processes is salt weathering and biological weathering. Salt attack is one of the most hazardous agents in the deterioration of historical architecture (Doehne, [2002](#); Goudie and Viles, [1997](#)). Salt weathering has been identified as a challenging conservation problem in rock-cut sites (Fauchard et al., [2018](#); Heinrichs, [2008](#); Ioannou and Theodoridou, [2011](#); Wedekind and Ruedrich, [2006](#)). These studies have largely been focused on identifying the source and types of salts and ex-

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perimentally analysing the rate of salt induced decay. Previous quantitative analysis of anions in soluble salts in Lalibela indicated low concentrations of salts (Renzulli et al., 2011). Based on this analysis, the study ruled out the possibility that salt crystallisation plays a significant role in weathering at Lalibela. However, field observations indicate that salt weathering plays a significant role in the deterioration of the churches at Lalibela. There is abundant evidence of salt efflorescence in the churches, courtyards and trenches at Lalibela. Quantitative analysis of the concentration of salts and the micro-climate conditions at Lalibela are essential to clarify the frequency and extent of salt-driven decay at Lalibela.

There is a geographical clustering of the studies of biological weathering on rock-cut structures. Most of the studies are carried out on sites located in Japan and China (Wang et al., 2010; Duan et al., 2018; Duan et al., 2017; Germinario et al., 2020; Ma et al., 2015). In Lalibela, the role of lichen induced biodeterioration via hyphae contraction/swelling and acidolysis/dissolution was noted as a significant problem that can cause both physical and chemical weathering (Schiavon et al., 2013). Lichens can also contribute to the protection of rock surfaces from abiotic weathering mechanisms such as temperature fluctuation (Carter and Viles, 2003). The dominance of biodeterioration or bioprotection is dependent on lichen species or on climatic conditions (de la Rosa et al., 2013). Characterising the climatic condition at Lalibela and seasonality in the proliferation of organisms will contribute to clarifying the role of biology on the rock-cut churches at Lalibela.

2.2.6 Conservation and preservation of rock-cut sites

The study of the deterioration and conservation of rock-cut structures has generally focused on material characterisation. Limited research has been carried out on scientific and long-term studies of the preservation and conservation efforts at rock-cut structures. Xie and Zhang (2020) have trialled an inorganic consolidant on the weakly cemented fine-grained sandstone with low strength used to build numerous grottoes in China. Their results suggest the consolidant has great potential for consolidating severely weathered sandstone. Alhasan et al. (2020) assessed the effectiveness of sodium ferrocyanide in retarding salt crystallisation damage in the sandstone in Petra, which is severely affected by salt weathering. Using a single salt (NaCl), they showed that the efflorescence could be moved to the surface where it is less destructive. However, their results for salt mixtures were less promising. Grouting and consolidation have been applied to stabilize cliff faces and fractured rocks at Petra (Cesaro et al., 2017), Yungang grottoes (Liu et al., 2011), Lalibela (Steel, 2016) and Mogao grottoes (Guo et al., 2009). Preventive methods such as open shelters are in use in Lalibela and megalithic structures in Malta (Becherini et al., 2016). Conservation approaches at rock-cut sites have focused on chemically altering the rock properties or introducing a physical barrier such as shelters. Both these solutions are focused on solving moisture-related decay, either in the form of salt crystallisation or rain infiltration. There is still a lot that remains unclear about moisture dynamics in rock-cut settings, field studies of moisture transport in

rock-cut structures can inform the development of conservation measures that can adequately protect these structures from moisture-related decay.

2.3 Lalibela: Environmental and historical context

2.3.1 Environment and Geology

Semi-natural sites are created by altering the geomorphology and hydrology of a landscape. Figure 2.2 presents a conceptual diagram showing the timeline of natural and human influences in creating semi-natural sites. In Lalibela, for instance, the excavation of the churches has changed the landscape. The processes of excavation created large heaps of debris that was deposited around the churches. Large drainage channels, trenches, and cisterns carved around the churches altered the site's hydrology from how it naturally existed. Additionally, geophysical surveys have indicated that there are cavities below the surface (Ranieri et al., 2005); there are also underground tunnels that serve as footpaths. The combination of natural and human influences contributes to a complex and dynamic semi-natural setting that is influenced by geological and climatic factors that operate at a range of scales.

Lalibela is located in the northern Ethiopian highlands in the province of North Wollo, Amhara region. Lalibela and its surroundings are made up of thick lava flows intercalated with fresh basaltic lava flows and steep cliffs (Ranieri et al., 2005). The geological framework of Lalibela is the result of Paleogene Ethiopian volcanism (Beccaluva et al., 2009). The churches at Lalibela are found 2430 - 2550 meters

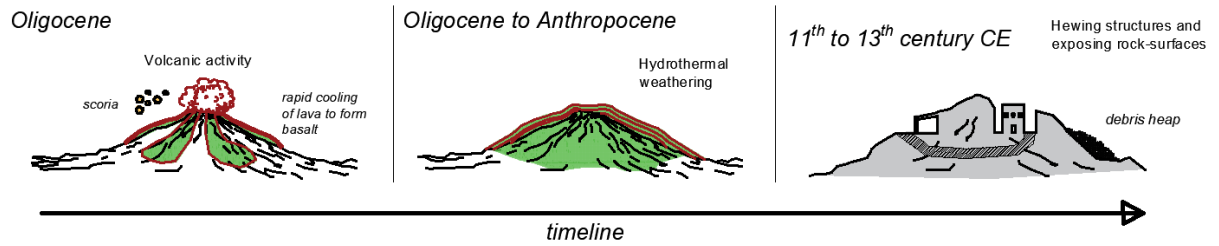


Figure 2.2: Conceptual diagram showing the transformation of a semi-natural landscape through natural (geological) processes and human activities (carving). *Source: Author's original diagram.*

above sea level in a very mountainous area with steep slopes and high elevations.

The churches are carved into a basaltic scoria hill at the foot of Mount Abune Yosef. Oligocene flood basalts (Aiba Formation) and the lower part of the Miocene Alaji Formation are exposed in Lalibela and its surroundings (Asrat and Ayallew, 2011) (Fig 2.3). The geology of the area is characterised by a basalt bedrock that is fresh at the base and weathered in the upper part (Delmonaco, Margottini, & Spizzichino, 2009). The basalt bedrock is overlain with a red moderately to highly weathered scoriaceous flow deposit that is basaltic in composition and has variously sized lithic fragments up to a diameter of 1 m (Ranieri et al., 2005). The churches are carved into the scoriaceous basalt layer deposit, which is 30 - 40 meters thick and is embedded within the massive basalt (Sani et al., 2012).

The method and the length of time it took to excavate the churches at Lalibela is not well known. The lack of sufficient archaeological data in the vicinity of Lalibela has made it challenging to ascertain the chronology of the churches and the method used to carve them. Fauvelle-Aymar et al. (2010) using morphological, functional and stylistic anomalies (like doors that lead to voids) suggest centuries-

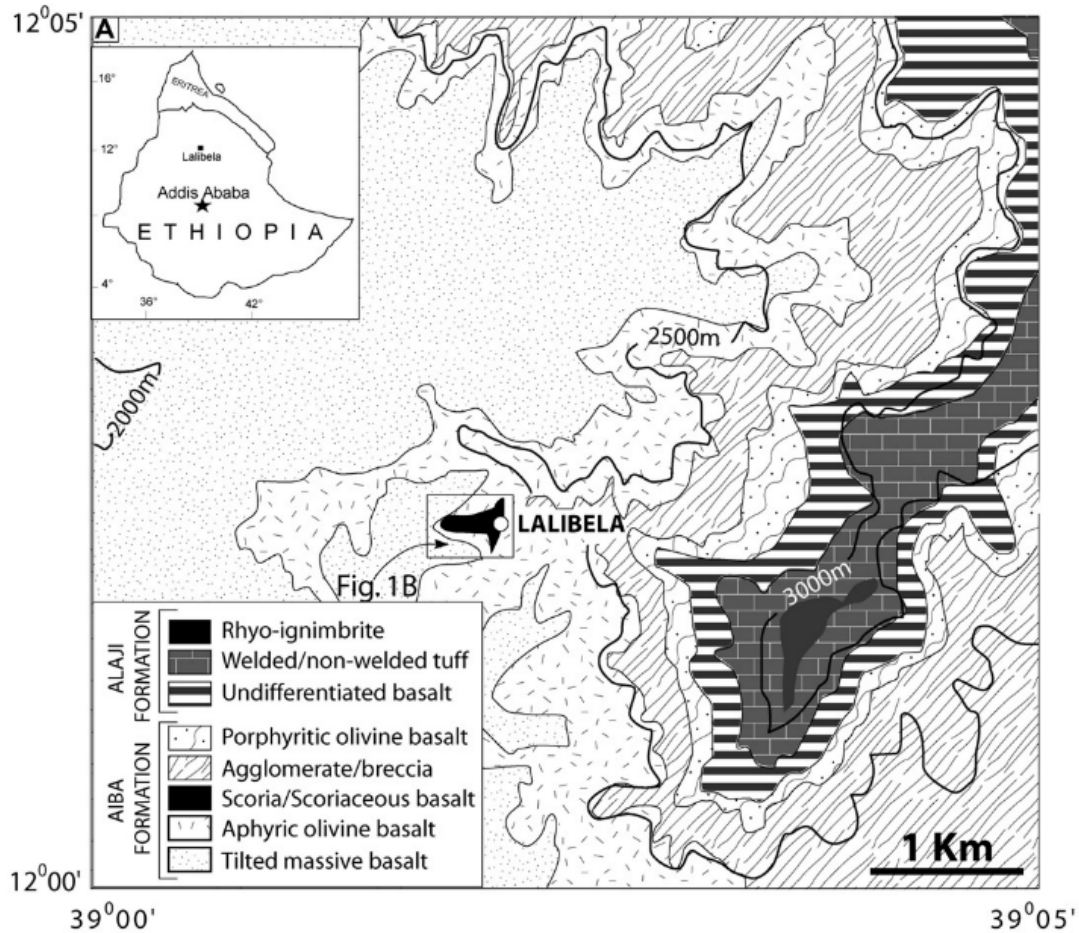


Figure 2.3: A simplified geological map of Lalibela area. *Source: Asrat and Ayallew 2011.*

long occupation and transformation of the site characterised by two monumental phases. Fauvelle-Aymar et al. (2010) do not convert this phasing into a chronology of the churches at Lalibela. Bosc-Tiessé et al. (2014) expand on the phasing principle using the same methodology and suggest that the morphology of the site continued to evolve with increasing human influences through time. They argue that the trenches, courtyards and churches were altered and restored episodically and that the ‘weakening of the rock’ led to the collapse of one of the churches. Philipson (2012), based on architectural features and stylistic differences, proposes five successive stages for the creation of the churches. In their assessment, Fauvelle-Aymar

et al. (2010), Phillipson (2012) and Bosc-Tiessé et al. (2014) have not sufficiently considered the role weathering plays on the durability of the churches. Gervers 2006 also uses stylistic anomalies and the condition (preservation state) of the bas-reliefs in Bete Golgotha to determine their age. He claims that the reliefs in ‘nearly perfect condition’ must have been carved after the reliefs in a deteriorated state. As discussed in section 2.2.3, variation in lithological and environmental conditions can cause localised deterioration. Using the state of bas-reliefs or the churches to determine their chronology must be done with great care. Given the complex historical and geomorphological settings, determining the phases of carving should be based on an understanding of the nature and rate of weathering at Lalibela. Weathering can exhibit non-linear and chaotic behaviour (Viles, 2005). Chronological phasing of the churches based on a simplified linear relationship between time and weathering may lead to inaccurate conclusions. A comprehensive approach to determine carving phases should integrate a detailed knowledge of the various lithological and climatic factors that control weathering of the churches at Lalibela.

2.3.2 Historical context

There is not much consensus among Ethiopian studies scholars on who built the churches at Lalibela. The Acts of Saint Lalibela are the first written accounts of the churches. It is believed to have been written a century after the churches were carved (Woldeyes, 2019). The Acts of Lalibela is a spiritual description of the life and miracles of Saint Lalibela. One of Saint Lalibela’s miracles is carving the churches

into a rock outcrop in the form and style God instructed him to do so. ‘He built the churches as God had shown him in the heavens. He changed neither the height nor the width’ (Acts of Lalibela, 2018, p. 213). A chapter in the Acts of Lalibela is dedicated to describing the churches and the order they were carved in. The book states that it took Saint Lalibela 24 years to build the churches with the assistance of workers and angles. Recent studies have challenged the timeline the churches were built and who built them. Nevertheless, research grounded in local knowledge (e.g., Woldeyes, 2019) is firmly based on the Acts of Lalibela. Gervers (2006), Fritsch, (2008) and Phillipson (2012) have argued that religious writings such as the Acts of Lalibela provide little information and are not reliable sources for historical research. These scholars have opted for an anthropological and art historical methodology and studied architectural and liturgical traditions to conclude that the churches were likely attributed to Lalibela posthumously. Mercier & Lepage (2012), drawing on a wide range of Ethiopian written sources (land grants and hagiographies) and art historical evidence, claim that Saint Lalibela built the churches.

Another point of contention among Ethiopian studies scholars is confirming date of construction. Saint Lalibela was the King of northern Ethiopia from 1133 to 1173 CE (Hable Selassie, 1972). Phillipson 2012 sets a much wider period from the 7/8th century CE to the 15th century CE and relies on the presence and absence of Axumite architectural features to determine the chronology of the churches. Recently archaeological studies have led to discoveries of rock-cut foundations of a built-up structure which was carbon-dated to the 11th and 12th century (Derat et al., 2021).

Gobezie (2018) took samples from a wooden door and chest and carbon-dated them to determine the age of the churches. The results showed that the wood used is from the 11th to 13th century CE. Gobezie's (2018) and Derat's (2021) carbon dating results correspond with Saint Lalibela's reign (12th century). Therefore, given the carbon dating and historical data available, it is possible to suggest, with some degree of certainty, that the churches were built between the 11th to 13th century CE.

2.3.3 Significance of the churches

The Axumite (4th – 9th century CE) period which preceded the Zagwe period (11th – 14th century CE) has numerous monumental architecture that attest to the nature of the Axumite civilisation (Hagos, 2010). The medieval Zagwe period of Ethiopia, on the other hand, does not have many monumental architectural legacies other than the rock-cut churches at Lalibela. The churches at Lalibela are regarded as important archaeological resources that convey the history and culture of the Zagwe dynasty. The churches also mark an important historical event: the geographical shift of the centre of the Christian Kingdom of Ethiopia to the south, from Aksum to Lalibela (Derat, 2020). The churches are an important historical archive because of the lack of architectural and archaeological evidence available for the study of the Zagwe civilisation.

The Ethiopian Orthodox Tewahedo Church considers the churches at Lalibela as holy sites and a place of pilgrimage. The rock-cut churches are perceived as 'living

entities endowed with the power to heal, teach, and bless' the faithful (Woldeyes, 2019, p. 12). Their largely uninterrupted use since their establishment and the wealth of manuscripts and crosses that are kept in the churches have added to their spiritual and heritage value. The preservation of the physical fabric of the rock-cut churches at Lalibela is essential to the continuation of a spiritual and material culture that has existed in that region for several centuries.

Several compelling interpretations have been suggested by scholars in terms of the reasoning behind the adoption of this building technique to carve churches in Ethiopia. Some have suggested that the rock-cut building traditions of Coptic Egypt came to Ethiopia due to the close relationship between the Coptic and Ethiopian Orthodox churches. Monastic asceticism has also been noted as one of the drivers of carving churches in inaccessible cliff faces. Gervers (2016) has argued that the motivation to carve churches instead of building them could be associated with the higher cost of procuring all the building materials required to construct a church rather than simply carving it into an outcrop. These observations are based on research on newly carved rock-cut churches in central and northern Ethiopia. The same argument has been proposed to justify the carving of rock-cut group-statues in the old Kingdom of Egypt (Rzepka, 1995). Regardless of the motivation of carving, it is evident that carving in rock outcrops has been widely used across the world for millennia and continues to be used in Ethiopia until present day.

2.4 Synthesis

Rock-cut architecture is found globally in various types of settings that can be generally described as semi-natural (Fig 2.1). The semi-natural sites framework shifts the paradigm away from a purely natural landscape or cultural landscape framework into a multifaceted conceptual framework that recognises the role played by both natural and human influences. This approach helps identify and characterise multiple weathering drivers that operate at various scales in semi-natural sites. It also highlights deterioration phenomenon that are rarely encountered in the built environment, such as geological discontinuities and joints that determine the durability of semi-natural sites.

Semi-natural sites are continually evolving through natural processes of weathering that are increasingly being influenced by human activity (e.g., carving, conservation, tourism and climate change). A broad review of the literature has shown that the interaction between rock mass and climate at rock-cut sites is assessed from two scales. The rock mass approach focuses on the geotechnical issues that can lead to mechanical failures and on rain infiltration through geological joints and fissures. The rock decay and rock properties approach has focused on lithological properties and the weathering features they are likely to produce. Salt weathering in semi-arid conditions like Petra has led to significant damage (Wedekind and Ruedrich, 2006). Biodeterioration has been the focus of research in cave temples that experience high humidity (see section 2.2.5).

2 Literature Review

To develop a comprehensive understanding of weathering in semi-natural settings, the nature of the interaction between rock mass and climate in this particular setting must be investigated holistically. In a semi-natural context, this interaction can also be conceptualised as architectural form (Fig 1.2), the point of contact between rock mass and climate. Rock-cut sites can have various architectural forms such as hypogean structures, cave/grottoes or monolithic structures, as shown in figure 2.4. The form of rock-cut structures will determine the extent of exposure to climatic variables and the nature of moisture-related damage. For instance, surface runoff is very common on cave/grotto type structures, as they are often carved into steep cliffs (see examples in table 2.2). While there are various lithological and climatic factors that control weathering, architectural form plays an important role in modifying the interaction of these two sets of factors in semi-natural settings.

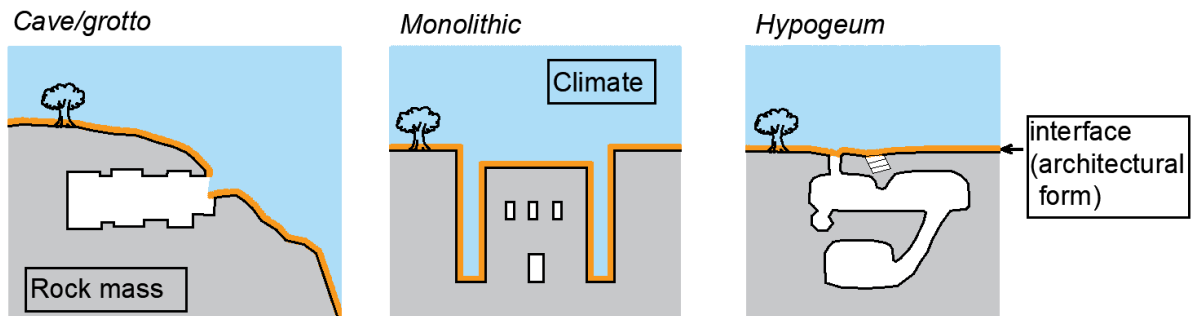


Figure 2.4: Conceptual diagram showing the influence of architectural form on the interaction between rock mass and climate at semi-natural sites. *Source: Author's own.*

2 Literature Review

Human activity in the form of carving, tourism and conservation are important factors that contribute to the transformation of semi-natural sites. ‘All building stones carry with them a stress history that reflects their origins, prior exposures to a range of environmental conditions and the treatment at the hands of quarrymen, builders and possibly conservators’ (Prikryl and Smith, 2007, p. 03). The origin of semi-natural sites is highly influenced by geomorphology and geology. There is not a clear separation of the stress history of rock-cut structures into pre-emplacment (e.g., stresses induced by quarrying process) and post-emplacment (e.g., conservation intervention) as is often done in masonry settings (McCabe et al., 2010; Prikryl and Smith, 2007). In semi-natural settings, pre-exposure and post-exposure are more relevant terms to describe stress history. Unlike pre-emplacment, pre-exposure stress history is mainly inherited from the geological processes that shaped the rock outcrop. The genesis of the rock outcrop will influence geotechnical properties and rock strength, which are inherited properties that influence the behaviour of semi-natural sites. The architectural form will control the post-exposure behaviour of newly exposed rock surfaces. The varied ways humans modify rock decay (conservation) will also play a significant role in post-exposure history.

The aim of the thesis is to develop a structured, holistic approach to understanding deterioration in a semi-natural setting by focusing on the rock-cut churches at Lalibela as a case study. The important roles of climatic and lithological controls on weathering in various contexts and at a range of scales introduced in this chapter. While the impact of history of conservation and architectural form in a semi-natural

2 Literature Review

setting are crucial factors that control deterioration, they have not been considered in detail in semi-natural settings. It is essential to analyse the key drivers of weathering of rock-cut architecture to develop a holistic approach to diagnosing deterioration at semi-natural sites. Using Lalibela as a case study, the four axes of change in semi-natural settings will be explored.

3. Methodology

3.1 Overview

This thesis investigates the four factors that drive weathering of rock-cut architecture. The role of climate, lithology, architectural form (the interface between climate and rock mass), and the history of conservation on weathering of the structures at Lalibela are presented in Chapters 4, 5, 6 and 7, respectively. By linking these key drivers of change, a holistic methodology for studying weathering of rock-cut architecture is developed (Chapter 8). Here, the overarching approach of the thesis and a brief overview of the methods used are presented. In particular, this section presents the multi-scale and multi-method approach followed in this thesis. The specific analytical and experimental methods used and the rationale for the use of methods are presented in detail in each results chapter.

For a comprehensive evaluation of stone decay, a multi-scale and interdisciplinary approach is required (Fitzner et al., 2002). Stone conservation deals with the conservation of historic masonry structures. It is a multi-disciplinary field that uses methods from art conservation, engineering, geochemistry and geomorphology (Doehne and Price, 2010). The methodology adhered to in this thesis builds on the inter-

disciplinary nature of stone conservation and integrates conceptual models from the field of geomorphology and architecture. Geomorphology, which deals with the slow physical and biogeochemical processes that occur to rocks in the natural environment (Pope et al., 2002), has contributed to the understanding of micro-scale stone decay in the built environment (Viles et al., 1997). The spatial and temporal scale of investigation in stone conservation is much narrower than in geomorphology. As stone conservation mainly deals with works of architecture, which are made through a scaling approach centred around humans, the scale of investigation is usually limited to buildings or urban landscapes. However, conservation of the architectural fabric, form and aesthetic is influenced by regional-scale processes like climate. A multi-scale approach is, therefore, essential to identify the processes that lead to weathering of semi-natural heritage sites like Lalibela.

3.2 Framework

Lithological and climatic variables interact at a range of scales in semi-natural sites. Up-scaling or down-scaling field and laboratory observation in weathering studies can be challenging (Viles, 2001). For a comprehensive assessment of weathering in rock-cut sites, it is essential to conduct the study over a broad spatial and temporal scale (Table 3.1). Characterisation of climatic conditions at Lalibela involved a multi-scale approach, ambient regional climate variables and micro-climate conditions were assessed at different temporal scales. Ambient climatic variables

3 Methodology

such as rainfall were analysed over a longer period of time to account for high inter-annual variability in rainfall in northern Ethiopia. The lithological and geological properties have been the focus of several research papers that focused on Lalibela (see section 2.3.2). In this thesis, the lithological studies focused on experimentally assessing the hygric and hydric behaviour of the clay-rich basaltic scoria the churches are carved into. To determine the influence of architectural form (exposure) on moisture dynamics, the distribution of moisture on the surface and subsurface of exterior walls was measured during the wet and dry seasons. Salt and moisture distribution were assessed in the interior walls of a church that exhibited localised deterioration. This was done to determine aspects of the architectural form that might be contributing to spatially localised decay. Archival research on the restoration of the churches and the traditional conservation methods used to protect them was informative of the conservation history of the churches. By combining data from the laboratory, archives, experimental analysis and onsite measurements, the nature and rate of weathering processes that operate at various spatiotemporal scales can be better understood. The discussion section of the thesis will synthesise the results presented in the papers into a holistic understanding of the processes that contribute to the deterioration of the churches at Lalibela and an approach to studying weathering in semi-natural contexts.

Table 3.1: Spatial and temporal scales of studies carried out in this thesis. For further information on each of the papers refer to section 1.2.2.

Papers	Topic	Spatial scale	Temporal scale
I	Micro-climate Regional climate	m km	seasons years
II	Characterisation of petrophysical properties Hygric and hydric behaviour of samples	cm cm	n.a. days
III	Temporal and spatial variation in surface and subsurface moisture (exterior)	m	seasons
IV	Moisture and salt distribution measurement (interior)	m	n.a.
V	History of transformation and conservation	n.a.	centuries

3.3 Study site

The diversity of rock-cut church types in Lalibela makes it a suitable site to investigate the factors that influence deterioration at rock-cut sites and develop a holistic approach to studying and preserving them. Rock-cut structures in northern Ethiopia have largely not been studied. Given the vast number (> 200) of rock-cut sites found in northern Ethiopia (Asrat, 2002) and the lack of research on weathering of these structures, an investigation of the climatic variables that control weathering at Lalibela will be informative for other rock-cut sites sharing a similar climate. It should also be noted that Lalibela has religious and cultural values and contributes to the tourist industry in Ethiopia. As such, the preservation of Lalibela will have broader cultural and economic implications.

3.3.1 Climate, mineralogy and petrology

Lalibela is located in the northern Ethiopian highlands in a rugged landscape with steep slopes. The complex topography of Ethiopia (Fig 3.1 a) plays a role in variation of climate across the country (Nyssen et al., 2005). The climate in northern Ethiopia is characterised by seasonal rainfall that mainly occurs in the main rains season (Jul - Aug). Temperature does not vary significantly across the year in the northern part of the country. Detailed information about the climate of Lalibela is provided in section 4.2.

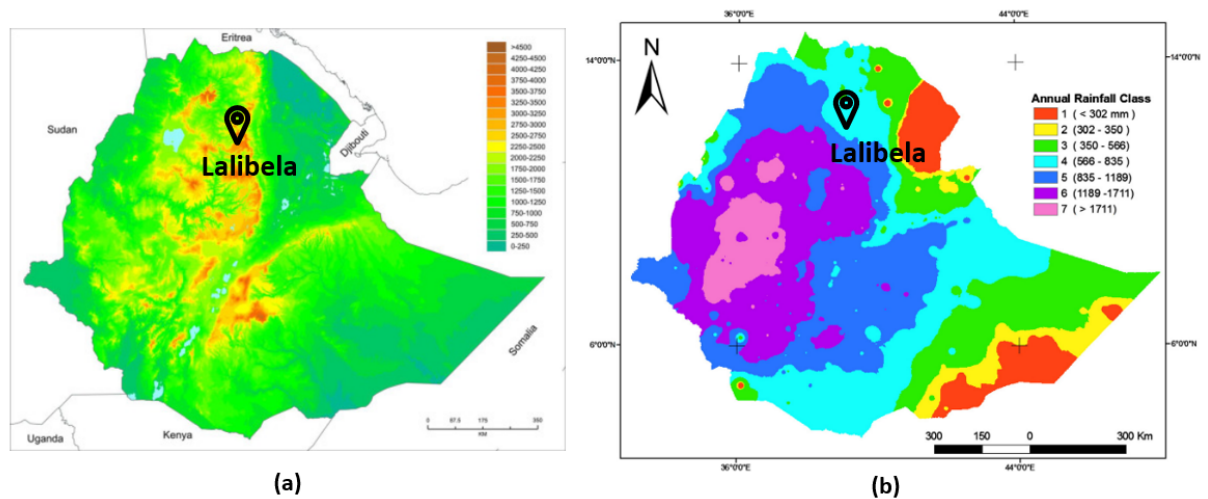


Figure 3.1: (a) Topographic map of Ethiopia. *Source: Asefa et al., (2020)*. (b) Map showing mean annual rainfall variation across Ethiopia. *Source: Berhanu et al., (2013)*.

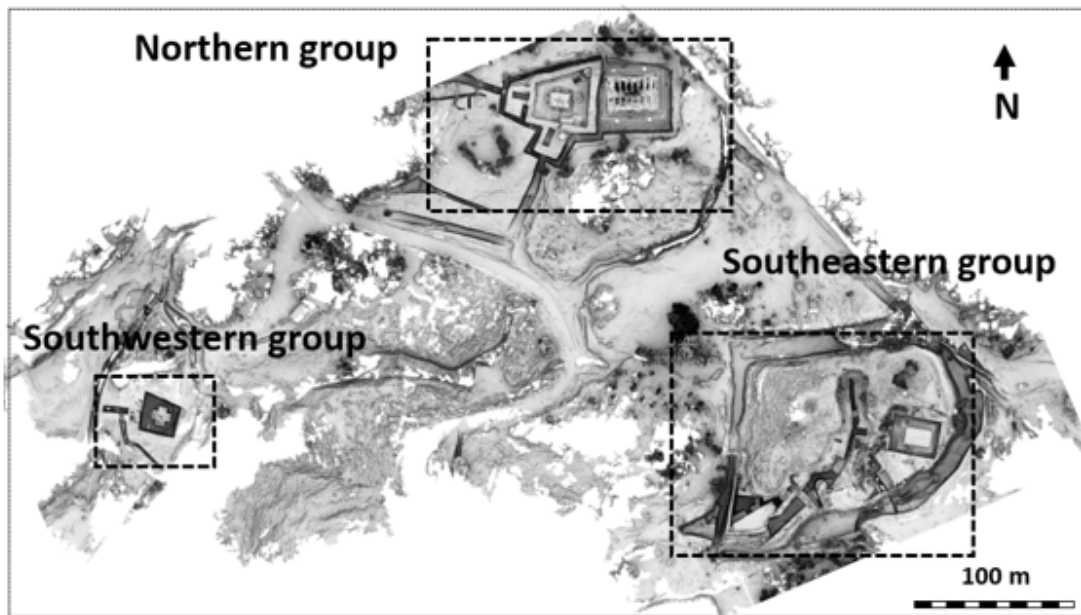
The churches are made from highly vesicular (35 - 70%) hydro-thermally altered basaltic scoria, that has low apparent density ($1.49 - 2.13 \text{ g/cm}^3$) and high open porosity (17.5 - 45.2 %) (Renzulli et al., 2011). The bulk petrography is characterised by a microlitic texture with a low porphyritic index (Schiavon et al., 2013).

Semi-quantitative X-ray diffractometry shows an abundant presence of smectite, zeolite minerals (analcite, heulandite and natrolite) and calcite, while primary minerals such as pyroxene and plagioclase are low in abundance (Renzulli et al., 2011). The vesicles are partially or fully filled with zeolite minerals (Asrat and Ayallew, 2011) which are potent water absorbers due to their abundant micropores (Galán, 2006). Fourier transform infrared spectroscopic analysis of the rocks at Lalibela identified montmorillonite (smectite) up to 20 mm in depth from the rock/atmosphere interface.

3.3.2 Layout of the churches

The churches at Lalibela are found in three groups that are connected via tunnels and pathways. The eleven churches of Lalibela are below the ground level and are accessed through tunnels that lead to the west-facing entrance of the churches. The complex also has crypts, cisterns and underground tunnels that are generally not accessible to the public. The type of churches found at Lalibela can be classified into two main types: the cave type and the monolithic type. The cave type of rock-cut church resembles enlarged caves (Bete Aba Libanos in Fig 3.2), and the monolithic types are carved out from all sides except the bottom that is still connected to the rock mass (Bete Giyorgis in Fig 3.2 b). The method of construction for the two types of rock-cut structures found in Lalibela is likely to have differed. The monolithic churches would have had to be built from the top down while the cave types would have been carved starting from the outward-facing wall into the

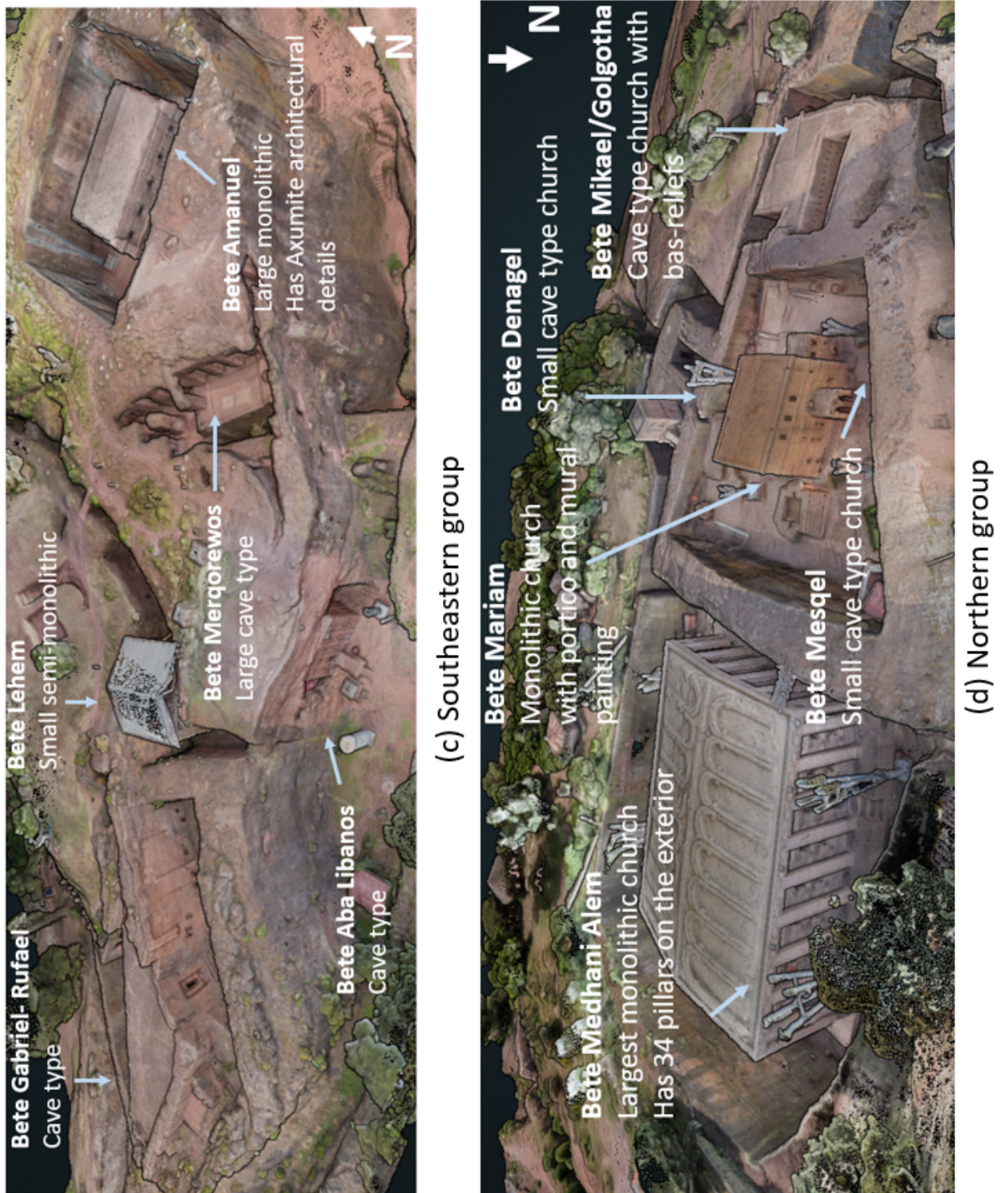
interior. The monolithic churches have a courtyard that is surrounded by a rock wall. Bete Mariam (Fig 3.2 d) has the most spacious courtyard of the monolithic churches.



(a) Site plan of the church complex



(b) Southwestern group



(b)

Figure 3.2: (a) Top view of a 3D laser scanned model of the group of churches at Lalibela. *Source: Zamani project, 2010.* Aerial view of a 3D photogrammetry model of the (b) southeastern group (c) southwestern group and (d) northern group. *Source: Archaeovision, 2019.*

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The monolithic churches are rectangular and have a basilica plan except for Bete Giyorgis, which has a cruciform plan. They are oriented to the cardinal directions with the *meqdes* or Holy of Holies in the east and the main entrance in the west. The Holy of Holies of the cave type churches faces east, but unlike the monolithic churches, their entrance does not face west (e.g., Bete Gabriel-Rufael and Bete Aba Libanos). The architectural style of the churches at Lalibela borrowed heavily from the architecture of the Axumite empire. The best example of this is the facade of Bete Amanuel, which is essentially a carved version of the Axumite method of creating alternating recessed and projected forms by layering long horizontal wooden beams with stones and mortar (Fig 3.3 a). Ornaments like string courses and pointed arches (Fig 3.3 c) were used to decorate the facade. The church of Golgotha in the Bete Mikael-Golgotha complex has life-sized bas-reliefs in the internal walls of the church (Fig 3.3 b). Unique among the churches, Bete Mariam has an exterior frieze of horsemen above the portico of the west-facing wall (Fig 3.3 d) and mural paintings of biblical scenes on the ceiling.

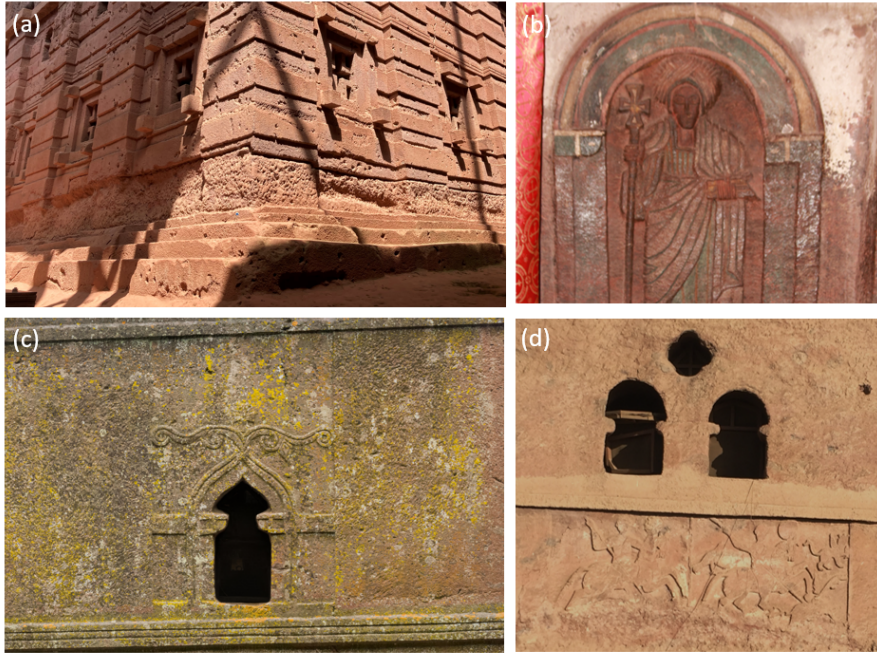


Figure 3.3: Architectural details of the churches at Lalibela.(a) monkey head styled facade at Bete Amanuel, (b) life sized bas-reliefs at Bete Golgotha, (c) pointed arch and string course at Bete Giyorgis and (d) frieze at Bete Mariam.

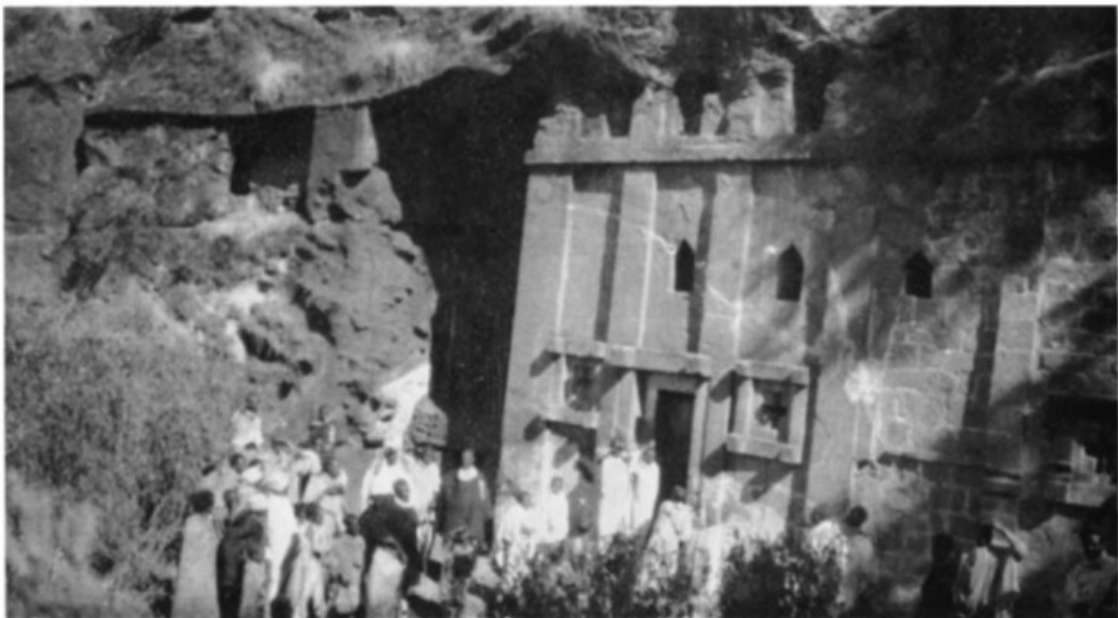
3.3.3 Conservation state of the churches

The state in which we find the churches in Lalibela today is a product of many conservation and restoration efforts to maintain the churches both functionally and aesthetically. Conservation reports and historical accounts and photos are useful resources that can reveal the post-exposure stress history of the churches. Conservation efforts in Lalibela can be classified broadly into three chronological categories: (1) conservation works carried out locally before 19th century, (2) conservation works done in the early 20th century and do not have adequate documentation and (3) late 20th and early 21th conservation works that were done by international and local experts and were adequately documented. Chapter 7 (Paper V) focuses on assessing

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the impact of 1 and 2 and the lessons that can be learned from traditional conservation efforts. This section briefly outlines modern conservation efforts to restore the churches (2 and 3).

One of the first restoration projects in Lalibela was commissioned by the then royal family in the 1920s (Angelini, 1967). There hasn't been sufficient documentation describing the extent of work that was done during this restoration campaign. Interviews with local community members whose families participated in the restoration have noted the use of cement to consolidate the walls (Ayalew, 2016). From photographs taken in 1925 by McGrath (1925), there are bright white areas that contrast with the reddish coloured rock walls that may be cement (Fig 3.4). The extent of the work done is not known but McGrath's (1925) photos show that there was some work done on the facade of Bete Aba Libanos.



FAÇADE OF LIBANOS CHURCH, RECENTLY REPAIRED WITH MUD BRICKS

Figure 3.4: Bete Aba Libanos as photographed in 1925. Source: McGrath, (1925)

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Restoration efforts in the 1950's employed aggressive techniques, such as the use of Portland cement to restore the roofs in some of the churches. The facades of Bete Amanuel, Bete Medhani Alem and Bete Mariam were entirely painted with a tar-based paint to prevent moisture-driven decay (Angelini, 1967). This significantly changed the appearance of the churches (Fig 3.5 a). Such works may have also facilitated salt loading, evidence of salt efflorescence likely caused by the excessive use of cement is visible at the base of Bete Aba Libanos (Fig 3.5 b).

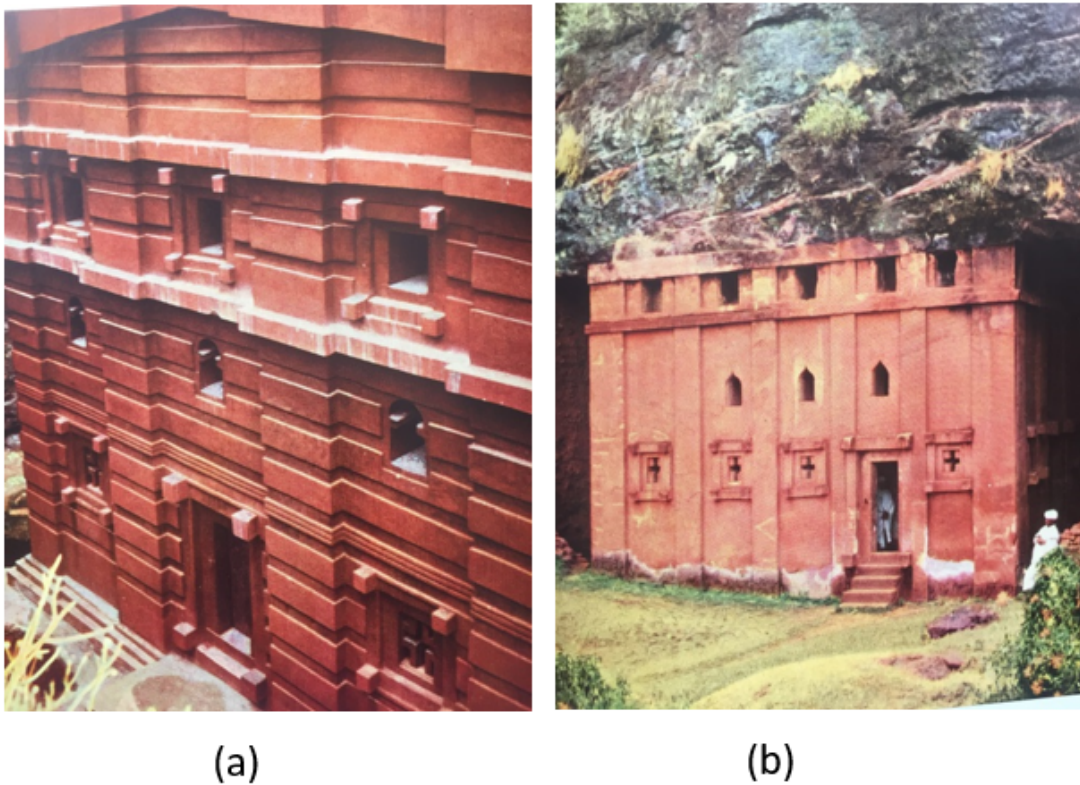


Figure 3.5: (a) Bete Amanuel and (b) Bete Aba Libanos as photographed in 1959. Source: Bidder, (1959)

In cooperation with the International Fund for Monuments and the Ministry of Public Works, a 3 year conservation project led by conservation architect Sandro Angelini was started in 1967 (Angelini, 1967). The guiding principle of this restora-

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tion campaign was to safeguard the churches from further deterioration, to remove ‘false’ additions and to re-establish the monolithic form of the structures. As such, the paint was removed from the churches and the cement layer on the roofs was also removed (Fig 3.6). While the materials used for restoration in the 1950s were incompatible, the process of removing them was also very destructive (Fig 3.6). Angelini, (1967) believed the principal agent in the deterioration of the churches was heavy rainfall. To protect the churches from rainfall, he applied a sacrificial mortar layer on the roof of Bete Medhani Alem and Bete Mariam and sealed the cracks on the roof. Water repellent solutions were sprayed on vulnerable facades to prevent further damage to the walls of the churches.

Protection of the roofs continued to be a challenge after the restoration works done in the 60s. In the 1980s and 90s, less intrusive methods such as open shelters were used to prevent rain infiltration. In 2007 large open shelters were placed to protect the roof of four churches. These shelters were implemented as a temporary measure (5 years), but they haven’t been removed after nearly 15 years. There hasn’t been an assessment thus far of the impact of the shelters on limiting the exposure of the structures to rainfall.

Conservation works carried out in 2016 and 2018 have focused on individual churches. In 2016 the surface of Bete Gabriel-Rufael was cleaned by scrubbing and washing biological growths on the surface, cracks and large detached material at risk of falling were stabilised by grouting and the roof was laid with an impermeable layer of mortar (hard capping) (Steel, 2016). In 2018, similar works were done at Bete

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(a)



(b)

Figure 3.6: Bete Medhani Alem (a) after it was restored with Portland cement in 1959. *Source: Bidder (1959)* and (b) subsequent removal of cement layer in 1967. *Source: Angelini 1967*

Mikael-Golgotha. These conservation efforts haven't been monitored to determine the efficacy of the conservation techniques applied. These conservation works were also done in the absence of studies on the climatic conditions, moisture dynamics and hydric and hygric properties of the stone.

Table 3.2 summarises the conservation works done on the churches and their present state. Field observations of major decay features such as fractures and cracks are also included in the table. The summary indicates that most conservation efforts were focused on tackling either rain infiltration or managing decay of the roofs.

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Table 3.2: Summary of conservation works carried out at Lalibela. Summarised from field observation and reports prepared by Steel, (2016) and Angelini, (1967)

Churches	Summary of conservation and current state
Bete Medhani Alem	<ul style="list-style-type: none"> • Pillars damaged and replaced with masonry • Heavily damaged roof • Sheltered • Has major cracks and fractures
Bete Mariam	<ul style="list-style-type: none"> • Roof of porticoes has been damaged and restored several time • Base of the church damaged due to damp rise • Sheltered • Has cracks and fractures
Bete Mikael-Golgotha	<ul style="list-style-type: none"> • Roof badly damaged and heavily weathered • Roots of plants deeply embedded on the roof. • Has cracks and fractures • Hairline cracks across the arches in the interior.
Bete Denagel	<ul style="list-style-type: none"> • Rain infiltration • Salt weathering on the ceiling of the church
Bete Mesqel	<ul style="list-style-type: none"> • Lower part of the exterior wall partially restored • Roof exposed to direct rainfall
Bete Gabriel- Rufael	<ul style="list-style-type: none"> • Biological soiling removed (2016) • Salt weathering in the interior of the church • Hard capping (2016) • Grouting of cracks (2016)

Bete Amanuel	<ul style="list-style-type: none"> ● Facades have large holes ● Weathered facade ● Surrounding courtyard wall has caverns ● Has cracks and fractures ● Sheltered
Bete Aba Libanos	<ul style="list-style-type: none"> ● Base of the church restored with masonry ● Has cracks and fractures ● Sheltered ● Pillars of shelter resting on the roof
Bete Merqorewos	<ul style="list-style-type: none"> ● Collapsed in the 1950s ● Restored with masonry in the 1960s ● Most of the original design and stonework lost
Bete Giyorgis	<ul style="list-style-type: none"> ● Has hairline cracks that diagonally transect the church ● In better condition relative to other churches ● Courtyard walls have caverns ● Biological soiling on roof

3.3.4 Deterioration of the churches at Lalibela

ICOMOS-ISCS Illustrated glossary on stone deterioration patterns (ICOMOS, 2008) was used to identify decay features at Lalibela. Areas exposed to moisture, such as the upper and lower part of the structures, show the most damage. The previous section has noted that several of the conservation efforts were focused on preventing rain infiltration through the roof. The lower part of the structures is also

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exposed to moisture through capillary absorption of groundwater. At Bete Giyorgis and Bete Medhani Alem, the base of the structures has developed a cavity (Fig 3.7 a and c). In Bete Merqorewos, a load-bearing column has been significantly eroded at the base, likely due to capillary uptake of moisture (Fig 3.7 b). The lower part of the facades at Bete Amanuel has noticeably deteriorated in the range of 1 to 1.6 meters above the base of the church (Fig 3.7 d).

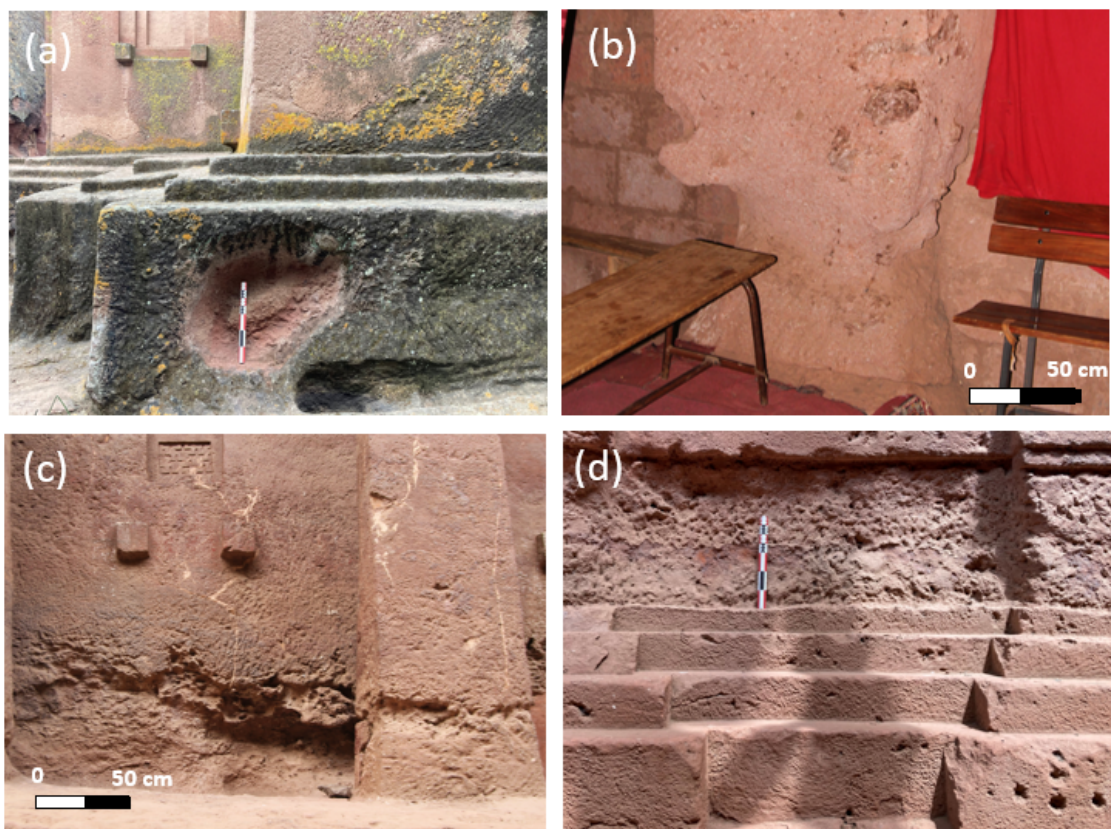


Figure 3.7: (a) South-facing wall at Bete Giyorgis showing a large cavity (> 60 cm). (b) Load bearing column in Bete Merqorewos eroded at the base. (c) Differential erosion on the base of the east-facing wall Bete Medhani Alem. (d) Deteriorated base of north facing wall at Bete Amanuel. *Source: Author's own.*

Salt weathering is also a major conservation challenge in Lalibela. Renzulli et al. (2011) and Delmonaco et al. (2009) have suggested that salts play a minor role in weathering at Lalibela. Field observation shows that contour scaling (Fig 3.8 d),

scaling and granular disintegration are driven by crystallisation of salts. The roofs of the churches that have been repeatedly restored using cement are rich in salts, as seen in Bete Mikael-Golgotha (Fig 3.8 a) and Bete Amanuel (Fig 3.8 b). Small (cms) networked cracks (craquele) also occur in some areas that don't appear to be significantly affected by salts (Fig 3.8 e).

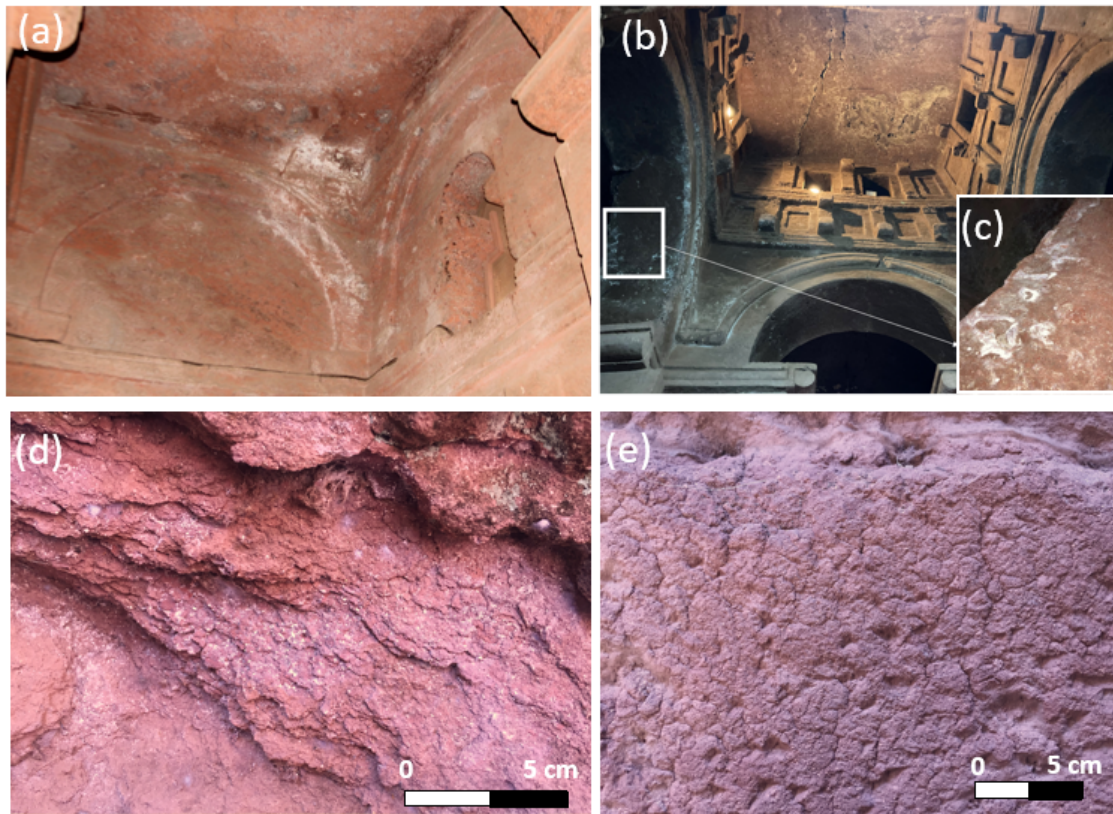


Figure 3.8: (a) Salt efflorescence on the ceiling of Bete Mikael/Golgotha (b) Salt efflorescence on the ceiling of Bete Mikael/Golgotha with an (c) inset showing salt rich areas. (d) Contour scaling and salt efflorescence on the entrance tunnel at Bete Giyorgis. (e) Craquele on the the south-facint wall at Bete Amanuel. *Source: Author's own.*

3.3.5 Rationale for selecting study areas

Measurements and monitoring in the field were carried out at strategic locations and times in representative study areas/churches. Great care had to be taken to se-

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lect study areas that were representative of the church complex and were accessible to the public. Lalibela is a high-profile UNESCO World Heritage Site, religious ceremonies, like mass, are held every day and Saints' days are celebrated every month. Before the start of the pandemic and the conflict in northern Ethiopia, the site was visited by thousands of tourists every year. The churches are usually surrounded by worshippers, monks, nuns and priests in the early hours of the morning and tourists swarm the area the rest of the day. Because of this, it was not possible to leave monitoring equipment unsupervised for long-term monitoring.

Accessible areas that represented the site as a whole and were suitable for comparative analysis were selected as study areas. Paper II (lithology) and Paper V (history of conservation) focused on a wide selection of churches. Mineralogy and petrology of samples collected from seven churches were assessed to determine their lithological properties. Similarly, the history of conservation of the sites included most of the churches. The climate at Lalibela was studied (Paper I) at the regional and rock-surface scale. Micro-climatic conditions were monitored at Bete Mariam because it is a monolithic church with each of its four walls facing a cardinal direction. It is also the only monolithic church with low enclosure walls that are at a distance and unlikely to have an effect on the micro-climate. The proximity of the enclosure walls to the church walls in Bete Amanuel and Bete Medhani Alem may lead to a shielding effect. Bete Giyorgis was also not chosen for this study because it has a cruciform plan, unlike the rectangular plan of the other churches. The influence of architectural form (Papers III and IV) was studied on the interior

of Bete Golgotha and the exterior of Bete Amanuel and Bete Giyorgis. The north and south interior walls of Bete Golgotha have two sets of life-sized bas-reliefs in very weathered and in good preservation states. This study area was considered ideal for determining the role of architectural form on localised deterioration. Moisture dynamics were assessed at a sheltered (Bete Amanuel) and unsheltered (Bete Giyorgis) churches to do a comparative analysis. A summary of the rationale for selecting study areas as the focus of the papers is provided in table 3.3.

Studies on ambient climatic conditions, lithological characteristics as well as history of conservation were done at a scale that is representative of a majority of the churches. Logistical limitations meant that studies on micro-climate, moisture dynamics and localised deterioration had to be done on four out of the eleven churches in the complex. Broader implications that apply to all the churches can be drawn from understanding the role of the ambient climate and architectural form on micro-climate and moisture dynamics at Lalibela.

Table 3.3: Rationale for selecting study areas as the focus of Papers I - V (see section 1.2.2).

Papers	Objective: to assess	Site	Rationale
I	ambient and micro climatic trends	Micro-climate monitoring at Bete Mariam	Has four walls facing each cardinal direction and the church has a regular shape (no large architectural details or cruciform plan).
II	lithological influences on weathering	Wider selection of churches	To characterise general mineralogy and petrology of the churches
III	moisture dynamics	Bete Amanuel & Bete Giyorgis	Compare sheltered and unsheltered monolithic churches during wet and dry seasons
IV	localised deterioration	Bete Golgotha	Four bas-reliefs in the internal walls of the churches in different preservation states

V	assess history of conservation	Wider selection of churches	To assess the impact of repeated conservation and restoration of the churches as well as the efficacy of traditional conservation techniques
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3.4 Methods

The studies in this thesis were conducted using a combination of field and laboratory methods, with additional analysis of secondary climatic data sets and archival data sources. Field studies informed laboratory experiments, and laboratory-based calibration of field equipment under controlled conditions in the lab was used to meaningfully interpret data collected onsite (Fig 3.9). Samples collected from around the vicinity of the churches were used to characterise the mineralogical composition of the basaltic scoria. As these samples were not large enough to conduct experiments on, fresh quarry samples were acquired from a nearby quarry for experimental assessment of the hydric and hygric properties and for gravimetric calibration. Inferential and descriptive statistical methods were used when handling large data sets such as the 29-year climate data (Chapter 4) and gravimetric analysis of non-destructive moisture measuring systems (Chapter 5).

3.4.1 Field methods

‘Fieldwork generates unique and vital insights into the processes that decay world heritage sites’ (Dorn et al., 2013, p.62). Field observation of a phenomenon within

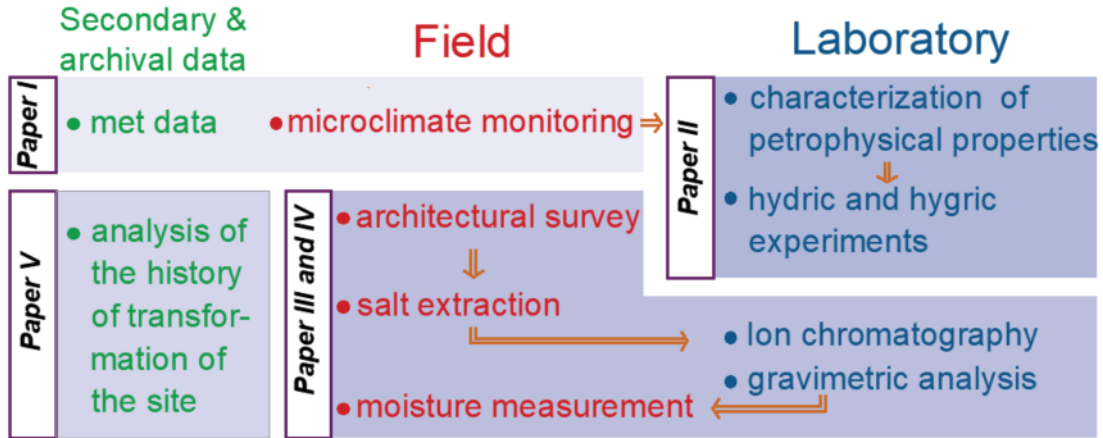


Figure 3.9: Sequence of field methods, laboratory methods, secondary data and archival data used to investigate weathering at Lalibela.

the context of its natural setting is one of the primary ways of understanding complex real-world phenomena (Turkington, 2010). In this study fieldwork involved a survey of the conservation state of the churches, micro-climate monitoring, collection of secondary data (Met data), collection of samples, and non-destructive on-site measurements.

While long-term field surveys have an overall advantage in capturing the full range of processes and fluctuations that affect weathering, short field surveys that are timed appropriately can produce useful information that can be used to build a broader understanding of processes in the natural and built environments. Field trips were timed outside of major religious holidays and were aligned to different climatic seasons. This was done to monitor the climate and take non-destructive measurements in different climatic conditions. Fieldwork was done in the following periods:

- 20 May 2018 – 30 May 2018 (Small rains season)

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- 17 Dec 2018 - 30 Dec 2018 (Dry season)
- 22 Jul 2019 - 01 Aug 2019 (Main rains season)
- 20 Oct 2020 – 31 Oct 2020 (Dry season)

The principle of built heritage conservation is concerned with preserving as much of the original fabric (ICOMOS, 1964) as possible; when samples need to be taken, they are usually done in a way that does not disturb the historic fabric. Given the heritage status and the spiritual/religious status of the churches taking samples is generally restricted. Sampling methods that are minimally destructive or destructive, like drilling or coring, are only allowed in exceptional circumstances. Therefore, in this study pieces of rocks that were detaching from the walls of the churches make up a majority of the samples used for lithological analysis. Quarry samples were acquired from the Yohannes Amba quarry, located approximately 2 km away from the church complex (Fig 3.10). Along with a permit to conduct research at Lalibela from federal authorities, local authorities and the Administration of the Lalibela Monastery, all samples taken from the churches also had to be inspected and approved by the Ministry of Mines in Addis Ababa.

3.4.1.1 Architectural survey

In stone conservation studies, the first stage in diagnosing weathering of building stones is understanding the background and extent of damage to the structures to clarify the underlying causes of the deterioration (Prikryl and Smith, 2007). There



Figure 3.10: Location of quarry (Yohannes Amba) and meteorological station relative to complex at Lalibela.

are different approaches to condition assessment of architectural heritage. Digital documentation and analysis of architectural heritage using methods like Building Information Modelling (BIM) and 3D scanning are advanced methods to analyse virtual historic building models. High-resolution 3D laser scanning is a very useful tool in documenting historic structures in great detail. 3D documentation of the churches at Lalibela was done in 2007 (Rüther and Palumbo, 2012) and more recently in 2019 by Archaeovision. BIM has advanced simulation capabilities and can be used with modelling techniques (Finite Element Modelling) for structural analysis of composite historic buildings (Barazzetti and Scaioni, 2009). However, while BIM is a robust method for integrated documentation of historic buildings, they have yet to integrate tools that allow simulation of data relevant to preventive conservation

(Pocobelli et al., 2018). At present, BIM is better suited for detailed documentation, but it is a complicated method to employ for a comprehensive understanding of decay patterns on historical monuments. Integration of BIM with hygrothermal models and structural analysis models might make these methods more applicable in stone conservation research.

Other methods of assessing the condition of architectural heritage rely on the expertise of the surveyor and visible decay patterns. The monument mapping method was developed by Fitzner (2003) to ensure a reproducible assessment of damage categories and damage indices for precise documentation, quantitative evaluation and rating of stone damage (Fitzner and Heinrichs, 2001). A more formal method of condition assessment of building stones was proposed by Warke et al. (2003) known as the Tumour (T), Nodes (N) and Metastasis (M) staging system. The TNM staging system is a classification scheme developed by clinicians to aid assessment and treatment planning for patients with cancer. Warke et al. (2003) adapted the TNM staging system to a Unit (U), Area (A) and Spread (S) staging system which indicates increasing problems with regard to deterioration and can be used to forecast the extent of remedial intervention. Monument mapping and the TNM (or UAS) staging system methods are useful in documenting and could have the potential to forecast future damage profiles. However, they are time-consuming techniques that are best to use when other aspects of weathering are well known and understood. Heinrichs (2008) applied the monument mapping method, but he had to supplement it with onsite measurements and laboratory investigations to diagnose weathering damage

at Petra (Heinrichs, 2008). Rodrigues (2015) proposed an innovative methodology moving away from mapping individual deterioration patterns to a comprehensive assessment of problems and conservation needs. The system relies on the expertise of the conservation scientist for reliable outputs. But it has the potential to be usefully implemented as an initial survey method to identify patterns of decay and vulnerabilities that need addressing through further research. In this study, Rodrigues' (2015) methodology was used for a rapid assessment of the state of conservation of the churches. High-resolution orthographic photographs (orthophotos) taken by Archaeovision in 2019 were used in this study, along with site visits and observations, to do a survey of the current state of the churches. The condition assessment was complemented by archival resources. The condition assessment was also useful in identifying localised deterioration, assessing the effectiveness of restoration and identifying common weathering features. This assessment was particularly useful in understanding the vulnerability of the site to moisture-driven weathering processes (Chapter 7).

3.4.1.2 Onsite measurements

By using onsite methods, it is possible to investigate architectural heritage at a larger scale and collect a larger set of data points that will allow us to gain an overview of the preservation state. This increases the reliability and representativeness of samples in non-uniform complex settings (Vandevorde et al., 2013) such as Lalibela. Micro-climate monitoring and non-destructive measurement of moisture and

salt distribution in this study were carried out on site.

On monitoring micro-climate Camuffo (2013, p.434) states: ‘When a survey cannot continue for a time interval that is statistically representative of all the conditions, it should at least document one, or a few examples, of key different conditions.’ Micro-climatic conditions were measured at different seasons using temperature and humidity data loggers (iButton Hygrochron DS1923) to gauge the fluctuations in micro-climatic factors seasonally. Monitoring micro-climate on walls exposed to different cardinal directions was also useful in characterising the change in the sun’s path across the year and its effect on rock surface temperature. iButton Hygrochron data loggers have been extensively used in cultural heritage for monitoring micro-climate conditions (e.g., Martínez-Garrido et al., 2018; Orr et al., 2020; Samant et al., 2017; Zornoza-Indart et al., 2017). While the failure of iButton dataloggers without warning is often an issue in field measurements, their small size and inconspicuous shape and colour make them suitable for field sites frequented by visitors.

Understanding the spatial and temporal variability of moisture is fundamental to the study of weathering processes (Hall, 1986). Using different handheld and portable non-destructive moisture measurement tools, it was possible to assess the spatial and temporal variability in moisture on the surface and interior walls. In the field of cultural heritage, the use of non-destructive testing (NDT) that can be applied onsite is preferred over analytical techniques that require destructive or invasive sampling (Moropoulou et al., 2013). The advantage of using non-destructive measurement tools onsite is that it reflects the value of the measured variable under

real-world conditions (Wilhelm, 2016). Despite these advantages, it is, nonetheless, imperative to select the best method and have a sufficient understanding of the basic processes to effectively use and interpret data generated with NDT (Cartz, 1995). NDT moisture measuring tools detect moisture indirectly, often using parts of the electromagnetic spectrum (Orr et al., 2019). Measurement values have to be interpreted as either relative values of moisture content or calibrated values (Camuffo and Bertolin, 2012). To overcome this drawback, a comparative approach (Paper III) or combinative (Paper IV) approach was used (Table 3.4). A Protimeter Surveymaster (GE), Moist 350 B microwave moisture system (hf sensor GmbH) and an Infrared camera (FLIR-T460) were used in combination (Paper IV). The Protimeter Surveymaster uses electrical conductance to measure moisture and is sensitive to the presence of salts (Pinchin 2008; Eklund et al., 2013), whereas Moist 350 B is negligibly sensitive to salts (hf sensor GmbH, 2014). Because of its response to salts, the Protimeter has been used to define damp/saline zones in buildings (Akiner et al., 1992; Mol, 2014). Soluble salts extracted using the paper pulp poultice protocol developed by Egartner and Sass (Egartner and Sass, 2016) were analysed (Ion Chromatography), and the presence of salts was compared to the NDT readings. For repeated measurements taken at different depths and times in the same location with the microwave moisture meter (Moist 350 B), laboratory gravimetric calibration was essential to meaningfully interpret field data (Paper III).

Table 3.4: Methodology used in non-destructive field survey of moisture and salt distribution at various churches.

	Methodology	Techniques
Paper III	Comparative: measurements taken at different times (wet and dry seasons) on the exterior of the churches are compared.	Moist 350 B
Paper IV	Combinative: multiple moisture measuring techniques are used in combination to measure moisture/salinity on internal walls.	Moist 350 B, Protimeter Survey-master, Infrared camera & Salt extraction

3.4.2 Laboratory methods

Laboratory-based characterisation of the mineralogical composition and mechanical properties of rocks are a fundamental part of understanding how rock decays in the natural and built environment. Qualitative characterisation of mineralogical composition was done by viewing thin sections of rock samples under an optical microscope. Thin sections were useful to study the micromorphology, texture, structure, minerals composition and pore volume (Delvigne, 1998). Previous studies on the basaltic scoria at Lalibela have shown that there is a significant presence of clay minerals in the rock matrix (see Chapter 2). Due to the fine-grained nature of clay minerals, it is challenging to identify them with a light microscope (MacKenzie et al., 2017). Quantitative and qualitative analysis of bulk mineralogy and clay phases can be done using Xray diffraction (XRD) (Środoń et al., 2001).

XRD and thin section analysis are used in this study for a qualitative and quantitative assessment of mineral composition and micromorphology of rock samples from the churches and the quarry. Thin sections were prepared at the Earth Sci-

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ences department in the University of Oxford. Rock samples were cut to make small fragments that can be embedded in resin (and dried) before being polished down to 30 microns. For the XRD analysis, 10 grams of rock was powdered with a mortar and pestle and analysed at the Earth Sciences department. XRD and thin section analysis was done for both quarry and church samples to determine if the quarry samples can be used as representative samples of church rock types. Quarry samples in this study were used for gravimetric calibration of Moist 350 B microwave moisture meter and experimental analysis of swelling potential.

The hygric and hydric behaviour of rocks are influenced by the amount of swelling clay minerals in the rock matrix. The deformation of rocks due to changes in moisture content is known as hygric (0 – 95% RH) and hydric (in contact with water or saturated) dilatation (Steiger et al., 2011). Cyclic swelling and shrinkage of clay containing rocks during wetting-drying cycles can cause damage (Gonzalez et al., 2002). Studies on clay containing volcanic rocks have shown that the presence of clay leads to high dilatation during wetting (Pötzl et al., 2018; Steiger et al., 2011; Wedekind et al., 2012). Wetting-drying cycles in clay and salt rich systems are likely to trigger both hydration-dehydration of clays and crystallisation-dissolution of salts. To assess the impact of these two decay processes acting both individually and synergistically in the lithological and climatic context of Lalibela, an experiment that was based on micro-climate monitoring and site observation was set up in the laboratory. Using 50 mm cube quarry samples that had the same mineralogical composition as the churches in Lalibela, their swelling and shrinkage were

measured during wetting and drying in salt-free and salt-contaminated states (Paper II). Apparent density BS EN 1936 (2006), open porosity BS EN 1936 (2006) and water absorption coefficient by capillarity BS EN 1925 (1999) were measured to assess the influence of these parameters on dilatation behaviour. In this experiment setup, hygric dilatation of quarry samples was measured under climate conditions that resemble Lalibela. Where experiments are a close approximation to nature, meaningful insights can be gained from laboratory simulations (Hall, 1986). High precision Linear Variable Displacement Transducers (LVDT) were used to measure dilatation in hygric and hydric experiments.

A large (220 x 150 x 140 mm) quarry sample whose physical properties closely matched that of churches was used for gravimetric calibration of the Moist 350 B. The gravimetric method was used in this study to determine the response of the Moist 350 B to a range of non-saturated moisture contents in basaltic scoria and to convert measurements to moisture content (Paper III). The gravimetric method is an accepted indirect bench-marking technique for converting measured values from handheld devices to percentage of moisture content in specific porous materials (Pinchin, 2008).

3.4.3 Secondary data and archival resources

The National Meteorological Agency (NMA) of Ethiopia has a meteorological station located approximately 800m away from the churches (Fig 3.10). This station has been logging data manually from 1989 onwards, with automatic logging starting

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in November 2011. Long-term (1992-2020) digitized met data was collected from the NMA's office in Addis Ababa and the meteorological station in Lalibela. Regional climate data is used along with micro-climate data to identify climatic factors that influence weathering at Lalibela (Paper I).

Historical research at Lalibela has mainly been concerned with human activity driven transformation of the sites in the post-exposure history of the churches. Given the semi-natural setting, natural processes have played a dominant role in the transformation of the site through the centuries since its carving. As such, a study of archival resources complemented by an understanding of the natural weathering processes that contribute to its transformation are essential for building a complete account of the evolution of the churches at Lalibela.

Except for religious manuscripts, most of the written works regarding the churches in Lalibela were done by foreign missionaries, emissaries, travellers, and historians. Archival resources were searched in the Bodleian Library's collection of books and online sources such as the Bibliothèque nationale de France Catalogue Général. This study relied on published works on Lalibela, which had descriptions, drawings and pictures of the site from the late 19th to the mid-20th century (also presented in 3.3.3). These resources and more recent studies on oral histories at Lalibela (Ayalew, 2016) are vital to understanding the transformation phases of the churches. But the sporadic and infrequent documentary sources on restoration and conservation of the churches have to be dealt with cautiously as they build an incomplete story.

Part II

Key Weathering Drivers

በስትፋላም ቅንዲት ታላቅ ቤተክርስቲያን ሠራ በብዙም ጌጥ አሳመራት
በብርኖ በወርቅ አይደለም፡፡ ጌጥዎ የዲንጋይ ነው እንጂ፡፡

*Later he [Saint Lalibela] built a great church, he ornamented
it with many gems, but they were not gems of silver or gold.
Its gem is rock.*

(Acts of Lalibela, [2018](#), p. 209)

4. Climate

Implications of climatic variability for the nature and rate of weathering of rock-cut churches in northern Ethiopia

Abstract

Despite the large number of rock-cut and masonry heritage sites in northern Ethiopia, the implications of climatic variability for weathering of historic structures in northern Ethiopia are largely unstudied. In strongly seasonal climates, such as found in Ethiopia, diurnal, seasonal and interannual variations in climatic variables (e.g. rainfall, relative humidity and temperature) are likely to impact rock weathering through influences on surface and deep-seated wetness, wetting-drying cycles and thermal cycling. These key weathering-related impacts influence historic rock-cut sites in northern Ethiopia such as the UNESCO World Heritage Site of Lalibela. In this study, data sets on long term ambient climate (1992-2020) and short-term micro-climate (2018-2019) from Lalibela are analysed to determine the implications of climatic variability for weathering. The results indicate intense rainfall, high RH and frequent sunny spells in the main rains season (Kiremt) will favour surface wetting-drying cycles, longer time of surface wetness and deep-seated wet-

This chapter has been submitted to Earth Surface Processes and Landforms with the following co-authorship: Taye Gemedo, B. and Viles, H.

ting. These conditions are favourable for frequent salt crystallisation/dissolution cycles and proliferation of organic growths. In contrast, the dry season (Bega) experiences very low RH ($< 50\%$) and high rock-surface temperature fluctuations (up to $25\text{ }^{\circ}\text{C}$), with west and south-facing walls experiencing particularly high diurnal temperature ranges that can lead to thermal fatigue. Contour scaling at Lalibela are likely formed as a result of the combination of repeated wetting-drying cycles in Kiremt and thermal cycling in Bega. The 29-year climatic data set shows an increasing trend in minimum annual temperatures. In future, higher temperatures combined with more intense wetting events may intensify salt weathering, biological weathering and thermal fatigue. The results from this first study of climatic trends and their influence on rock weathering at Lalibela should help conservation and management practice at rock-cut sites in northern Ethiopia.

4.1 Introduction

The climate of Ethiopia has been extensively studied with the aim of determining vulnerability to droughts and impacts of climate change on agricultural produce (Bewket and Conway, 2007; Fentaw et al., 2017; Jury and Funk, 2013; Viste et al., 2013). However, despite their importance, the impacts of climate and micro-climate on the historic built environment in Ethiopia have received far less attention. Climatic factors strongly influence the nature and rate of rock weathering in both the built and natural environments. Following the work of Peltier (1950), regional classifications based on annual rainfall and mean annual temperature have often been used to identify regional weathering regimes. However, using mean values to categorise weathering regimes is not reliable because it does not consider interannual, seasonal and diurnal variations in climate as well as any long-term trends. Annual and monthly mean temperatures are, therefore, not the best way to determine the characteristics of the climate that influence weathering of rock surfaces. Moreover, micro-climate conditions on and around a building or rock outcrop can differ significantly from ambient climate regimes (Warke, 1996). Micro-climate con-

ditions cannot be inferred from ambient data alone (McAllister et al., 2016) as the ranges of climate variables can greatly differ between these two scales (André et al., 2012; Paradise, 1995; Viles, 2005). The complex interaction between ambient and micro-climate regimes can be better understood when measurements are taken over a sufficiently long period of time to give a complete description of the climate variability in the interannual, seasonal and daily cycles (Camuffo, 2013). In Ethiopia, interannual variability in rainfall, high seasonality in rainfall and strong diurnal fluctuations in temperature are likely to be important climatic factors in explaining the nature and rate of rock weathering. In this paper, we use long-term ambient climate data (29 years of record) and short-term micro-climate data from Lalibela, Ethiopia to investigate the influence of climate variability and trends on weathering of the rock-cut churches found in Lalibela.

The rock-cut churches at the UNESCO world heritage site of Lalibela were carved in the 11th to 13th century CE (Gobezie 2018; Derat et al. 2021). The eleven rock-cut churches at Lalibela are carved out of a single hydrothermally altered Oligocene basaltic scoria hill (Asrat and Ayallew, 2011). The basaltic scoria the churches are hewn into contains a significant amount of swelling clay and zeolite minerals (Gemedda et al., 2018; Kiros et al., 2013) and has a wide range in open porosity and density (Renzulli et al., 2011). Previous research on these churches has focused on the roles that petrophysical properties of the rock (Delmonaco et al., 2010), structural instability of the joints (Asrat and Ayallew, 2011; Sani, 2012), and biological weathering (Schiavon et al., 2013) play in the weathering of the churches at Lalibela. Other weathering processes and features that are common across the churches like salt weathering, contour scaling, scaling and granular disintegration have not been studied despite their obvious importance in the deterioration of the churches at Lalibela. Diurnal wetting-drying cycles and thermal cycles are likely driving these weathering processes. Field observation shows that biological colonisation and proliferation at Lalibela is associated with seasonality in rainfall. Moss and other plants grow on the rock walls only during the rainy season. Longer time of

surface wetness during the rainy season is likely to promote the colonisation and proliferation of organisms. Intense rainfall during the rainy season is also likely to lead to deep-seated wetting which will spread salt forming ions deeper into the interior of the rock (McCabe et al., 2013). The seasonality in rainfall and the degree and frequency of temperature and humidity fluctuations will likely impact the nature and rate of weathering at Lalibela. A changing climate may increase or decrease the frequency and intensity at which weathering occurs. As such, the climatic conditions at Lalibela have to be characterised to determine their impact on the rate and nature of weathering at the historic rock-cut structures. The main aim of this paper is to characterise interannual trends in temperature and rainfall as well as seasonal and diurnal fluctuations in ambient climate and micro-climate variables. Implications of these climatic trends on weathering at Lalibela and other rock-cut sites that experience a similar climate to Lalibela will be discussed.

4.2 Climate of Ethiopia

The complex topography of Ethiopia, with elevations ranging from 4620 m above sea level to below sea level (Dinku et al., 2007), plays a significant role in the variation of climate (including rainfall and temperature regimes) across the country (Nyssen et al., 2005). Ethiopia's climate is typically tropical in the south-eastern and north-eastern lowland regions, but much cooler in the large central highland regions of the country (McSweeney et al., 2008).

Lalibela is located in the northern highlands of Ethiopia (Fig 4.1). According to the Köppen-Geiger Climate Classification Lalibela is classified as having the Cwb climate subtype, which is characterised by a warm temperate climate with dry winters and warm summers (Kottek et al., 2006). In the tropics, a subtropical highland climate tends to feature spring-like weather year-round with temperatures remaining relatively constant throughout the year. The Köppen-Geiger climate classification is based on temperature and precipitation patterns; conversely, the Ethiopian classification of climate is based on elevation; with classification for low altitude (Qolla)

4 Climate

below 1800 m above sea level, medium altitude (Woina Dega) 1800 to 2400 m above sea level, and high altitude (Dega) above 2400 m above sea level. At 2430 - 2550 m above sea level Lalibela belongs to the high altitude (Dega) zone. The high-altitude zone is characterised by lower annual temperatures than the other zones, with Lalibela having a mean annual temperature of 18.70°C. In the high-altitude zone, there are three seasons: the short rains season from February to May, Belg; the main rains season from June to September, Kiremt; and the dry season from October to January, Bega.

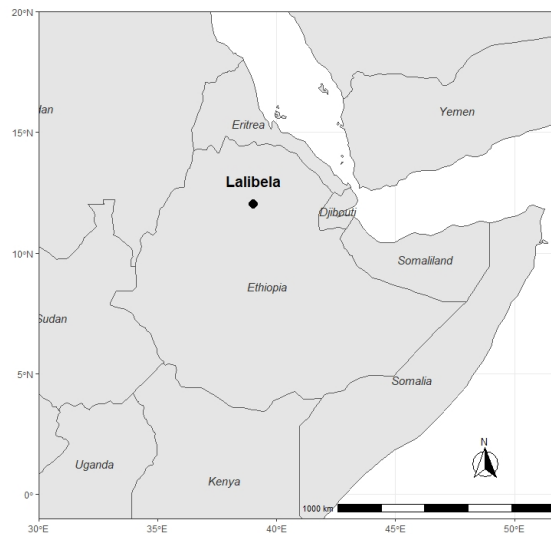


Figure 4.1: Location of Lalibela, Ethiopia.

4.3 Methodology

To characterise the temporal and spatial variation in climatic variables that influence weathering rates and processes at the rock churches in Lalibela, both ambient and rock surface micro-climate conditions were assessed. Ambient climate observations from the weather station in Lalibela were acquired from the National Meteorological Agency (Ethiopia). The weather station is located approximately 800 m away from the rock-cut churches. Meteorological observations were available from 1992 onwards with data recorded manually every 3 hours from 06:00 to 18:00 until 2011. In Nov 2011, an automatic weather station that takes measurements

every 15 min was installed. For this study, the manual observations data from Jan 1992 to Nov 2011, and the automatic weather station data from Nov 2011 up to Dec 2020 were combined to give a total of 29 years of data.

The rock-cut churches at Lalibela were carved in three groups which are connected via pathways, trenches and tunnels (Fig 4.2). All the rock-cut churches are situated below ground level and surrounded by trench walls. Bete Mariam, a monolithic church in the north group, was chosen for this study because its four walls face each cardinal direction and it has a regular shape. The rock surface micro-climate was monitored in each Ethiopian season at Bete Mariam (Fig 4.2). Temperature and humidity data loggers (iButton Hygrochron DS1923) with an accuracy of $\pm 0.5^{\circ}\text{C}$ and 5% RH were used at a sampling interval of 15 minutes. Short term micro-climatic conditions were monitored over 9-12 day periods in May, July and December. Although these are short term micro-climate datasets, they are representative of the warmest (May), rainiest (July) and driest (December) periods in Lalibela. Rock surface temperature and relative humidity were monitored during the following periods:

- Belg: 20 May 2018 – 30 May 2018
- Bega: 17 Dec 2018 - 29 Dec 2018
- Kiremt: 22 Jul 2019 - 01 Aug 2019

The iButton data loggers were fixed on the north, east, south and west-facing walls approximately 2.5 m above the floor level using Blue Tac. To shield the data loggers from direct sunlight, they were covered with a thin layer of Blue Tac while leaving the tiny opening that allows water vapour to reach the internal humidity sensor open.

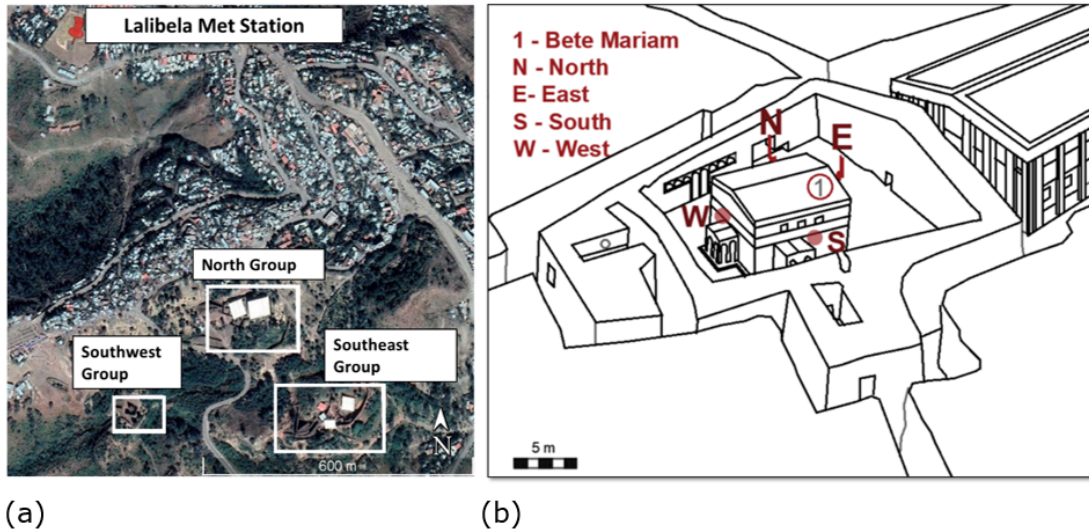


Figure 4.2: a) Site plan of the church complex and the Meteorological (Met) station at Lalibela and (b) a perspective drawing of the north group showing the location of the micro-climatic monitoring sites at Bete Mariam.

4.3.1 Data analysis

Descriptive statistical methods were used to analyse the data collected at the meteorological station and at Bete Mariam. Coefficients of variation were used to assess interannual variability in rainfall, and linear regression analysis performed to determine any trends in rainfall and temperature. The Simple Daily Intensity Index (SDII) of rainfall was used to assess the intensity of rainfall. SDII is an Expert Team on Climate Change Detection and Indices (ETCCDI) index which is calculated as the ratio of annual total precipitation to the number of wet days ($> 1\text{mm}$) (Zhang et al., 2011). As mean monthly values is less easy to relate to individual weathering processes such as salt weathering, frequency distribution frequency distribution curves of daily minimum and maximum values are used instead to show the ranges in ambient temperature and relative humidity and their seasonal shifts. These methods were preferred over those using average values as they are more powerful in highlighting the interannual variability and seasonal and daily cycles of climate variables (Camuffo and Sturaro, 2001).

4.4 Results

Analysis of the 29-year ambient climate data confirms that the climate of Lalibela is characterised by a bimodal rainfall pattern and a moderate temperature regime. Kiremt (main rains season) contributes 77% of the annual rainfall, whereas Belg (short rains season) only accounts for 17% of the long-term annual rainfall (791.14 mm/year). In Lalibela, the average annual temperature for the period 1992 - 2020 is 18.70 °C and the mean monthly temperature throughout the year fluctuates between 15 – 20 °C. The high average elevation across the northern and southern highlands of Ethiopia reduces the temperature in Lalibela from what would be considered normal in the tropics (Fazzini et al., 2015). However, like other tropical areas the variation in mean monthly temperature is quite low; and the diurnal range is about an order of magnitude larger than mean monthly temperatures because day-periodic processes and circulations dominate regional climate in the tropics (Hastenrath, 2012).

4.4.1 Rainfall

The intensity of Kiremt rains is a result of the combined effect of the northward migration of the Inter Tropical Convergence Zone (ITCZ), local land surface heating, and topographic forcing exerted by the Ethiopian highlands (Li et al., 2016; Segele and Lamb, 2005). The variation in the movement of the ITCZ and the El Niño Southern Oscillation causes high interannual variability in rainfall in northern Ethiopia (Fer et al., 2017; Seleshi and Zanke, 2004). El Niño years are accompanied by below-average Kiremt rainfall in large parts of Ethiopia (Segele et al., 2009). There were four El Niño years during the period 1992-2020 at Lalibela. While the 1997 El Niño did not exhibit reduced rainfall and was not associated with intense or extended drought conditions in Ethiopia (AKLDP, 2015), the 2002, 2009 and 2015 El Niño events showed a marked reduction in Kiremt and Belg rains at Lalibela (Fig 4.3).

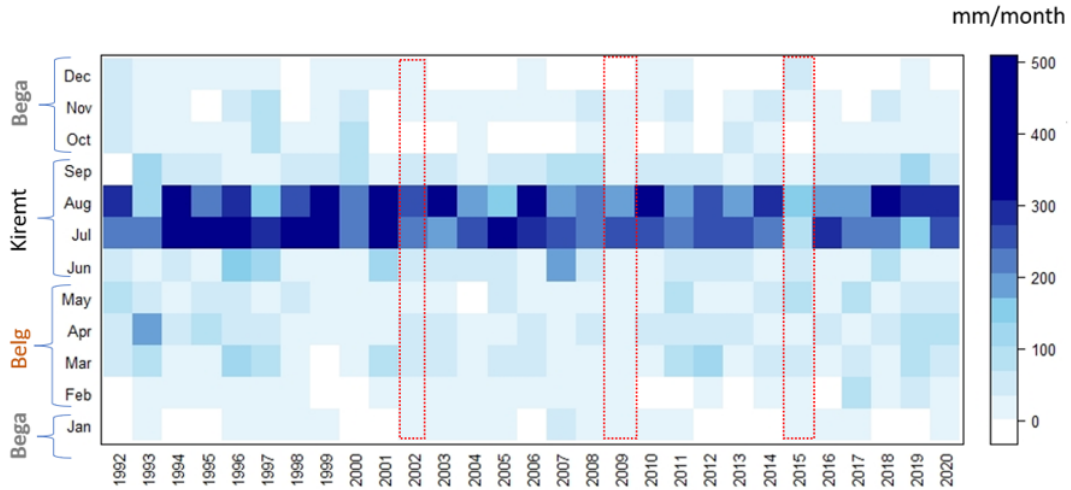


Figure 4.3: Monthly rainfall at Lalibela for the period 1992-2020 plotted as a heatmap. El Niño years are highlighted in red boxes.

Nearly half the annual rainfall at Lalibela occurs during July and August in Kiremt (Fig 4.3) as heavy rainfall ($> 10\text{mm}$). The 95th percentile (very wet days) of the daily rainfall data is 25.2 mm. Rainfall on very wet days ($> 25.2\text{ mm}$) accounts for about 20% of the total annual rainfall at Lalibela. The intensity of rainfall is higher during Kiremt at 9.78 mm/wet day than the annual average intensity of rainfall (Table 4.1). Most rain events in the year can generally be classified as intense as there is an average of 8.85 mm/wet day annually. The intensity of the rainfall determines the extent to which the rock structures at Lalibela will be wetted and is therefore an important factor to consider in studies of rock weathering. Belg and Bega see far fewer rain days and have higher interannual variability than Kiremt (Table 4.1). Belg and Bega have about 6.5 mm/wet day of rainfall. Over the period 1992 - 2020 there was an average of 4.17 heavy rain ($> 10\text{ mm}$) days in Belg, and these heavy rain days make up a third of the Belg rains, which is otherwise dominated by dry days. The coefficient of variation of rainfall in Bega and Belg rains over the 29-year period studied here is 0.98 and 0.52, respectively, whereas for Kiremt it is 0.20 (Table 4.1). Although the rains in Belg and Bega contribute a quarter of the annual rainfall, the rainfall in these two seasons is highly variable, and contributes to the interannual variability of rainfall in Lalibela.

Table 4.1: Summary rainfall statistics from Lalibela, 1992-2020.

	Annual	Belg (short rains) Feb - May	Kiremt (main rains) Jun - Sep	Bega (dry season) Oct-Dec & Jan
Mean rainfall (mm)	791.14	135.58	607.22	48.43
Mean number of rain days (> 1 mm)	89.41	19.63	62.03	7.71
Mean number of heavy rain days (> 10 mm)	27.75	4.17	22.10	1.48
Simple daily intensity index (SDII) (mm/wet day)	8.85	6.90	9.78	6.28
Coefficient of variation	0.15	0.52	0.20	0.98

Linear regression analysis of the annual rainfall at Lalibela over the period 1992-2020 showed a non-significant (p -value = 0.051) declining trend in annual rainfall (Fig 4.4), with a similarly non-significant trend in seasonal rainfall. Other studies have reported an increasing trend in rainfall for both annual and Kiremt rains at Lalibela (Abera et al., 2020; Bewket and Conway, 2007; Fentaw et al., 2017; Getachew Feleke and Abera, 2020). However, those studies did not look at the same period of record. Yimer et al. (2020) studied the trend of homogenised rainfall data for the period 1978 to 2016 and found an insignificant decreasing trend for annual rainfall, similar to the results in this study. The strong interannual and inter-decadal variability in rainfall in Ethiopia (McSweeney et al., 2008) along with inconsistent recording methods makes it difficult to accurately detect long-term trends in rainfall.

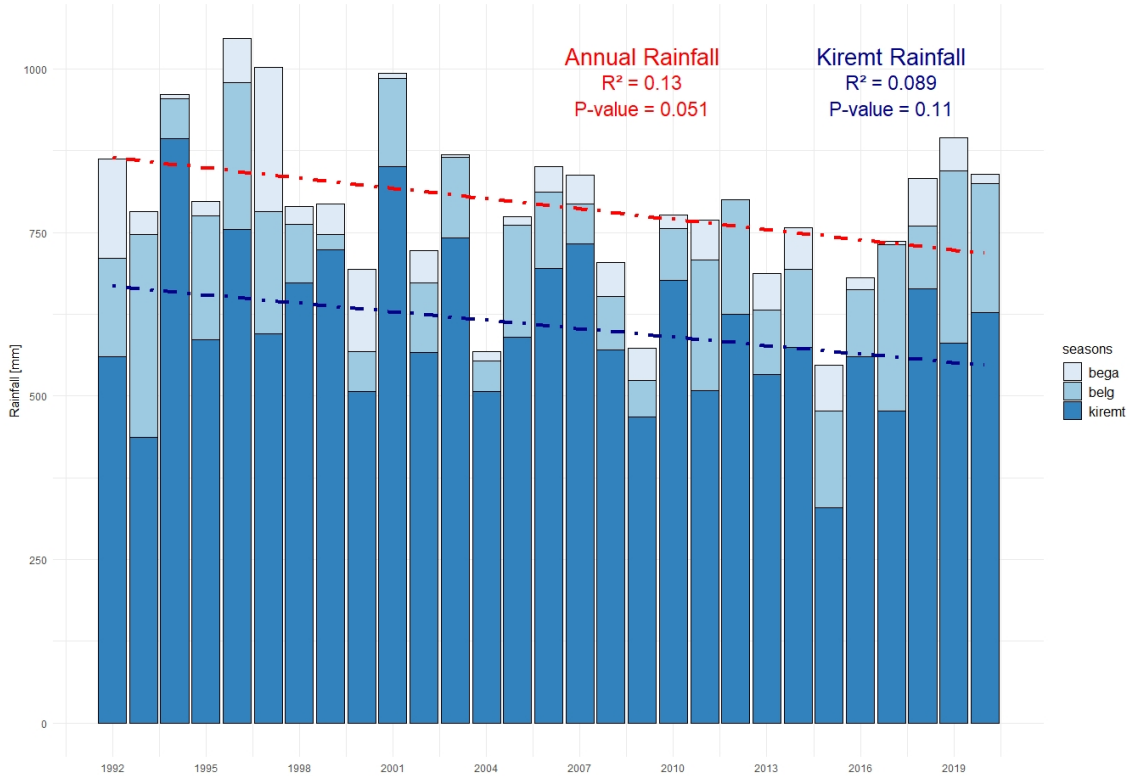


Figure 4.4: Seasonal rainfall at Lalibela, 1992 – 2020 with linear least squares regression line of annual rainfall (red) and Kiremt rainfall (dark blue).

4.4.2 Relative Humidity

4.4.2.1 Long-term ambient data

The ambient relative humidity at Lalibela fluctuates throughout the year, driven mainly by the seasonal rainfall and the dry air masses that makes most of northern Ethiopia dry during Bega (Seleshi and Zanke, 2004). Figure 4.5 shows the daily minimum and maximum RH recorded over a 29-year period at Lalibela plotted as frequency distribution curves. The minimum and maximum RH frequency distributions are widely spread for most of the year except the wettest months, i.e., July and August, where the min and max daily RH values are more tightly distributed and higher than those found during the rest of the year (Fig 4.5). The min and max RH are widely spread during June and September, the interquartile range (the distance between the first and third quartiles shown as lines in figure 4.5) is higher for these months. As these months are transition periods from dry to wet seasons, the RH is

likely to spike during rainy days and reduce in drier days. Similarly, the intermittent rains in Belg that mainly occur from March to May increase the interquartile range during those months. After the cessation of Kiremt rains, the min and max relative humidity decrease during the dry season (Bega).

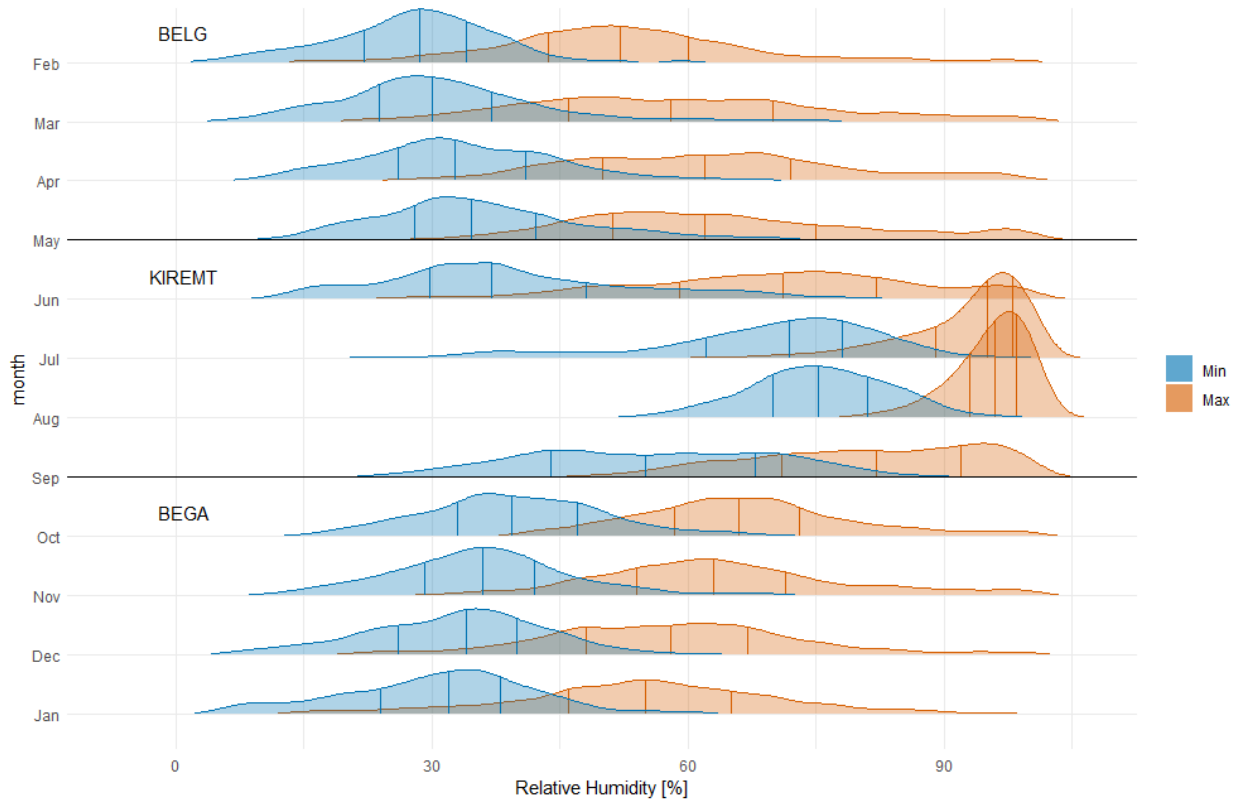


Figure 4.5: Frequency distribution curves showing the distribution of daily maximum and minimum RH values measured from 1992 -2020 plotted for each month of Belg (top), Kiremt (middle) and Bega (bottom). The first, second and third quartiles are shown as vertical lines.

The diurnal range in RH (the distance between the median of the minimum and maximum distribution curves) does not change much throughout the year. It is slightly higher in June and September but in a comparable range for the rest of the year. This indicates that the largest diurnal variation in ambient relative humidity might occur in June and September.

4.4.2.2 Short-term rock-surface micro-climatic and ambient data

Similar to the ambient relative humidity, the relative humidity measured on the walls at Bete Mariam varies significantly between Kiremt and the other seasons (Fig

4.6). The minimum RH measured on the walls during Kiremt is above 60% while in Belg and Bega the maximum RH is below 60% (Fig 4.6). Diurnal range in RH varied significantly during Bega. The maximum daily ambient RH decreased by 22% from the first 5 days of measurement to the last 5 days of measurement in Bega (Fig 4.6c). The RH measured on the walls also decreased by 16 – 20% from the first to the last 5 days of measurement. The lowest RH was recorded on the south-facing wall which had less than 10% RH in the afternoons.

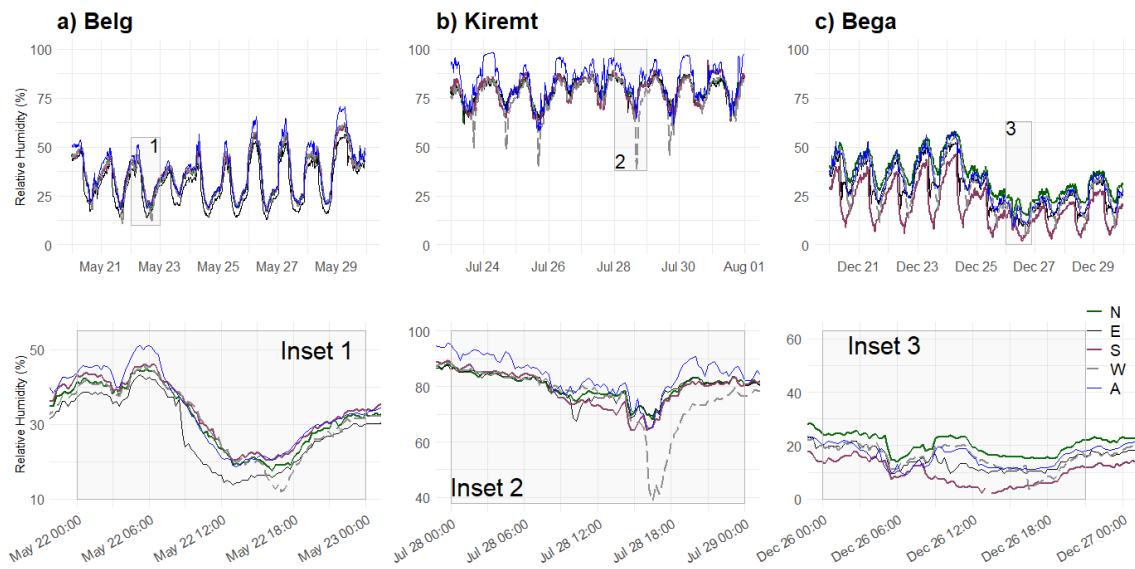


Figure 4.6: Relative humidity measured at the weather station (A-Ambient) and on the north (N), east (E), south (S) and west (W) walls of Bete Mariam during (a) Belg, (b) Kiremt and (c) Bega. Insets 1, 2 and 3 show one diurnal cycle taken from a, b and c, respectively. Note the difference in relative humidity scale in the data presented in the insets.

During Kiremt and Belg, there was very little shift in maximum daily RH. Rapid temperature fluctuations due to short sunny spells during Kiremt greatly affect daily fluctuations in relative humidity, particularly on the west-facing wall (Fig 6b). During the 9 days the micro-climate at Bete Mariam was monitored in Kiremt, the minimum daily RH on the west-facing wall declined rapidly several times by up to 20%.

4.4.3 Temperature

Temperature in Lalibela stays within a very narrow range across months and seasons and does not fluctuate significantly annually (Fig 4.7). In Lalibela, the mean monthly temperature throughout the year is between 15 – 20 °C. The distribution of minimum and maximum daily temperature is only slightly variable seasonally. The maximum and minimum temperatures are highest in Belg and lowest in Kiremt, making Belg the warmest season and Kiremt the coldest season at Lalibela. Minimum temperatures during Bega and Kiremt are comparable, but Bega has higher maximum temperatures.

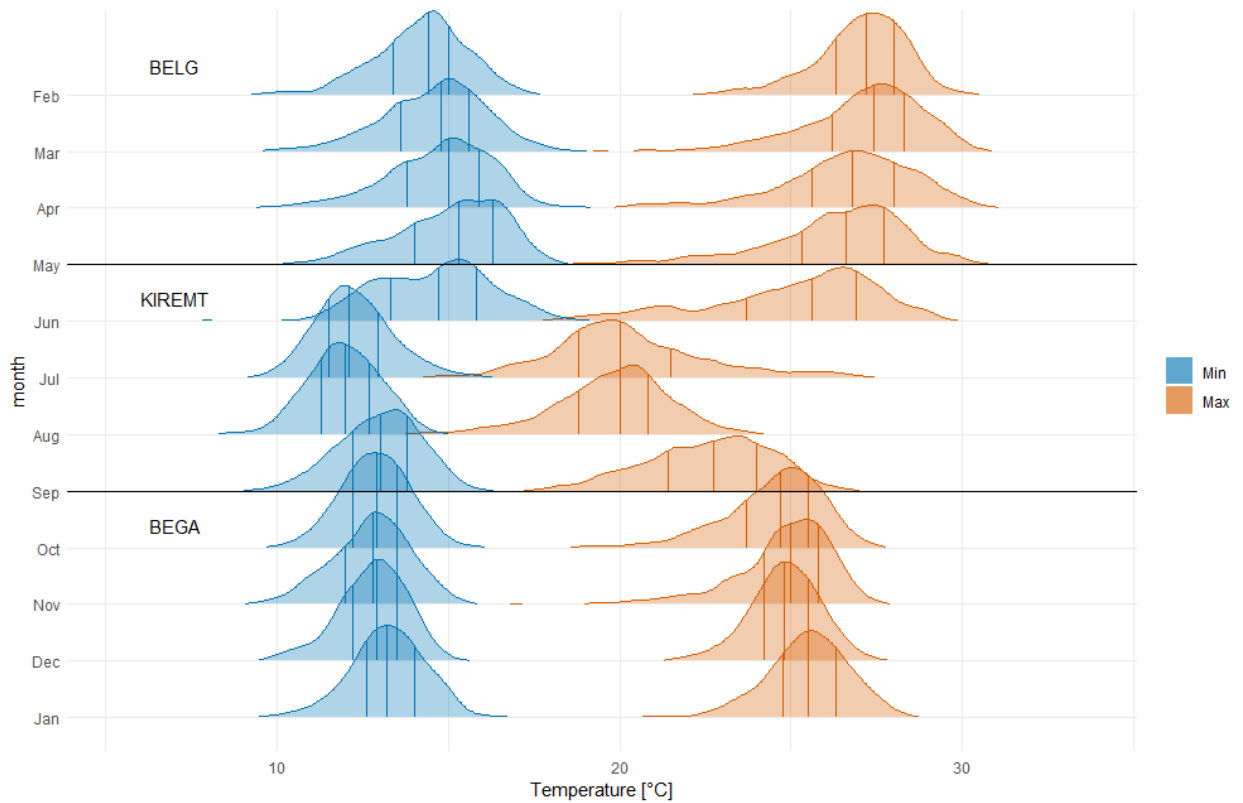


Figure 4.7: Frequency distribution curves showing the distribution of daily maximum and minimum temperatures data from 1992 - 2020 plotted for each month in Belg (top), Kiremt (middle) and Bega (bottom). The first, second and third quartiles are shown as vertical lines.

The maximum daily temperature throughout the year tends to fluctuate more than the minimum daily temperature. The spread in maximum daily temperatures is the primary driver of seasonal fluctuation in temperature at Lalibela. The maximum

temperature shifts to the right in Belg increasing the diurnal temperature range (difference between maximum and minimum temperature) for that season. During the dry period (Bega), the maximum temperature is higher than in the rainy season. The distribution of maximum temperatures is also narrower during Bega because this season is less affected by clouds and is more likely to have a predictable temperature regime. Belg and Kiremt have less predictable temperature regimes, with both showing a wider distribution of temperature and more variability from month to month. June (Kiremt) for instance has the highest interquartile range for both the minimum (2.5) and maximum (3.2) temperature in comparison to other months (Fig 4.7). As a transition month from the warmest to the coldest season in Lalibela, June experiences a wider range of temperatures.

There is agreement in different climate models and studies that there will be an increase in temperature over northern Ethiopia due to climate change (McSweeney et al., 2008; Osima et al., 2018; Tegegne et al., 2021). From the trend assessed over the 29-year period of measurement studied here, there is no significant trend in mean annual temperature nor annual maximum temperature, but there is a significant increasing trend in minimum annual temperature (Fig 4.8 a and c).

The trend in monthly means of maximum and minimum temperature indicate the same trend as seen at the inter-annual scale. Except for May (p-value =0.075), August (p-value =0.052) and September (p-value = 0.095), all months had a significant (p-value < 0.05) increasing trend in minimum temperature (see appendix 3). There were no significant trends in maximum temperature, except for December where there was a significant negative trend (Fig 4.8 b and d). With a positive trend for minimum temperature and a negative trend for maximum temperature, the temperature range in December is decreasing.

4.4.4 Short-term rock-surface and ambient temperature data

The largest difference between ambient and rock surface temperature was observed in Bega, the dry season (Fig 4.9 c). The rate of temperature change, both

4 Climate

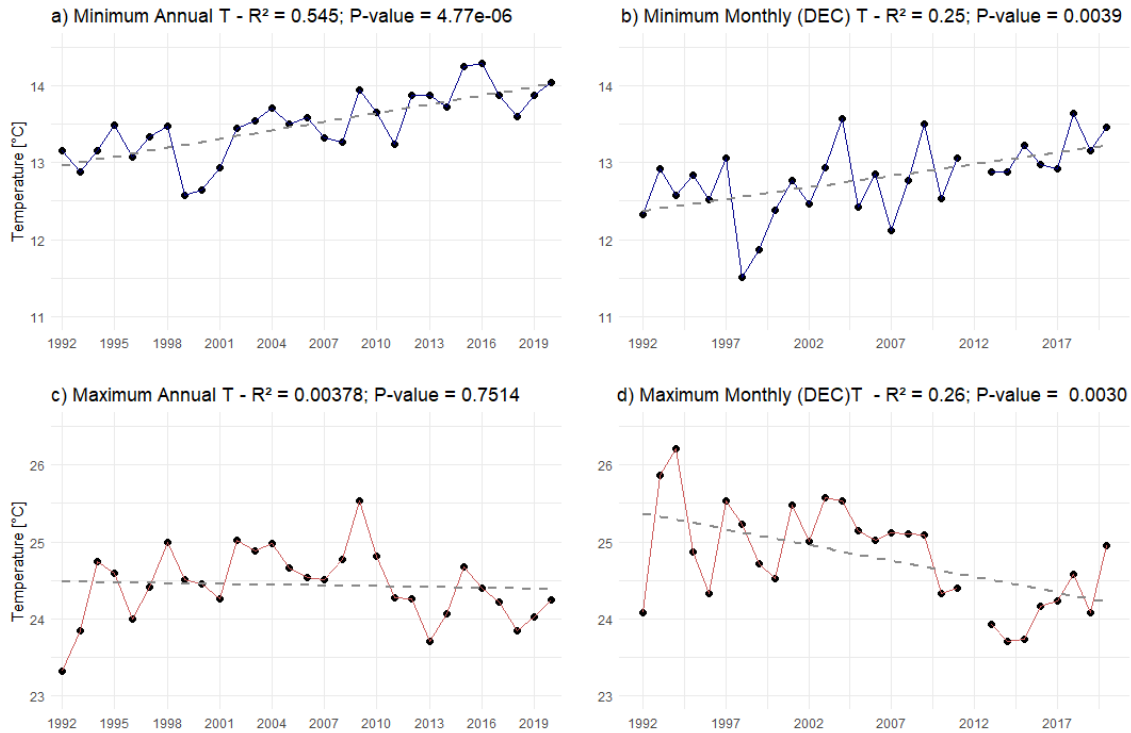


Figure 4.8: Comparison of time series plots (1992 -2020), with linear least squares regression lines of (a) minimum annual temperature, (b) minimum monthly temperature in December, (c) maximum annual temperature and (d) maximum monthly temperature in December. Note the different temperature scales between a) and b) and c) and d).

for heating and cooling, on the walls was higher than the rate of change of ambient temperature in Bega. This is due to an increased rate of heating from incident solar radiation and an increased rate of cooling due to periods of shade. The surface temperature on the walls at Bete Mariam in Kiremt and Belg was comparable to the ambient temperature.

The seasonal variation in rock surface temperature range was accompanied by a spatial variation in the temperature cycle of the walls exposed to different cardinal directions. Bega sees very little rain (Table 4.1) and has clear skies; cloudy conditions during Belg and Kiremt lead to more variation in temperature range between days on the west-facing wall. The direction the walls are facing, i.e., aspect, plays an important role in controlling the temperature cycle on the walls. This effect is particularly noticeable in Bega where the south-facing wall has a diurnal temperature range 21 °C higher than the north-facing wall (Fig 4.9 c and inset). The amount

4 Climate

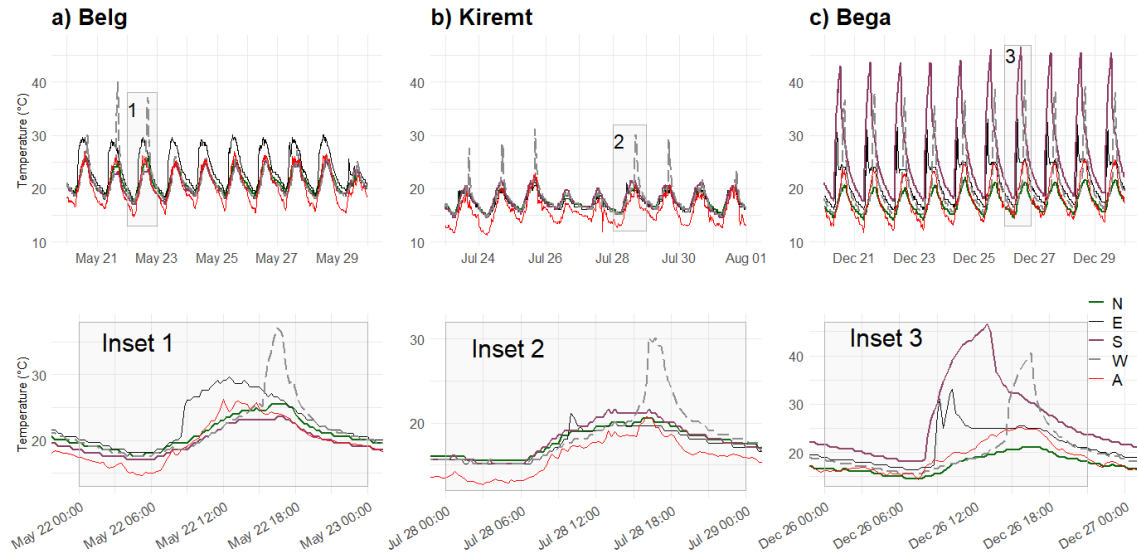


Figure 4.9: Temperature measured at the weather station (A-Ambient) and on the north (N), east (E), south (S) and west (W) walls of Bete Mariam during (a) Belg, (b) Kiremt and (c) Bega. Insets 1, 2 and 3 show one diurnal cycle taken from a, b and c, respectively. Note the difference in temperature scale in the data presented in the insets.

of solar radiation the wall is exposed to greatly influences the temperature. The shifting of the sun's path in Bega exposes the south-facing wall to direct sunlight. This leads to a significant variation in temperature range between north and south-facing walls. The east, south and north walls in both Kiremt and Belg had a more predictable daily thermal regime. During Belg the west-facing wall experienced a step rise in surface temperature (about 10°C) in a short span of time twice in the 10-day period measured (Fig 4.9). The west-facing wall in Kiremt had a more variable daily temperature range than the other walls. The daily variations in the range of temperature in the wet seasons are likely driven by changes in cloud cover which will affect the amount of solar radiation the west wall receives. Both aspect and cloud cover play a significant role in determining the seasonal variation in temperature and humidity cycles on the walls at Bete Mariam.

4.5 Implications for weathering

The results from the ambient and micro-climate data illustrate strong seasonal variations in rainfall, relative humidity and rock surface temperatures at Lalibela. These are likely to influence the nature and rate of weathering across the seasons (Fig 4.10). The key weathering-related impacts of the climate in Lalibela are wetting-drying cycles, deep wetting, increased time of wetness and thermal cycling. The conditions in Belg, i.e. intermittent rains in a season otherwise dominated by dry days, are likely to cause wetting-drying cycles to occur as often as rain days occur. Wetting-drying cycles are also likely to be frequent in Kiremt, where despite the large number of rain days, sunny spells also occur frequently. Kiremt is also likely to experience deep wetting and longer time of wetness. Deep wetting of rock walls occurs when moisture has penetrated sufficiently far into the rock that it is not directly affected by surface cycling (McCabe et al., 2013). Given the frequency of heavy rain days in Kiremt it is very likely that deep wetting will occur. The dry season (Bega) experiences high range of thermal cycling that may cause the physical breakdown of rocks due to thermal fatigue. The seasonal variations in climate conditions at Lalibela are ideal for moisture driven weathering to take place during Kiremt and Belg and thermal fatigue during Bega.

4.5.1 Moisture driven weathering during Kiremt

Heavy rainfall, high fluctuation of relative humidity (due to sunny spells) and long periods with high humidity make the conditions during Kiremt suitable for moisture driven weathering processes to occur. Moisture driven weathering is unlikely to be prevalent during Bega and Belg because of their very low ranges of relative humidity (Fig 4.5 and 4.6). Belg has 20 rain days (Table 4.1) and the rock surface temperature is between 18 - 30°C (Fig 4.9) and the ambient temperature is about 20 °C. Wetting-drying cycles in Belg are likely to be associated with individual rain events and will be less frequent than Kiremt. The environmental conditions

during Kiremt are favourable for wetting-drying cycles, deep wetting and a longer time of wetness.

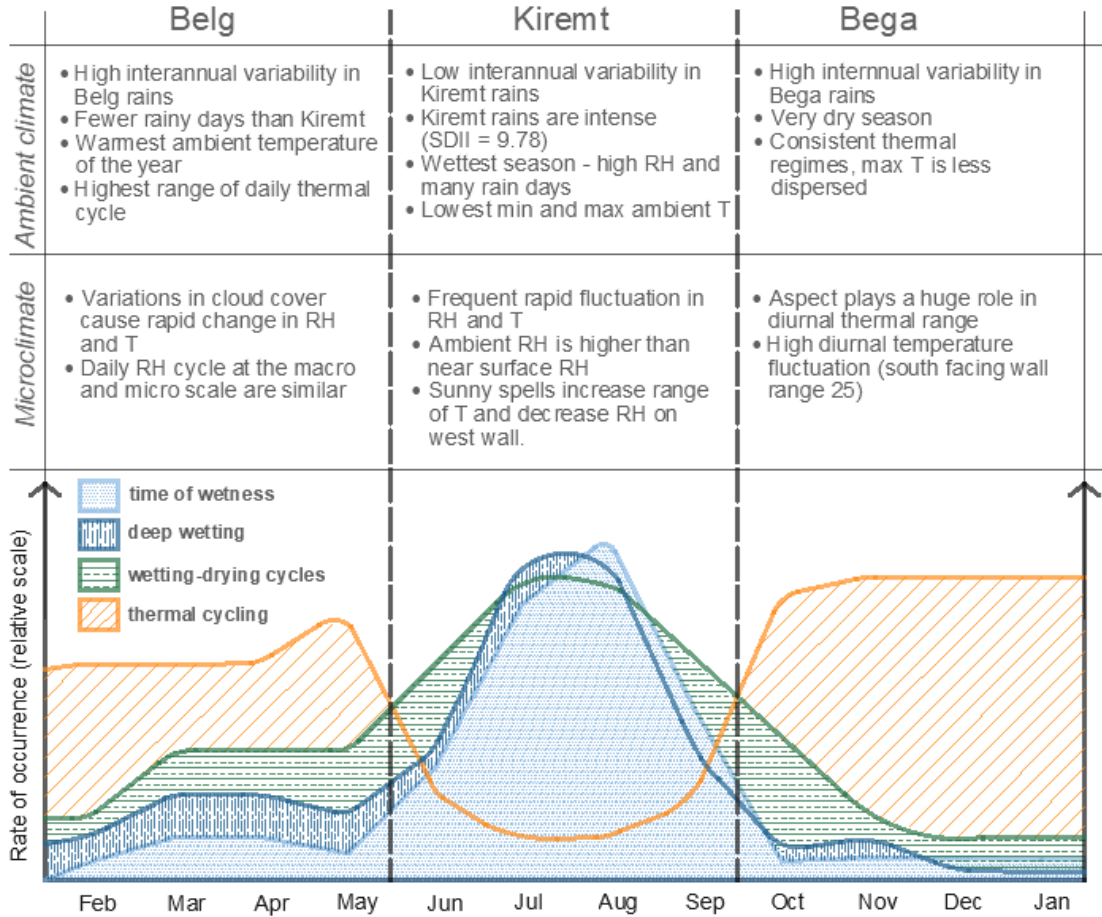


Figure 4.10: Summary of the main ambient and micro-climate trends in the three seasons (top) and (below), and a conceptual diagram showing the key weathering-related impacts of the seasonal climate trends – which are: wetting-drying cycles, deep wetting, time of wetness and thermal cycling.

4.5.1.1 Wetting-drying cycles

During Kiremt, the relative humidity measured on the walls fluctuates across a range (55% to 95% RH) that will cause frequent wetting-drying cycles. Wetting-drying cycles on rock surfaces can occur when rain events are followed by a period of evaporation (Camuffo, 1984). Or when the humidity reaches a level that can cause condensation in the open pores of the rock. The basaltic scoria the churches are carved into contains significant amounts of swelling clay minerals (Renzulli et al.,

2011). Swelling clay minerals change their volume when exposed to high humidity and shrink when exposed to low humidity. This dependency on humidity fluctuation as well as the salt crystallisation/dissolution cycles that occur means that periodic wetting-drying cycles can have significant impacts on weathering at Lalibela. The frequency of wetting-drying cycles during Kiremt is influenced by aspect; the west-facing wall experiences more frequent thermal and humidity fluctuations. Short sunny spells increase the surface temperature causing the relative humidity to drop by up to 50% (Fig 4.6) and cross critical RH values such as 75.5% where NaCl changes from a dissolved to a crystalline state (Brimblecombe et al., 2010). These randomly occurring short term RH fluctuations will lead to repeated salt crystallisation/dissolution and clay swelling-shrinkage cycles.

4.5.1.2 Time of wetness

While fluctuations in moisture content can facilitate salt and clay driven weathering processes, so can the length of time the rock walls remain wet. The meteorological approach defines time of wetness as hours of days where the relative humidity is greater than 80% (McCabe et al., 2013). A more precise estimation of the time of wetness can be reached by using the relative humidity measured on the walls as an indicator of the time of surface wetness. The relative humidity measured on the walls at Lalibela shows that the RH is above 80% only during Kiremt (Fig 4.6). The mean daily time of wetness (calculated as time above 80% RH) for the walls at Bete Mariam during Kiremt ranges from 10.44 hrs per day on the west wall to 12.30 hrs per day on the north wall. Aspect will determine the length of time of wetness because the duration of incoming solar radiation will directly influence the relative humidity. As a result of intense short sunny spells, the relative humidity cycle on the west wall is lower than the north wall. The duration of wetting is an important factor that can encourage biological growth (Viles and Cutler, 2012). Biological growth on the walls intensifies during Kiremt, from onsite observation it has been observed that moss and other plants readily grow and cover the walls of

the churches at Lalibela during this season. As the walls are wet for nearly half of the day during Kiremt the rock-cut structures will be most affected by biological growth in this season.

4.5.1.3 Deep-seated wetness

The persistent rainfall in consecutive days coupled with low temperatures, cloud cover and high humidity in Kiremt is likely to facilitate the penetration of moisture into the interior of the rock walls. Both accumulation of surface moisture and absorption of groundwater through the thick rock walls (> 1 m) will aid the penetration of moisture at depth. The nature of these buildings also allows moisture to circulate freely within the structure as there are no joints within the rock to impede the movement of moisture. The moisture that has penetrated in depth to the interior of the rock will not evaporate as a result of the short-term thermal cycling that occurs in Kiremt. The wetting-drying cycles that occur will likely be limited to the outer surface of the rock walls, particularly in the wetter months of Kiremt (July and August: > 250 mm/month) where heavy rains occur frequently. As a result of the deep-seated wetting that occurs in Kiremt, salts are likely to penetrate deeper and become redistributed within the rock wall (McCabe et al., 2013) and serve as a reservoir that can drive future surface retreat even while salt-rich surface material is being lost by scaling (Smith et al., 2011). Long periods of internal saturation can also lead to the reduction of mechanical strength (Benavente, 2011). Drying of the surface while the subsurface is still wet can cause cracking of the surface material due to tensile failure, particularly in clay-rich rock types (Jiménez-González and Scherer, 2006) such as those Lalibela is carved into. Moreover, long term deep-seated wetting during Kiremt will likely exaggerate physical damage (Smith et al., 2011), because chemical weathering will continue to occur in the interior of the stone where it remains wet.

4.5.2 Thermal fatigue in Bega

Stresses induced by cyclic or rapid changes in temperature lead to expansion and contraction that eventually result in the physical breakdown of rocks (Bland and Rolls, 2016). Depending on the range of temperature fluctuation and the rate of temperature change either thermal fatigue or thermal shock can occur. Thermal fatigue is produced by repeated thermal stresses like diurnal temperature fluctuation and can lead to failures that exploit existing weaknesses in the rock (Hall and Thorn, 2014). Thermal shock occurs due to a rapid change in temperature that leads to stress that exceeds the elastic limit of the rock (Yatsu, 1988). There is no general consensus on the rate of temperature change that can cause thermal shock (Hall and Thorn, 2014). Yatsu (1988) and Hall (1999) have proposed a 2°C per minute threshold, but the rate of change in temperature on the walls at Lalibela is much lower than this threshold. Thermal fatigue is more likely to occur in Bega because the rock surface temperature range is at its highest during this season. Belg has the highest ambient temperature, but the surface temperature range is much lower than Bega (Fig 4.9). The west wall during Kiremt often has rapid fluctuation in temperature of about 10 °C in 3 hours, but this is a much lower range compared to the south wall in Bega which experiences 25 °C temperature fluctuations in 4 hours daily (Fig 4.9 c and inset). The rapid increase in temperature on the walls will create a thermal gradient from the surface to the depth of the rock. As the surface rapidly warms up due to direct exposure to insolation the inner part of the rock will remain cooler; which will lead to a steep temperature gradient that is likely to be associated with a similarly steep stress gradient in the outer layers of the rock (Bland and Rolls, 2016). The stress caused by high thermal gradients within a thin layer will facilitate scaling of rock surfaces (Yatsu, 1988). The combination of wetting-drying cycles in Belg and Kiremt and thermal cycling in Bega is likely to contribute to contour scaling of the rock surfaces at Lalibela.

Aspect and the shifting of the sun's path toward the south play an important role in the extent of thermal weathering of the rock structures during Bega. Bega is the

season with the highest range in thermal cycles for west, east and south facing walls. West and east facing walls have large diurnal temperature fluctuations throughout the year, whereas the south facing wall experiences a large diurnal temperature fluctuation only during Bega (Fig 4.9). The temperature range on the south wall is nearly 5 times higher during Bega than Kiremt. The diurnal temperature range is low and does not change much for the north wall throughout the year because the north wall receives little direct solar radiation. This is unsurprising as low diurnal temperature ranges have been reported for north facing walls in heritage sites elsewhere in the tropics (Paradise, 1995; Waragai and Hiki, 2019). The thermal gradient between the north and south walls during Bega (about 25 °C at noon) across the diurnal temperature cycle is high enough to lead to differential heating of the monolithic structures. Thermal fatigue due to repeated heating and cooling cycles at high temperature gradients over centuries at micro and macro scale is likely to have a significant impact on the rock churches.

4.5.3 Implications of climate change and trends

Climate change poses a threat to the conservation and management of heritage sites across Africa (Brooks et al., 2020). Coarse spatial resolution and variability of the climate across the continent have led to uncertainties in predicting the future climate in Africa. East Africa is a region known to be highly vulnerable to climate change, the regional climate is influenced by the complex topography and the monsoon system's complexity (Gebrechorkos et al., 2019). McSweeney et al. (2008) reported a projected slight decrease in the amount of rainfall in north-eastern Ethiopia by the 2060s and 2090s using a General Circulation Model. Tegegne et al., (2021) reported a projected increase in rainfall over most parts of Ethiopia and a decline in rainfall in North Wollo region (where Lalibela is located) in the 2020s, 2050s and 2080s, under both low and high emissions using the CORDEX-Africa model. There is some consensus amongst Osima et al. (2018), Endris et al. (2019) and Tegenge et al., (2021) that there will be lower rainfall and consecutive dry days

during Belg, but annual and Kiremt rainfall projections are less clear. There is a consensus on a general warming of the climate in northern Ethiopia due to climate change (McSweeney et al., 2008; Osima et al., 2018; Tegegne et al., 2021). Over the 29-year period studied in this paper a significant increasing trend in minimum annual temperature was identified (Fig 4.8 c), whilst there were no significant trends in maximum annual temperature, annual rainfall or seasonal rainfall. Given the inherent uncertainty in model projections and the strong spatiotemporal variation in climate in Ethiopia, it is difficult to have any certainty about future trends in rainfall at Lalibela. However, the projected decline in Belg rains is likely to lead to less frequent wetting-drying cycles, as the wetting in this season is mainly driven by rain. The high probability of exacerbation of hydro-meteorological extremes in the Horn of Africa (Betts et al., 2018) due to climate change might lead to more wetting events and longer time of wetness in Kiremt. Increasing temperatures may make conditions in Kiremt more favourable for frequent wetting-drying cycles to occur.

4.6 Conclusions

The data analysed in this paper highlights the climatic variability across inter-annual, seasonal and diurnal scales at Lalibela. The key weathering related impacts of the climate on the rock-cut churches at Lalibela are wetting-drying cycles, temperature fluctuations and surface and deep-seated wetness. The intensity of Kiremt rainfall and longer time of wetness are favourable for organisms to flourish in Kiremt, as seen in field observations. Deep-seated wetting during Kiremt will lead to a more pronounced surface to depth moisture gradient which is likely to cause surface cracks. Wetting and drying cycles are frequent in Kiremt and less frequent in Belg which has fewer rainy days. Moisture related weathering processes are unlikely to occur often in Bega due to low RH ($> 50\%$ RH), but high rock-surface temperature fluctuations will likely cause thermal fatigue. Aspect plays an important role in the range of thermal and RH fluctuations. The south facing wall is more vulnerable to thermal fatigue in Bega while the west facing wall experiences more temperature

and RH fluctuations than the other walls the rest of the year. Scaling and contour scaling that are common across the churches in Lalibela are likely caused by the combined effect of wetting-drying cycles in Belg and Kiremt and thermal fatigue in Bega. Detachments and weaknesses formed by repeated wetting-drying are driven to failure by thermal fatigue. The long-term ambient data set showed an increase in minimum annual temperature. While rainfall did not show a significant trend it is likely that more intense wetting events may occur in the future due to climate change. Higher temperatures and more intense wetting events may intensify salt weathering, biological weathering and thermal fatigue at Lalibela.

This study sets the background to understanding the history of weathering at Lalibela and the nature and rate of weathering in the future. This is crucial for the protection of rock-cut structures in Lalibela and elsewhere in northern Ethiopia. The key-weathering related impacts of a northern Ethiopian climate highlighted here should be considered in order to understand the risks posed by moisture and temperature driven weathering processes. With climate change exacerbating hydro-meteorological events and increasing temperatures, rock-cut sites found in northern Ethiopia may become more vulnerable to moisture driven weathering and thermal fatigue.

5. Lithology

Influence of salt (sodium chloride) on hydric and hygric dilatation of clay-rich rocks

Abstract

The mechanisms through which crystallisation of salts and hydration of swelling clays cause deterioration of rocks are generally understood. However, how these two decay mechanisms operate synergistically is less clear. In this study, we investigated the impact of a salt (sodium chloride) on the deterioration of clay-rich basaltic scoria from which the churches forming the UNESCO World Heritage Site of Lalibela in Ethiopia are hewn. The basaltic scoria is rich in smectite (swelling clay) and zeolitic minerals which have micropores and an affinity for efficient water absorption. Hydric and hygric swelling experiments were carried out on 50 mm cube quarry samples and continuous measurements were taken with Linear Variable

This chapter has been submitted to the Journal of Cultural Heritage with the following co-authorship: Taye Gemedo, B., Viles, H. and Zhang, H.

Displacement Transformers (LVDT). Hydric (liquid water) tests involved partially submerging the samples in deionised and saline solutions. Hygric (water vapour) tests were done in an environmental cabinet where the RH fluctuated between 60% to 90% RH with salt-free and salt-contaminated samples. The results showed that contamination with salts alters both hydric and hygric behaviour. Hydric swelling was reduced in most samples when contaminated with salt, while the expansion and contraction phases in hygric tests were reversed after contamination with NaCl. Continuous measurement of dilatation allowed us to quantify the strain developed during the phase transition of NaCl. Due to the crystallisation pressure, hygric dilatation increased significantly in salt-contaminated samples. Salt-contaminated samples also showed frequent episodic changes in volume that corresponded both with the hydration/dehydration of clay interlayers and crystallisation/dissolution of NaCl. These volume changes correspond with the damage profile on the surface of the samples, i.e., scales and granular disintegration. The experimental results indicate that the contour scaling and granular disintegration commonly seen in areas rich in salts at Lalibela are likely caused by episodic changes in volume due to diurnal hygric cycling.

5.1 Introduction

Several studies on sandstones and limestones that contain swelling clays (Jiménez-González and Scherer, 2006; Kühnel et al., 1994; Pye and Mottershead, 1995;

Rodriguez-Navarro and Doehne, 1999; Veniale et al., 2001; Wangler and Scherer, 2009) have shown that repeated wetting and drying cycles weaken grain boundaries and create differential stresses and strains that lead to cracking and buckling. Swelling clay minerals are secondary minerals that are formed by moisture or air driven transformation of rock forming silicates (Galán, 2006). The most common ones belong to the smectite group which includes montmorillonite, nontronite and hectorite (Odom, 1984). Swelling clays have an aluminosilicate layered structure held together by cations. Absorption of water into these layers results in strong repulsive forces that cause the clay minerals to expand (Hensen and Smit, 2002). Consequently, clay swelling is driven by changes in moisture content, which also influences salt crystallisation and dissolution cycles. Salt weathering is recognised as one of the primary agents in the deterioration of historical architecture (Doehne, 2002; Goudie and Viles, 1997). Crystallisation of salts in the pore walls of rocks generates pressure against the pore walls and eventually leads to damage (La Iglesia et al., 1997; Rodriguez-Navarro and Doehne, 1999). Where salt forming ions and swelling clays are present, wetting and drying cycles will trigger both crystallisation/dissolution of salts and hydration/dehydration of clay minerals. While it is understood that these decay processes can cause damage, how they synergistically operate is less clear.

The effect of salt contamination (NaCl) on the hygric (60 – 90% RH) and hydric (immersion into water) dilatation behaviour of clay rich rocks is experimentally studied in this paper. Dilatation is an indication of the swelling potential of a rock

and the damage it can cause (Madsen and Müller-Vonmoos, 1989). The dilatation of samples free of salt and contaminated with salt are compared to clarify the role of salts in wetting and drying cycles of a clay containing rock. Measurements are taken continuously to quantify the strain caused by the crystallisation pressure of NaCl. Samples from the rock-cut churches at Lalibela, which is a UNESCO world heritage site hewn into a clay-rich basaltic scoria outcrop, are used in this study. Even minor quantities of clay minerals in basaltic rock can strongly affect the durability of the rock (Kühnel et al., 1994). The abundance of clay in the basaltic scoria is very likely affecting the degree of expansion and contraction during wetting and drying cycles. Field observation at this site has also shown evidence of salt efflorescence on most of the church walls, and research has shown that soluble salts are responsible for localised deterioration of bas-reliefs at Lalibela (see section 6.2). Characterising the hygric and hydric dilatation properties of the basaltic scoria will clarify the synergistic interaction of swelling clays and salt in weathering of basaltic. Insights gained from this experimental study can help in developing preservation strategies for salt affected clay rich rock-cut sites.

5.1.1 Introduction to Lalibela

Lalibela is located in the northwestern Ethiopian plateau in a mountainous area made up of outcropping of Tertiary volcanic rocks (Delmonaco, Margottini, Spizzichino, and Mazzolani, 2009). The eleven rock-cut churches that make up the UNESCO world heritage site of Lalibela were carved into a basaltic scoria hill be-

tween the 11th and 13th century AD (Derat et al., 2021; Gobezie, 2018). Micro (in mm) to macro (in cm) contour scales have developed to varying degrees of severity on the surfaces of the churches (Fig 5.1), which are likely caused by repeated wetting and drying cycles. When the scales fall off the area underneath is usually rich in white salt crystals (sub-florescence).

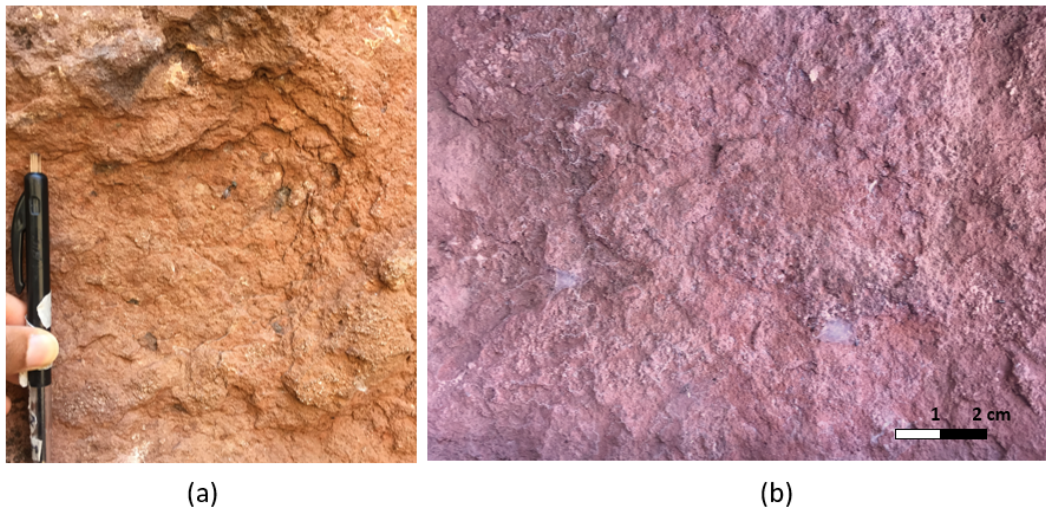


Figure 5.1: Macro (left) scaling at and micro (right) scaling on the church walls at Lalibela

Recent climatological investigations have shown that wetting and drying cycles and deep wetting occur almost daily during the main rainy season (June to September) at Lalibela (Chapter 4). The rest of the year is fairly dry with relative humidity fluctuating below 60% RH and some rain during the short rainy season. The diurnal humidity fluctuation (60 to 90% RH) in the main rainy season is in the range that would allow for hygric wetting and drying to occur.

5.2 Research Aim

This paper aims to assess the impact of salt on clay-rich rocks and the decay features it produces. Hydric and hygric swelling was measured before and after contamination with NaCl to identify how the degree and frequency of swelling changes when clays are exposed to salt. To measure the strain produced by crystallisation pressure, swelling measurements were done continuously as NaCl changed phases. Characterisation of mineralogical and petrological properties was also done to determine how they may influence swelling behaviour.

5.3 Materials and Methods

5.3.1 Petrology and Mineralogy

5.3.1.1 Petrology

The bulk petrology of the basaltic scoria has been characterized as hydrothermally altered and laterized basaltic scoria (Renzulli et al., 2011). It is a porphyritic rock type with a fine-grained texture and containing brownish/reddish haematite rich matrix (Fig 5.2 b). The rock has abundant open voids and vesicles that occupy about 40-50 % (Schiavon et al., 2013), often partially (Fig 5.2 a) or fully filled with secondary minerals (Fig 5.2) zeolitic minerals. Pyroxene and plagioclase are the primary mineral phases (Delmonaco et al., 2010). Secondary clay minerals are

widespread within the matrix (Asrat and Ayallew, 2011; Renzulli et al., 2011). The main secondary minerals that are found in the matrix and in the filled vesicles are hematite, zeolite, calcite and clays of the smectite group (Schiavon et al., 2013).

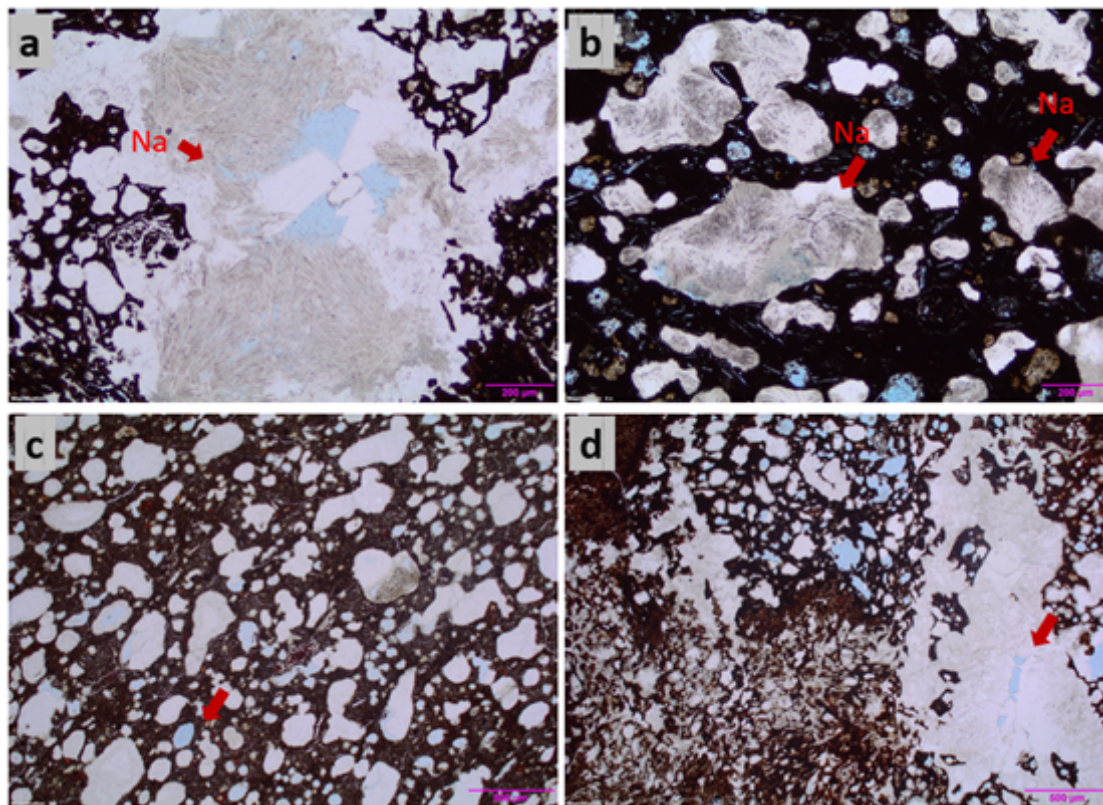


Figure 5.2: Thin sections of porphyritic basaltic scoria from Lalibela exhibiting a fine-grained matrix and vesicles partially or fully filled with Natrolite (Na – red arrows) and open pores (blue colouration). Samples collected from the following churches (a) Bete Amanuel, (b) Bete Giyorgis, (c) Bete Medhanialem and (d) Bete Giyorgis.

5.3.1.2 Mineralogy

Bulk mineralogy analysis and quantification of clay minerals of quarry samples and weathered samples from some of the churches was performed using X-ray diffraction (XRD) to compare the mineralogical composition of the rock from the quarry and the churches. Two types of quarry samples (type A and type B) and twelve

representative samples collected from the churches were analysed. Quarry types A and B were extracted from different layers of horizontally layered units in the Yohannes Amba quarry (see appendix 4). Due to logistical limitations 7 samples of quarry type A and 3 samples of type B were available for this study. A Panalytical Emyrean Series 2 diffractometer operating at 40 kV and 40 mA with a Co K source was used to identify the minerals. Quantitative analysis of clay content used ZnO as an internal standard following (Środoń et al., 2001). A 1:0.111 ratio of powdered sample to ZnO was used to determine the clay quantity in each sample. Mineral identification and quantification were carried out using the mineral standard pattern provided by the RockJock 7 program. The samples collected from the churches were weathered samples that were detaching from the surface of the walls. Because of the heterogeneity of the volcanic rocks at Lalibela, where possible, two samples each were analysed from both quarry and church types.

Table 5.1 shows that zeolite, smectite, pyroxene, hematite, ilmenite and K-feldspars were the main mineral types found in both the quarry and church samples. Zeolite and smectite are very abundant in all the samples analysed, while pyroxene and K-feldspars are present in varying levels of abundance. Hematite and ilmenite are present in all the samples. Samples of quarry type A were the only ones that had very abundant pyroxene. Of the church samples analysed, only Bete Giyorgis had abundant plagioclase. Gypsum was present in some of the church samples, but not in the quarry samples. This is likely due to gypsum occurring as a soluble salt within the weathered church samples.

Table 5.1: Bulk mineralogy XRD analysis of quarry and church samples

	Smectite	Zeolites	Pyroxene	K.feldspar	Hematite	Ilmenite	Plagioclase	Calcite	Dolomite	Gypsum	Epidote	Muscovite
Type A	++++	++++	++++	+	+	+	+	-	-	-	-	-
Type A	++++	++++	++++	-	+	+	-	-	-	-	-	-
Type B	++++	++++	+	++++	+	+	-	-	-	-	-	+
Type B	++++	++++	+	-	+	+	-	-	-	-	-	-
Mariam	++++	++++	+	++	++	+	-	-	-	-	(+)	-
Medhaialem	++++	++++	++	+	+	+	-	-	-	-	-	-
M/Golgotha	++++	++++	+	++	+	+	-	+	+	+	-	-
M/Golgotha	++++	++++	+	+	+	+	-	+	-	-	-	-
Libanos	++++	++++	+	+	+	+	-	-	(+)	-	-	-
Libanos	++++	++++	+	-	+	(+)	(+)	+	+	-	-	-
Amanuel	++++	++++	+	+	+	+	-	-	-	-	(+)	-
Amanuel	++++	++++	+	+	+	+	+	-	-	-	-	-
G/Rufael	++++	++++	+	++	++	-	-	-	-	-	-	-
G/Rufael	++++	++++	+	++	+	+	(+)	-	-	-	-	-
Giyorgis	++++	++++	+	++	+	+	++	-	+	(+)	-	+
Giyorgis	++++	++	+	++	+	+	++	+	(+)	(+)	-	+

++++: very abundant, ++: abundant, +: present, (+): suspected and -: absence

The abundance of smectite and zeolite substantially affects the physical properties of the rock. Smectites are phyllosilicates with two tetrahedral sheets and one octahedral sheet. The 2:1 sheet layers are loosely held together by cations (Odom, 1984). The hydration of the interlayer cations leads to an increase in the layer spacing to accommodate the water molecules. This is known as crystalline swelling and is one of the mechanisms through which clays swell. Clays can also swell because of the repulsion between the electric double layers of the clay, which is known as osmotic swelling (Norrish, 1961). The species of the changeable cation, the surface charge and the valence of the cations in the double layer determine the degree of hydration and dehydration (Madsen and Müller-Vonmoos, 1989). Zeolites have similar

cation exchange properties as smectites, but they have a rigid tetrahedral framework and fixed pores (Schulze, 2005), so their interlayer space does not increase. Zeolites have molecule sized channels and voids in their structure that makes them potent water absorbers (Buekenhoudt et al., 2010). As a result of these properties, considerable amounts of swelling clay minerals and zeolites can contribute to a sensitivity to expansional forces and salt crystallisation (Pötzl et al., 2022).

5.3.2 Experimental Methods

5.3.2.1 Materials

Fresh quarry samples were used in the experiments. Ten 50 mm cube samples, seven of type A and three of type B were prepared. Water absorption coefficient by capillarity BS EN 1925 (1999), apparent density BS EN 1936 (2006), open porosity BS EN 1936 (2006), dry weight, saturated weight, and saturated water content of the quarry samples were measured in the laboratory. The quarry samples have an open porosity above 30% and water absorption coefficients above $50 \text{ g/m}^2 \cdot \text{s}^{0.5}$ (Table 5.2). The saturated water content was between 15.41 and 16.40%; apparent density was 1.68 to 1.86 g/cm^3 ; and open porosity was 31.49 to 34.28%. The water absorption coefficient was between 62.1 and 71.9 $\text{g/m}^2 \cdot \text{s}^{0.5}$ for all the samples except B3 which had a water absorption coefficient of 55 $\text{g/m}^2 \cdot \text{s}^{0.5}$. High open porosity of the samples could be due to the presence of open vesicles in the rock matrix. The high water absorption coefficient is likely due to the abundance of zeolite in these

rocks (Table 5.1).

Table 5.2: Physical properties of the 50 mm cube quarry samples used in the experiment.

Sample	Saturated water content (%)	Apparent density (g/cm ³)	Open porosity (%)	Water absorption coefficient (g/m ² .s ^{0.5})
A1	15.50	1.85	34.04	64.0
A3	15.47	1.84	33.75	71.9
A4 (control)	15.58	1.84	34.06	63.0
A5	15.75	1.83	34.28	62.1
A6	15.59	1.84	34.11	63.4
A7	15.45	1.86	34.10	64.4
A8	15.69	1.83	34.23	62.3
B1	16.05	1.70	32.58	68.1
B2	16.40	1.68	33.12	67.7
B3	15.41	1.72	31.49	55.0

5.3.2.2 Experimental Design

Hygric and hydric properties of salt-free and salt-contaminated quarry samples were assessed on two rock types using a similar protocol to Snethlage and Wendler (1997) with some modifications. The main modifications are: (1) higher number of samples (10) were used; (2) to avoid sample-to-sample variation in misleading interpretation of results, changes in dilatation behaviour was measured in the same sample before and after contamination with NaCl; (3) swelling strain was measured continuously which allowed us to measure dilatation as NaCl crystallises and (4) hygric experiments were carried out between 60 – 90 % RH to replicate the wetting and drying cycle that occurs most frequently at Lalibela. NaCl was chosen because it is a strong electrolyte and likely to affect the swelling mechanisms of clays. In this study we used 12 wt % concentration to assess the impact of high concentration of

salts in clay swelling. Other studies (Müller-Vonmoos and Løken, 1989; Ruedrich et al., 2007; Scheerer et al., 2009; Wangler and Scherer, 2009) have used 5 to 16 % concentrations of salts in similar experimental setups.

To measure hygric and hydric dilatation, three GT2 series Linear Variable Differential Transformers (LVDT) from Keyence with an accuracy of 1 μm and a resolution of 0.1 μm were used. LVDT's are effective in high accuracy measurements of dilatation of building materials (Akoğlu and Caner-Saltik, 2015; Jiménez-González and Scherer, 2006; Sebastián et al., 2008; F. Zhang et al., 2012). Dilatation is the ratio of the change of length (Δl), which is measured by the LVDT, to the original size of the sample (l_0), that is, $\Delta l/l_0$. In this paper, dilatation is presented in mm/m. The experiment protocol involved two sets of tests, one in salt-free conditions and another with the samples contaminated with salt. At the start of the experiment, the samples were oven-dried at 70 °C and kept in a desiccator to cool down. This drying temperature was chosen to limit any alteration of the samples that may result from exposure to very high heat. Figure 5.3 shows the experimental setup and workflow carried out in this study. The hygric dilatation was measured in an environmental cabinet (Binder - KBF 115) at a constant temperature of 18 °C and fluctuating relative humidity. The RH was set to alternate between 60% and 90% RH every 12 hours, and the experiment ran for four consecutive cycles. Temperature and RH in the environmental cabinet was monitored with Tinytag data loggers (TGP-4703). The hydric swelling measurements were done in a lab setting where the temperature was 20 ± 2 °C and RH was between 50 % and 60 % RH. Hydric dilatation was mea-

sured by partially submerging the bottom 3 mm of the samples in deionized water for 48 hours and measuring the dilatation every minute. The same procedure was repeated with 12 wt% NaCl solution. After the samples were contaminated with salt by capillary absorption, they were oven-dried at a low temperature (30 °C) until a constant weight was reached. Then the hygric swelling experiment was repeated in the environmental cabinet. Drying at a low temperature was done to ensure that all the salt was not lost via efflorescence. One sample was not contaminated with salt (A4) and underwent repeated salt-free hydric and hygric tests. A4 was used as a control sample to explore whether there are any significant changes in swelling after repeated salt-free wetting and drying cycles. All measurements were taken perpendicular to the layering direction of the basaltic scoria, as this direction has been shown to produce the highest swelling potential for volcanic rocks and sandstones (e.g.; Steiger et al., [2011](#); Wedekind et al., [2012](#)).

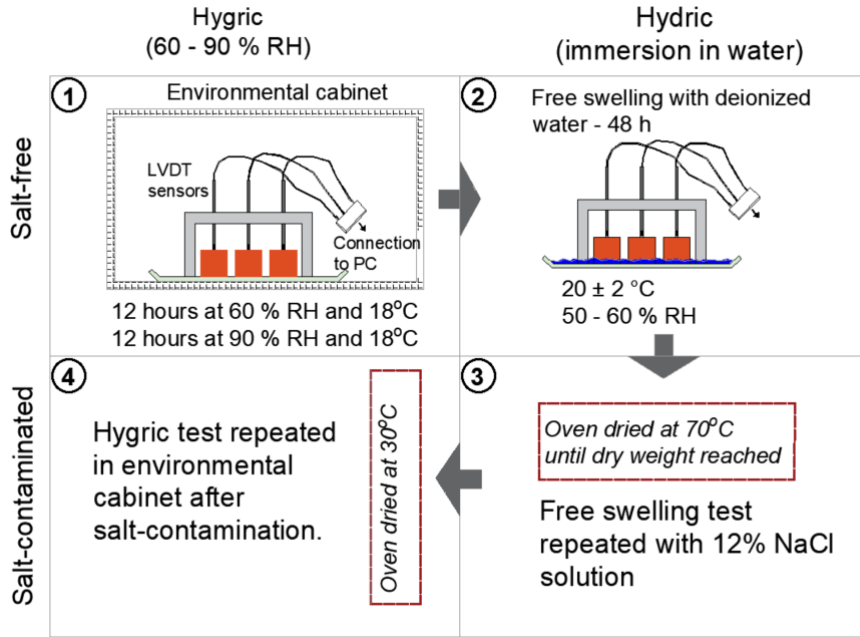


Figure 5.3: Workflow diagram showing salt-free and salt-contaminated experiments carried out in this study.

5.4 Results

5.4.1 Hydric Dilatation

Hydric dilatation of the samples in deionised water is between 0.17 to 1.21 mm/m (Fig 5.4). This range of hydric dilatation is comparable to tuffs (Pötzl et al., 2018; Wedekind et al., 2013) and sandstones (Benavente and Cultrone, 2008) containing smectite. Contamination with salt reduced the dilatation and, in some cases, led to shrinkage. Sample B2 shrunk significantly (-0.36 mm/m) after contamination with salt while A5 dilatation tripled. Large sample-to-sample variation in dilatation is common in clay-rich rocks (Jiménez-González et al., 2008). Variation in microporosity and location of clay minerals within the pore space has been correlated with significantly altering the hydric swelling behaviour between samples (Ruedrich et

al., 2011; Wedekind et al., 2012). The control samples which underwent two hydric dilatation cycles with deionized water showed no significant difference in dilatation between the first (0.27 mm/m) and the second (0.34 mm/m) measurement. The slight increase in dilatation is expected as samples that undergo repeated wetting and drying cycles tend to have higher dilatation (Snethlage and Wendler, 1997). The large difference in dilatation between salt-free and salt-contaminated measurements is therefore mainly driven by the introduction of NaCl to the rock samples, rather than a consequence of repeating the tests.

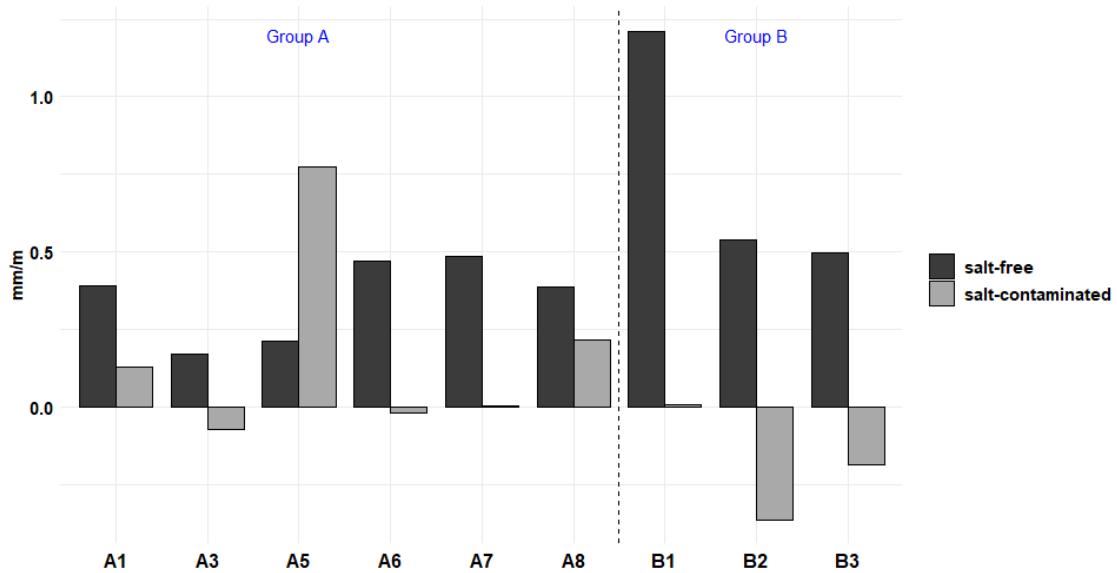


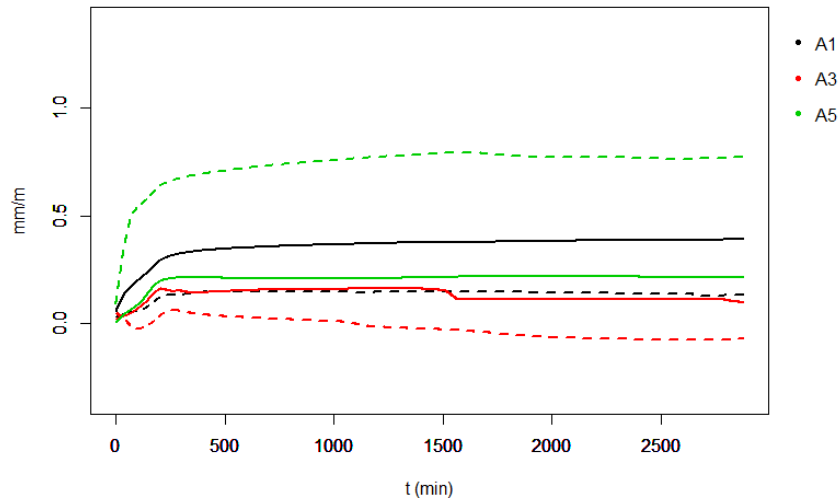
Figure 5.4: Salt-free (black) and salt-contaminated (grey) hydric dilatation.

Hydric dilatation in deionized water showed a strong time dependency. The expansion of A1 was completed in about 4 hours whereas for sample B3 it took 24 hours for the main expansion (Fig 5.5). B3 had the lowest water absorption coefficient (Table 5.2) of the sample set, which means it takes more time for water to penetrate and be distributed within the pore network of the rock. Conversely, B1

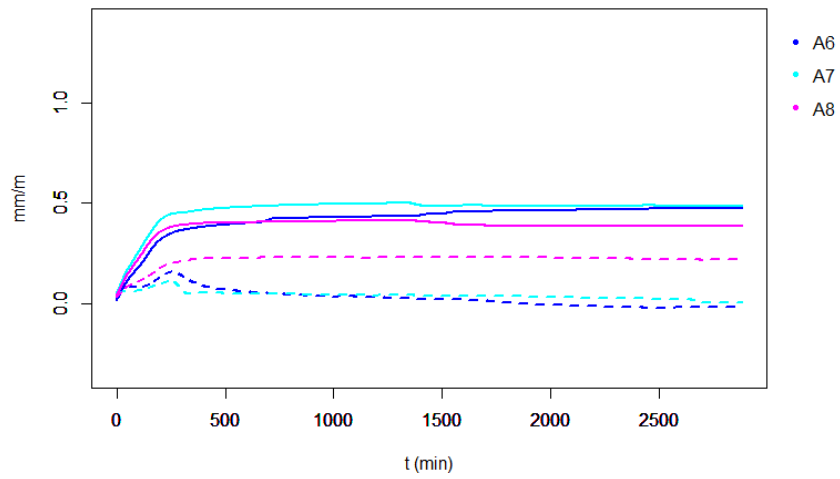
had one of the highest water absorption coefficients and a faster rate of dilatation. Water absorption rate has been shown to correlate well with hydric dilatation rate (Berthonneau et al., 2016). Porosity influences the rate of hydric expansion, rocks with higher porosities have faster rates of expansion (Steiger et al., 2011). B3 also has the lowest open porosity which will affect both the rate of hydric expansion and distribution of NaCl within the pore network.

The results show that the amount of hydric swelling is significantly different between salt-free and salt-contaminated samples. Both crystalline swelling and osmotic swelling are high in salt-free samples (low electrolytic potential) and lower in salt-contaminated samples (high electrolytic potential). Osmotic swelling is high in salt-free samples because of the high ionic concentration difference between the negatively charged clay particles and the deionized water in the pores (Ruedrich et al., 2011). In contrast, osmotic swelling can be very low in salt-contaminated samples because there is no large ionic concentration difference. If the ionic concentration between the double layers of the clay is much lower than the pore water, water will be driven out of the interlayer space of the clays to the pore space of the rock (Wangler and Scherer, 2008) which will cause a contraction. The contraction of some of the salt-contaminated samples after an initial phase of expansion is likely due to the osmotic effect (Fig 5.5). Crystalline swelling will also decrease with the incorporation of cations from the salt in the intermediate layers of the clay minerals leading to a reduction in hydration potential (Steiger et al., 2011).

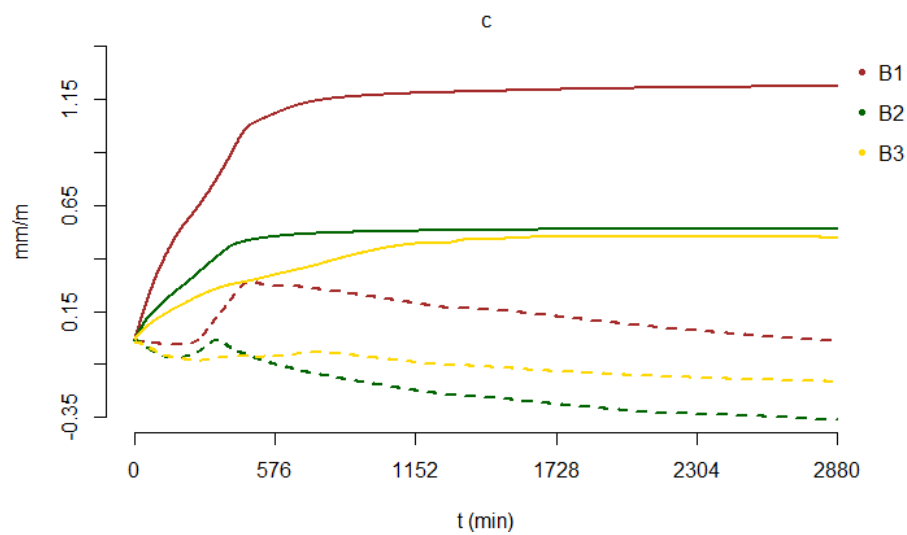
5 Lithology



(a)



(b)



(c)

Figure 5.5: Salt-free (solid line) and salt-contaminated (dashed line) hydric dilatation plotted as a function of time.

5.4.2 Hygric Dilatation

Hygric swelling was measured before and after contamination with salt where relative humidity fluctuated between 60% RH and 90% RH every 12 hours. The salt-free samples expanded during wetting (90% RH) and contracted during drying (60% RH). After contamination with salt, the samples behaved in the opposite way (Fig 5.6), contracting during the wetting phase and expanding during the drying phase. B1 had the highest hygric dilatation as well as hydric dilatation. While B3 behaved differently from the other samples, the results after salt contamination did not differ much from the salt-free measurements (Fig 5.6 c). As pointed out earlier this sample has a slower water absorption rate and lower open porosity. This likely affected the distribution of salts within the sample and thereby its response to RH fluctuations. The dilatation in the salt-free samples is consistent with clay swelling mechanism. Similar to the hydric swelling test, crystalline and osmotic swelling have been disrupted by the presence of NaCl in salt contaminated samples. In the hygric test because the RH fluctuates in the range where NaCl can shift between a solid and a liquid phase, the crystallisation pressure of NaCl will also contribute to the dilatation/contraction of the samples. The crystallisation pressure, which is dependent on the supersaturation and amount of salt crystals forming, influences the degree of swelling and contraction of salt contaminated samples (Derluyn et al., 2014). There were larger changes in volume after contamination with salt as a result of the crystallisation pressure leading to higher expansion rates.

5 Lithology

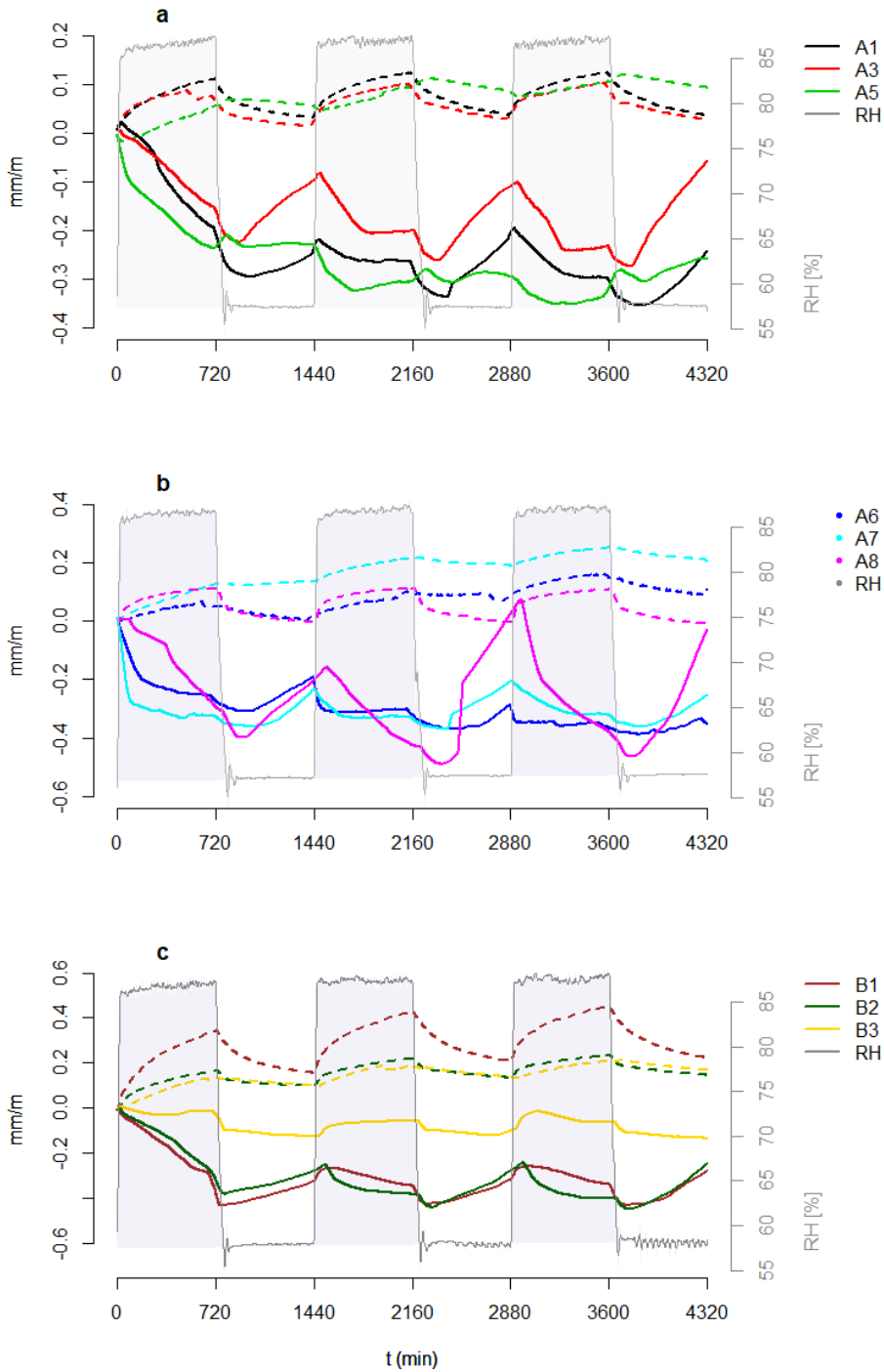


Figure 5.6: Hygric dilatation of salt-free (dashed lines) and salt-contaminated (solid lines) samples. Note the y-axis scales are different. The shaded boxes indicate periods when RH levels are 90% RH.

The dilatation in each cycle was not fully reversible in both salt-free and salt-contaminated tests. Within the three cycles that were run in this experiment the dilatation increased slightly in each cycle in most samples (Fig 5.6 b and c). The

control sample which underwent 6 hygric cycles in total showed a slight increase in hygric dilatation with successive cycles. Repeated wetting and drying cycles lead to small incremental non-reversible dilatation as reported for sandstones containing smectites (Colas et al., 2011; Snethlage and Wendler, 1997).

In an analogous experiment set up, Snethlage and Wendler (1997) compared salt-free and salt-contaminated clay containing sandstones and found similar hygric dilatation behaviour as presented here. In their experiment the hygric dilatation was measured at two RH values, 35% and 90 % RH, and measurements were not taken at the critical RH value where NaCl phase transition occurs (75.5 % RH). The effect of crystallisation pressure on dilatation is likely to start at this critical RH value. In this experiment, it was possible to identify episodic changes in volume that corresponded with phase transition of NaCl and hydration and dehydration of clay interlayers in all the samples that were contaminated. Figure 5.7 shows a selection of the samples that had episodic phases of hygric dilatation and stasis during one RH cycle. While the increase in dilatation in Phase 1 and the decrease in dilatation in Phase 4 correspond with the hydration and dehydration of the clay interlayers, the rapid reduction in Phase 2 and the rapid expansion in Phase 5 correspond with the crystallisation and dissolution of NaCl. The hygric dilatation phases that are driven by salt (Phase 2 and 5) are preceded by a shorter phase of response of the clay interlayer to either hydration or dehydration (Phase 1 and 4). Hygric swelling of the salt-free sample had two phases of volume change that are gradual expansion and contraction of the sample. Salt contamination of samples rich in swelling clays

led to more frequent and abrupt changes in volume that are reversible in laboratory conditions but are likely to contribute to irreversible displacements that lead to material fatigue in the natural environment.

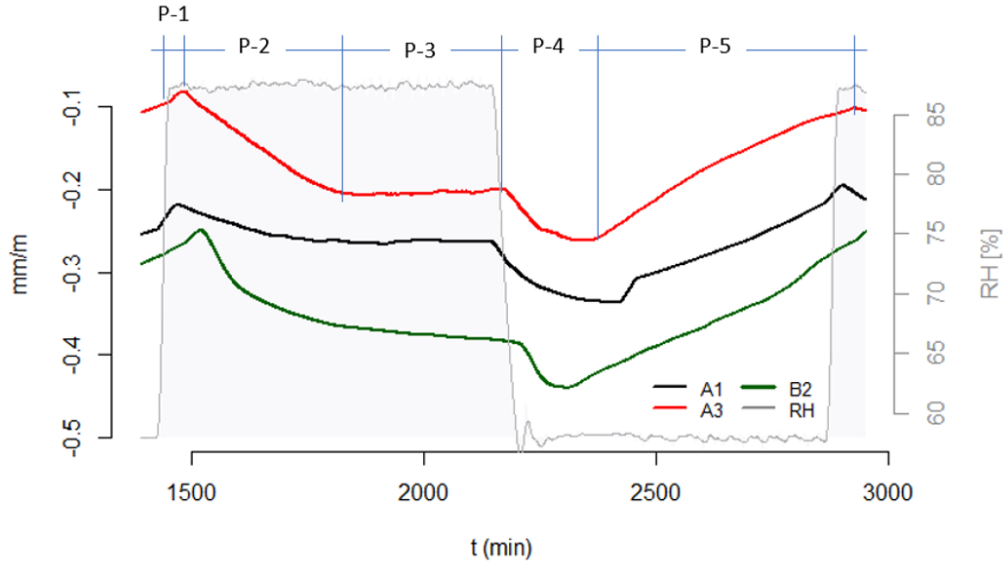
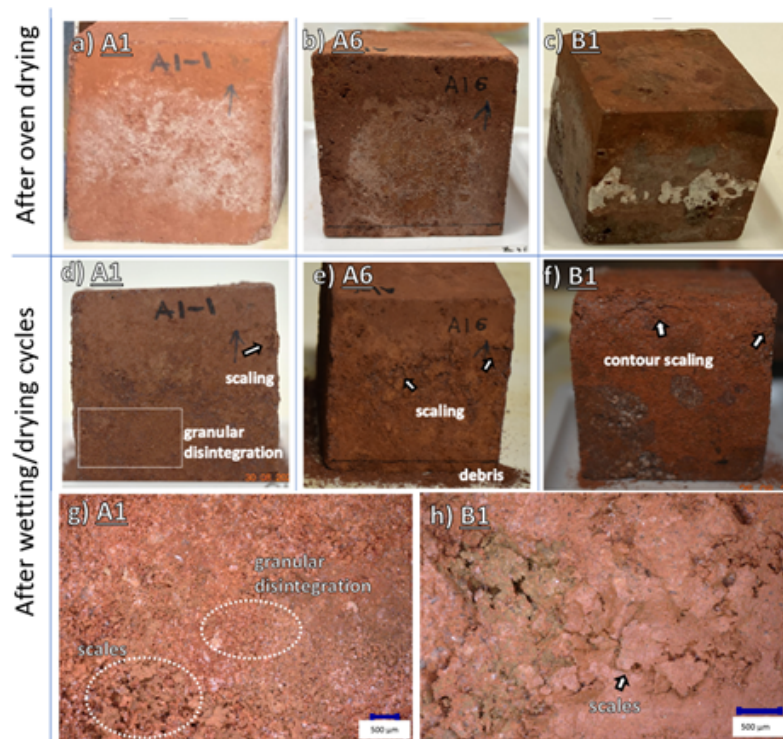


Figure 5.7: Hygric dilatation phases in salt-contaminated samples in A1, A3, and B2. P-1: hydration of clay interlayer, P-2: dissolution of NaCl, P-3: stasis, P-4: dehydration of clay interlayer and P-5: crystallisation of NaCl.

5.4.3 Macroscopic and Microscopic Decay Features

Salt-free samples and the control sample did not show any macroscopic or microscopic decay features after undergoing hydric and hydric wetting and drying cycles. After salt contamination the samples began to exhibit some signs of deterioration. During the salt contamination processes, at the stage samples were dried in the oven, salt effloresced on the surface of the samples (Fig 5.8 a, b and c). After undergoing four hygric wetting and drying cycles the spatial variation in the distribution of salts led to the formation of different decay patterns. Fine-grained debris was formed through granular disintegration of the lower half of the sample that was

covered with salt efflorescence prior to the start of the wetting and drying cycles. Where salts are present on the surface, granular disintegration occurs through disruption of intergranular cohesion (Warke and Smith, 2000). In the upper part of the samples, which did not have much salt efflorescence, scaling and contour scaling were more common. Scales occur when the maximum moisture content is below the surface (Snethlage and Wendler, 1997) leading to the crystallisation of salts in the subsurface. Contour scaling occurs where salts concentrate at depth (Smith and McGreevy, 1988). The decay features that form on clay-rich rocks may be dependent on the spatial distribution of salts and moisture.



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Figure 5.8: The surface condition of salt-contaminated samples before [a), b) and c)] and after wetting and drying cycles [d) to h)]. Images a), b) and c) show the samples with salt efflorescence after contamination with NaCl. Images d), e) and f) shows granular disintegration, scaling and contour scaling after wetting-drying cycles and images g) and h) show optical microscope images of the weathering features (scale bars = 500 microns)

5.5 Discussion and Conclusions

The results of this study demonstrate that the clay-rich basaltic scoria rocks at Lalibela have high hygric and hydric dilatation capacities and that this behaviour is radically changed with contamination with salt. Contamination with salt led to lower hydric dilatation than the salt-free tests. In saturated conditions (hydric) the reduction in swelling potential when contaminated with salt is likely driven by the osmotic effect, where the ionic concentration difference between the clay layers and the pore water results in a reduction of the interlayer repulsive forces. Low concentration of salts will lead to a less significant reduction in hydric swelling. During a wetting event like a rain spell, the spatial variation in the distribution of salt will determine the strain profile.

Unlike hydric dilatation, hygric dilatation increased after salt contamination. The response of the salt-contaminated samples to hygric cycling mainly reflects the crystallisation/dissolution of salts, but smaller changes in volume that correspond with hydration/dehydration phases of clays are also at play. The significant damage to the samples after just a few wetting and drying cycles is likely due to the combined effect of the swelling clays and crystallisation pressure of salts. Clay minerals are brittle when dry (Torraca, 2009) and plastic when wet. In the absence of salts, this plasticity allows a reversible volume change during wetting and drying, with some incremental damage with successive cycles. But the addition of salts to this system means that salt will crystallise when clays are in a dry brittle state. This

is more likely to lead to non-reversible deformation, as demonstrated in this study. As moisture is the driver of both these decay processes, salts are more likely to effloresce in areas already weakened by repeated swelling/shrinkage cycles of clay. Swelling clay can also have an indirect role by contributing to the microporosity which favours salt damage (McGreevy and Smith, 1984) and being the source of salt forming ions (Steiger, 2003). Salt contamination of clay rich rocks is therefore able to cause accelerated damage due to a high degree of dilatation (strain) and an increase in the frequency of volume change.

This study provides additional information on the impact of salts on clay-rich rocks and the decay features it produces. Previous research has shown that the response to moisture expansion behaviour of clay-rich rocks is dependent on various petrophysical properties. However, how salt, the most common decay agent, affects the dilatation behaviour of clay-rich rocks has been less clear. In this study, using 9 samples with comparable petrophysical properties, some general characteristics of the swelling behaviour of clay-rich rocks are identified:

- Hydric swelling is reduced in saline solution and may lead to shrinkage (Fig 5.5).
- Contamination with salts reverses hygric swelling behaviour in 8 out of the 9 samples, that is, expansion occurs during drying and contraction occurs during wetting (Fig 5.6).
- In the sample set studied here, wetting and drying cycles led to accelerated

rock decay once clay-rich rocks are exposed to salts. This is as a result of more frequent changes in volume and a higher degree of swelling strain due to crystallisation of salt while the clay mineral is in a dry brittle state that (Fig 5.6 and 5.7).

- Granular disintegration, scaling and contour scaling are the most common decay features produced by salt weathering of clay-rich rocks.

The experimental results indicate that the contour scaling and granular disintegration commonly seen in areas rich in salts at Lalibela (Fig 5.1) are likely caused by high crystallisation pressure of salts in brittle clay-rich rock fabric. Spatial distribution of salt and moisture will lead to different strain and stress profiles that determine the decay patterns that form on the rock walls. Frequently occurring diurnal hygric cycling, therefore, has a lot of potential to cause surface material loss.

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6.1 Seasonality in moisture dynamics in the walls of the rock-cut churches in Lalibela, Ethiopia: Implications for weathering

Abstract

Moisture plays a key role in rock weathering in the built and natural environments. Rock-cut sites are particularly vulnerable to moisture-related weathering as they are carved into rock outcrops and do not have impermeable foundations or roofs to retard the flow of moisture. To characterise the moisture dynamics and its influence on weathering of rock-cut sites, we undertook a moisture monitoring campaign using a non-destructive Microwave Moisture Measurement System (MMMS) at two monolithic rock-cut churches in Lalibela, Ethiopia. The results showed that the walls were more saturated at depth than on the surface during the wet season.

This section has been submitted to the International Journal of Architectural Heritage with the following co-authorship: Taye Gemed, B., Viles, H. and Orr, S.A.

This suggests that low surface temperature and higher moisture content at depth will lead to constant-rate drying and accumulation of salts on the surface of the walls during the wet season. In the dry season, there was higher saturation near the surface than at depth (falling-rate drying). High rock surface temperature during the dry season contributes to subsurface drying and accumulation of salts below the surface. This seasonally shifting moisture dynamics will lead to a complex and dynamic damage profile. This study highlights the significant wetting facilitated by a lack of impermeable roofs and foundations at rock-cut structures during rainy periods. Moreover, it showed that the MMMS can be effectively applied on basaltic scoria.

6.1.1 Introduction

Moisture plays a crucial role in weathering processes on rock surfaces in both built and natural environments. Wetting-drying, salt efflorescence and hygric expansion-contraction are induced by fluctuations in moisture content. Understanding the spatial and temporal variation of moisture (moisture dynamics) in porous building materials is therefore essential for informing heritage management. Two key sets of factors control moisture transport within porous building materials: environmental and structural/material characteristics (Hall and Hoff 2003). The amount of rain, the duration of rainy periods and the range of temperature fluctuation are key environmental factors that determine moisture dynamics (McCabe et al., 2013). As a result of environmental conditions and material properties (pore network), the rate

of drying (evaporation) in porous building materials may be constant-rate (stage I drying) or falling-rate (stage II drying). Constant-rate drying occurs when there is a connected hydraulic pathway that can efficiently transport liquid water to the drying surface of a material; whereas falling-rate drying refers to a slow rate of evaporation where flow to the surface stops and liquid is removed from the surface as vapour through diffusion (Scherer, 1990). Structural factors, such as building type, whether it is a masonry structure composed of mortar joints and stones or a carved rock-cut site, will hugely influence the rate of moisture transport and evaporation. Rock-cut sites that are usually found carved into hills or on cliff faces are homogeneous in composition aside from inherent lithological variation that might be present. The moisture dynamics in this type of structure are likely to be different from that of masonry structures that usually have a semi-impermeable foundation to prevent groundwater uptake and a roof to stop rain infiltration.

Much focus has been given to studying moisture transport in masonry and rock walls in temperate climates (Hall et al., 2011, Hall, 2004, McAllister et al., 2016; Sass and Viles, 2006, 2010; Smith et al., 2011), but other areas, including tropical climates, have received less attention especially those with strong seasonal contrasts. Many culturally important rock-cut heritage sites exist in tropical climates characterised by seasonal rains, such as Petra in Jordan, Ellora in India, Lalibela in Ethiopia, and several rock-cut sites in Northern Ethiopia.

In this study, the moisture dynamics of the rock-cut churches at Lalibela is assessed by using field-based monitoring of the spatial and temporal variation in

moisture content in both the wet and dry seasons. On site observations show significant moisture-related damage to the churches at Lalibela. Salt weathering, granular disintegration and spalling have damaged the lower and upper parts of most of the churches. Determining the spatial distribution and temporal variation of moisture is crucial to understanding the weathering processes that lead to the deterioration of the churches at Lalibela.

6.1.1.1 Study site and research aims

The UNESCO world heritage site of Lalibela is a large complex of rock-cut churches that are carved in the base of Abune Yoseph Mountain in northern Ethiopia. The churches are connected via underground tunnels and trenches and are carved below the ground level. They were built between the 11th to the 13th century CE (Gobezie, 2018; Deart et al., 2021). They are considered as one of the holiest sites in the Ethiopian Orthodox Church and have been a place of pilgrimage and worship since their establishment in the medieval period (Woldeyes, 2019). This study aims to identify the spatial and temporal variation in moisture distribution in the walls of two monolithic rock-cut structures in Lalibela during the wet and dry seasons. Rock-cut sites have a unique method of construction, they are made through a subtractive processes that involves removing material to create spaces. The output of these works of architecture are structures that are whole in the sense that they are rock masses from which space has been carved out. The roof, walls and base of the structure are all one body of mass or monolithic structure. The wholeness or ho-

mogeneity of rock-cut buildings influences how moisture is transported throughout these structures; two pathways of moisture transport will be dominant: the upward flow of groundwater will be facilitated by the network of pores, and rainwater percolates downward through the roof directly into the walls. The input of driving rain to the rock-cut walls is relatively low given the narrowness of the corridor between the rock mass and the churches. The upper part of the wall which is less shielded may be exposed to wind-driven rain. Condensation of water vapour in the pore networks are unlikely to occur at Lalibela given the high temperatures of the rock surface. These modes of moisture transport can facilitate the movement of water through a rock-cut structure in a different way to that of built structures. Most masonry structures have a semi-impermeable base (foundation) or an impermeable roof to slow down or prevent the downward and upward flow of moisture through the walls. Conversely, monolithic rock-cut structures do not have semi-impermeable foundations or roofs to block the flow of moisture from the groundwater or rain percolation. Moreover, rock-cut structures are often carved into outcrops that are easy to work (Asrat, 2002), which usually means the rocks have poor mechanical properties and higher permeability and porosity. Therefore, the spatial and temporal variation in moisture at rock-cut structure sites is likely to be different from that found in masonry structures and highly influenced by seasonal fluctuation in environmental conditions.

The main objectives of this study are to identify the temporal and spatial moisture distribution on the surface and subsurface of the rock-cut walls at Lalibela

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during the wet and the dry seasons. Two monolithic churches at Lalibela were selected for this study: Bete Amanuel and Bete Giyorgis (Fig 6.1). Bete Amanuel has a protective open shelter which was installed primarily to stop rain infiltration during the wet season. These two churches were selected to assess the impact of an open shelter in limiting moisture ingress in rock-cut structures that are in climates prone to extreme seasonal variation in rainfall.

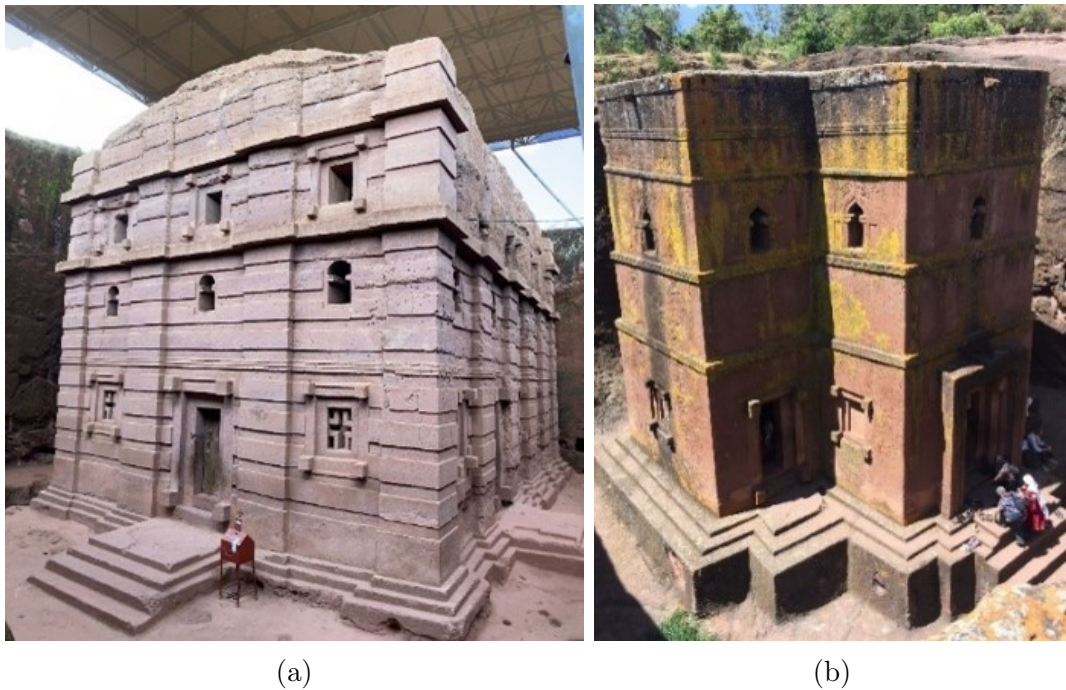


Figure 6.1: (a) Bete Amanuel (sheltered) and (b) Bete Giyorgis (unsheltered).

6.1.2 Methodology

There are three seasons in Lalibela: short rains (Feb - May), main rains (Jun - Sep) and dry (Oct - Jan) seasons. The main rains season is the wettest period and accounts for most of the annual rainfall (Chapter 4). In contrast, the dry season is characterised by high rock surface temperatures, low humidity and less than 10 rain

days throughout the whole period. Given the difference in rainfall between the wet and dry season, moisture dynamics in the two seasons is likely to be hugely dissimilar. Spatial variation in moisture content in Bete Giyorgis and Bete Amanuel was monitored in the wettest and driest periods of the year to assess the range of temporal variation in moisture in the rock-cut walls. The seasonal variation of the height of moisture rise can also be determined by measuring the spatial variation in moisture seasonally. A handheld non-destructive moisture measuring system was used to measure the moisture content onsite. To meaningfully interpret data collected onsite into saturation state, the moisture measuring system was gravimetrically calibrated in a controlled laboratory setting in ambient conditions. The temporal variation in moisture content is presented as percentage increase between the wet and dry seasons. Moisture monitoring and interpretation were complemented with onsite observation of moisture-related damage.

6.1.2.1 Deterioration survey

Photographic survey and on-site observation (done in 2018 and 2019 field seasons) were used to assess areas of the façade that were damaged or restored. The drawings show moisture-related damage observed on site. This simple assessment allowed us to characterise the spatial distribution and patterns of damage as they appear at Bete Amanuel and Bete Giyorgis. Rock decay features are identified through the use of the ICOMOS-ISCS Illustrated Glossary on Stone Deterioration (2008) and the terminology used to describe decay features is also based on this

glossary.

6.1.2.2 Microwave moisture measurement system and principle

To monitor moisture distribution in porous building materials non-destructive methods that are capable of scanning large areas of a surface at different depths are preferred (Pinchin, 2008). The Moist 350B Microwave Moisture Measurement System (MMMS) from hf sensor GmbH (Leipzig, DE) is a suitable technique for field measurements because it is portable, negligibly sensitive to salts and optimised for simple acquisition of data in a grid pattern (Lataste and Göller, 2018). This method is well suited for monitoring temporal and spatial variation of moisture. In this study, two sensors with a penetration depth of up to 2 - 3 cm (surface sensor - R1M V2) and up to 20 - 30 cm (subsurface sensor - PM V2) (hf sensor GmbH, 2014) were used.

The MMMS is a dielectric moisture measurement method that takes advantage of the significant difference in dielectric permittivity between water and most building materials. MMMS can be applied effectively in ambient temperatures of 0 - 50°C (hf sensor GmbH, 2014). Both rock-surface and ambient temperature did not exceed 50°C at Lalibela during the periods moisture was monitored (Chapter 4). The device uses sensing heads that have a microwave source and detector to measure the reflection coefficient (the ratio of reflected and transmitted wave) and gives an output in Moisture Index (MI). MI is a unitless value that is a result of the reflection coefficient multiplied by a fixed factor (Lataste and Göller, 2018). MI is

not an absolute measure of moisture content, but as it is related to the microwave reflection coefficient which is determined by the amount of moisture present in the material, it can be usefully employed to indirectly measure moisture content in stone built heritage (Orr et al., 2020). Depending on the physical property of the rock the range in reflection coefficient between wet and dry states will vary. To reliably represent moisture content from MMMS readings, studies have relied on gravimetric calibration (Gartner et al., 2010) and percentile representation (Orr et al., 2020). Percentile representations are advantageous in that they allow direct interpretation of field data without additional laboratory analysis. However, in data sets that are representative of upper and lower limits of saturation (wet vs dry season) percentile ranking would lead to measurement values clustering near 0 and 100. The advantage of gravimetric calibration is that it determines the range of MI that corresponds to the dry to wet saturation range of the rock type under study. It also allows comparison between the surface and subsurface sensors which do not have comparable scales of MI. Laboratory based gravimetric calibration is used to assesses the responsiveness of the MMMS to a range of non-saturated moisture content for the basaltic scoria.

6.1.2.3 Gravimetric Calibration

The efficacy of the microwave moisture meter in accurately sensing a range of moisture contents for different building stones (Blaeuer & Rousset, 2009; Kurik et al., 2017; Orr et al., 2020) and brick (Gartner et al., 2010) has been tested

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in laboratory settings with different set ups. Granite, limestone, dolostone and sandstones have been the focus of these studies but as yet no studies have been done to test the MMMS on basaltic scoria (as found at Lalibela). To validate how effectively this device senses a range of moisture contents for this particular rock type, gravimetric assessment was done. The sample used in this study was extracted from the Yohannes Amba quarry (2 km from the church complex) and has similar petro-physical properties to the rock the churches are carved into (Table 1). The dry weight of the samples was determined following BS EN 16682 (BSI, 2017) which involved drying the samples at 105 °C in a ventilated oven until their mass differed by less than 0.5% in consecutive weighting. After drying for 72 hrs, the sample were cooled in a desiccator, and 3 moisture readings were taken on each face of the block (generating 18 measurements per block). Measurements were taken at different moisture content levels after the samples were saturated with deionized water for 3 h and allowed to dry under laboratory conditions. The sample were placed on a stone slab during the measurement to ensure there was no interference from metallic objects under the lab counter.

Table 6.1: Physical properties of samples used for gravimetric analysis in comparison with data from the churches Bete Amanuel and Bete Giyorgis.

Sample	Quarry sample	Bete Amanuel	Bete Giyorgis
Density (kg/m ³)	1762	1490 – 1730 *	1810 - 2090*
Saturated water contents (%)	14.65	-	-
Open porosity (%)	26.05	34.9 - 45.2*	21.6 - 28.3*
Dimension (mm)	220 x 150 x140	-	-
Mass(kg)	8.145	-	-

* Porosity and density values from fallen rock samples nearby the churches (Renzulli et al., 2011).

Linear regression analysis was done to determine the strength of the relationship between the moisture index values and the gravimetric water contents (Fig 6.2). This analysis showed a consistent linear ($R^2 = 0.95$) relationship between gravimetric measurements of water contents and the MI readings for both the sensors used in this study. The range of moisture index measurements from dry to saturated is comparable for the surface and subsurface probes. Given that the range of moisture index and the slope of the regression model of both the probes is comparable; it is reasonable to assume that both probes will respond in a similar way to an increase in moisture content. Overall, the linear regression assessment showed that the microwave moisture meter is equally and sufficiently responsive across the whole range of moisture contents from saturated to dry for this rock type. Since the surface and subsurface probes respond at a comparable rate, it is possible to compare the percentage difference in MI between the two probes to determine at which depth there has been a greater increase in moisture content. Moreover, the calibration function can be used to interpret the moisture measurements taken in the field to percent of saturation.

6.1.2.4 Data acquisition

The gravimetric assessment showed that the MMMS is able to accurately measure a range of unsaturated moisture contents accurately for basaltic scoria. By taking measurements in the same area at different times of the year, any impact of the heterogeneity in petro-physical properties on measurements can be discounted

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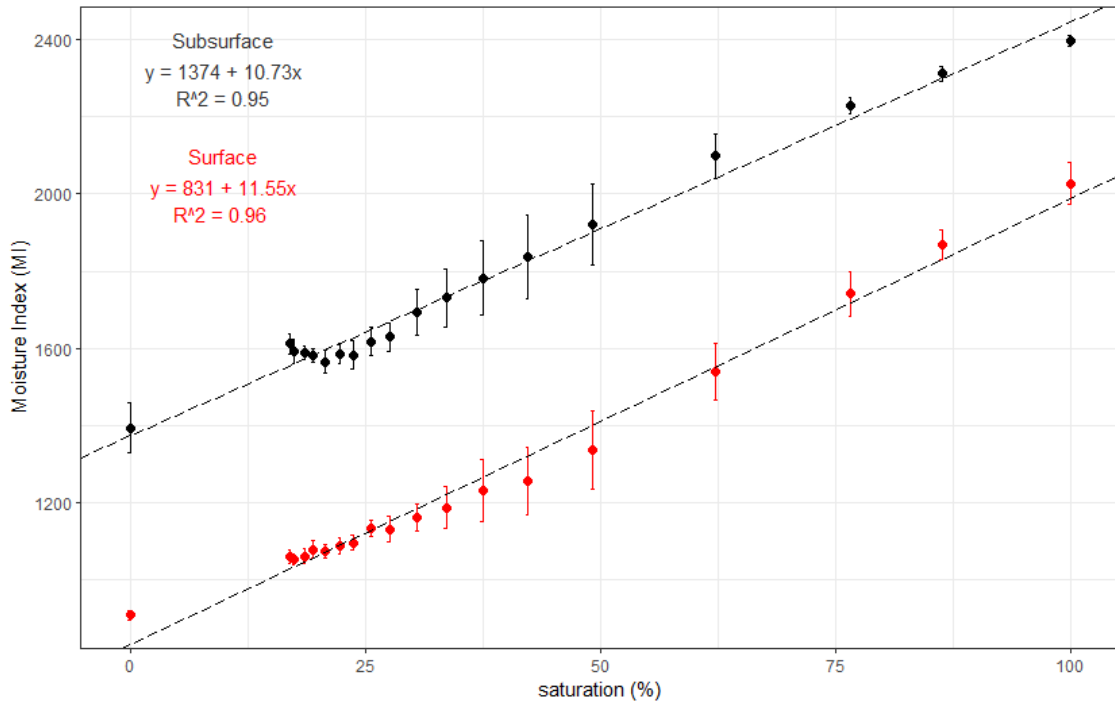
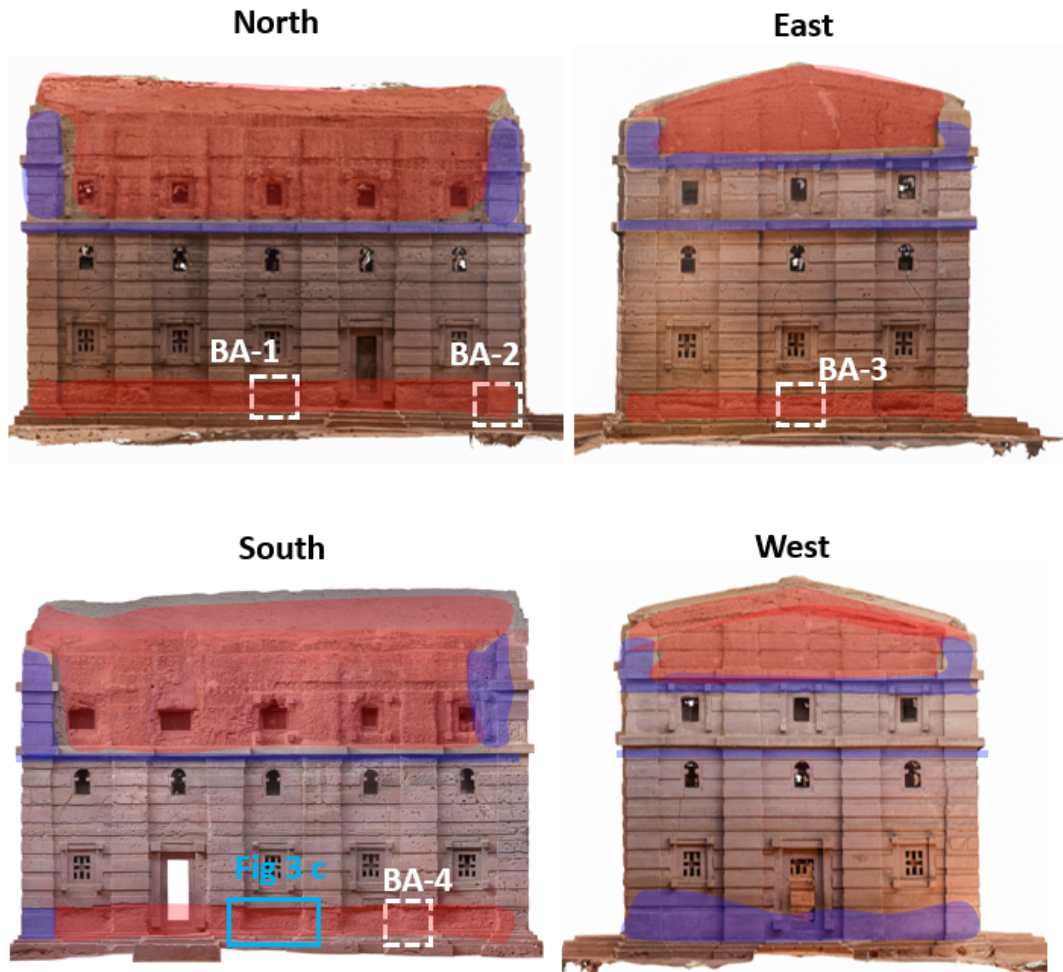


Figure 6.2: Gravimetric analysis regression models for the surface and subsurface sensors with the vertical bars representing standard deviation of 18 measurement taken.

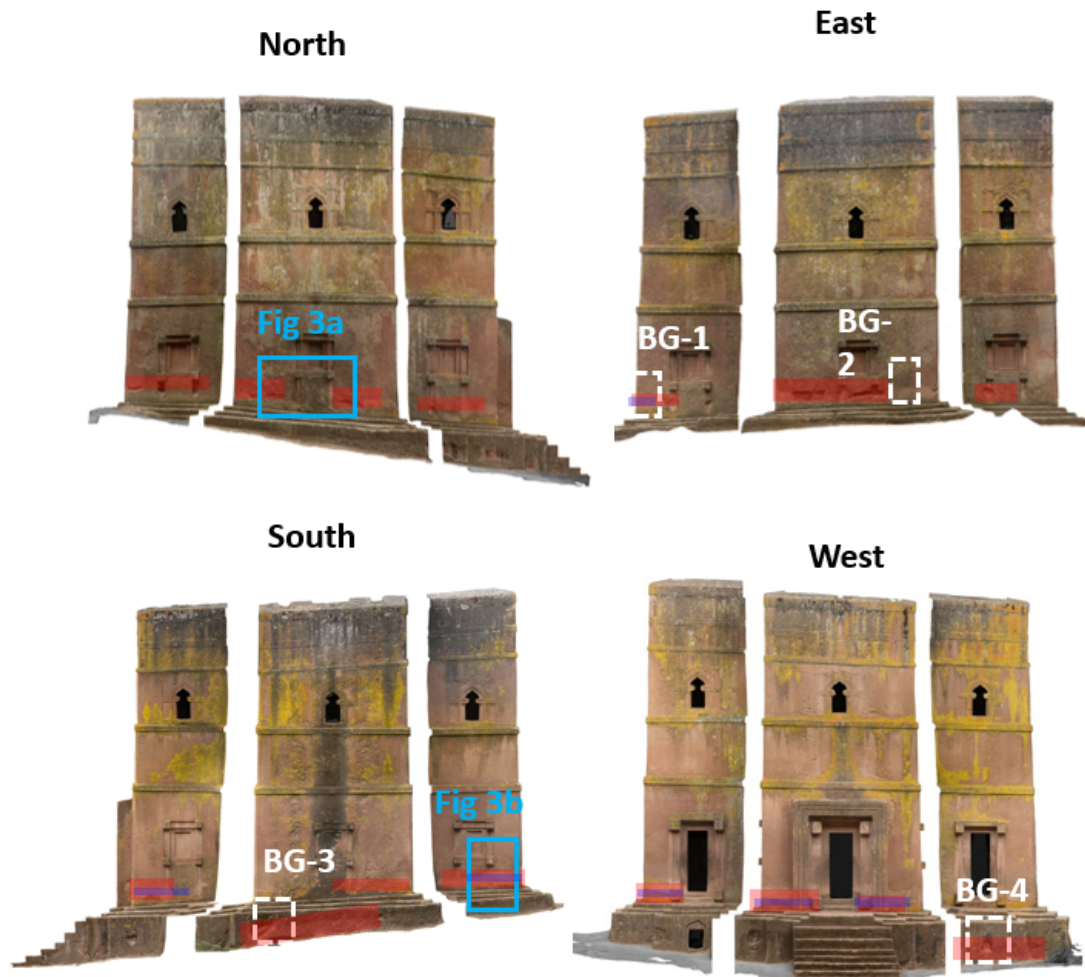
for assessments of temporal variation. The MMMS was used to take moisture readings on four zones in Bete Giyorgis and four zones in Bete Amanuel in the wet and dry seasons (Fig6.3). Moisture content measurements were taken at regularly spaced points on the selected areas of the walls, in a grid pattern (9 rows by 7 columns) with each point 15 cm apart starting from the base of the churches (Fig 6.3). At each of the 63 points of measurement, readings were taken with the MMMS surface and subsurface sensors. The areas that were measured were selected based on their accessibility and preservation state. The lower parts of the building that were likely to absorb moisture via capillary uptake were selected to determine the height of moisture rise. The west-facing wall at Bete Amanuel was excluded because the lower part of this façade has been restored with cement-based mortar (Fig 6.3).

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As the range of MI will differ for different materials, the comparison of moisture content between the original material (basaltic scoria) and restored areas may be misleading. The north-facing wall at Bete Giyorgis was also excluded for similar reasons.



(a)



(b)

Measurement zones
 Images in Fig 3
 restored
 weathered

Figure 6.3: Orthophotos (@Archaeovision 2019) of facades of (a) Bete Amanuel (BA1-4) and (b) Bete Giyorgis (BG1-4) showing zones where measurements were taken. Areas shaded in red and purple are indicating weathered and restored areas, respectively. A close up of areas in the blue squares are presented in Fig 4.

6.1.2.5 Data handling and representation

Data acquired in the field are represented in two ways: (1) percentage increase (% increase) is used to determine the temporal variation in moisture content between the wet and dry seasons. The mean of the 63 readings taken in each zone are used to assess the overall increase in moisture seasonally and to compare the % increase between zones and churches. (2) To assess the spatial distribution of moisture on the surface and subsurface, MI values are converted to percent saturation (%) by using the gravimetric calibration function. Spatial distribution of moisture are represented with saturation (%).

6.1.3 Results

6.1.3.1 Moisture-related deterioration

To understand the impact of moisture on rock-cut structures it is important to consider the nature of rock-cut structures, that is, the fact that they do not have an impermeable roof or foundation to prevent moisture ingress. These factors will hugely influence how moisture is transported throughout rock-cut structures. At Lalibela, the climate is characterised by short intense wet periods and long dry periods. The thick (> 2 m) gable and flat roofs of the churches have low slopes and are directly exposed to the intense rainfall during the wet season. The lower part of the structure is affected by moisture absorbed through ground water uptake. Wind-driven rain is likely to affect the facades to a limited extent; as the churches are

below the level of the ground, the courtyard walls that surround them will partially shield them. Deteriorated areas correspond with the exposure to moisture. Moisture related deterioration is present on the upper and lower part of the structure where they are exposed to ground water uptake and rainwater infiltration (Fig 6.3).

The type and severity of damage varies between the churches. Compared to most of the churches at Lalibela, Bete Giyorgis is in a very good state of preservation. The upper part of this church has been discoloured by biological soiling (see Fig 6.3 b) but has not suffered from extensive damage like the roof at Bete Amanuel (see Fig 6.2 a). Coving (a cavity formed by granular disintegration) has formed 30 to 60 cm above the base of Bete Giyorgis due to scaling caused by sub-florescence of salts (Fig 6.4 a and b). At Bete Amanuel, both the upper and lower parts of the church are damaged. The roof was severely damaged in the late 19th and early 20th century and had to be restored several times in the mid 20th century to prevent infiltration of rain (Taye-Gemeda et al., 2020), currently there are several cracks on the ceiling and a shelter has been placed over this church to protect it from further damage by rain. The four walls of Bete Amanuel are significantly weathered due to scaling on the lower parts (60 - 150 cm above the base of the wall) of the walls (Fig 6.4 c and d). Bete Amanuel has a larger surface area that is deteriorated or restored than Bete Giyorgis. Nonetheless, the bulk of moisture related damage is concentrated on the lower and upper parts of both structures (see red shaded areas in Fig 6.3). This implies that groundwater uptake and rain are likely the most dominant sources of moisture for all the rock-cut churches at Lalibela.

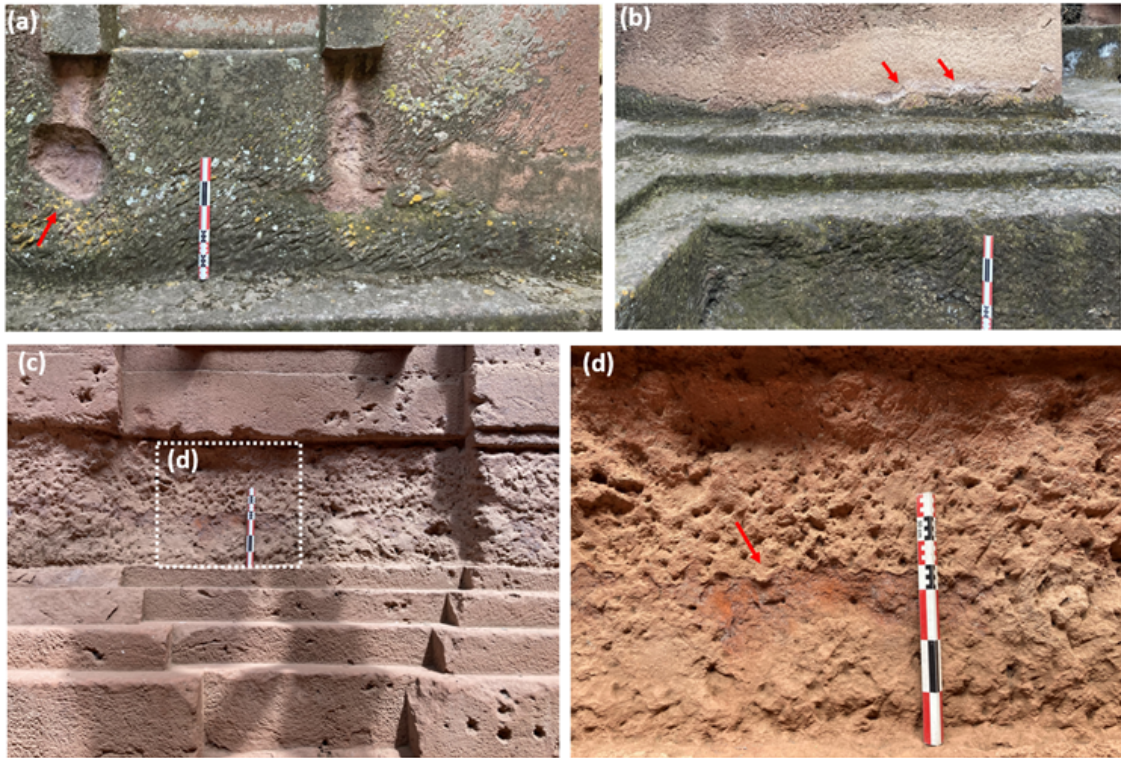


Figure 6.4: Images of Bete Giyorgis showing (a) coving and (b) restored area with salt efflorescence and images of Bete Amanuel (c) showing moisture-related damage and (d) granular disintegration and scaling. Note the scale in the images is 50 cm.

6.1.3.2 Temporal variation

The difference in moisture content between the wettest and dries periods is a good indication of the range of moisture fluctuation annually. The % increase in Moisture Index (MI) values between the wet and dry seasons for the surface and subsurface is presented in figure 6.5. The sheltered church (Bete Amanuel) shows a % increase between wet and dry seasons in comparison with the unsheltered church (Bete Giyorgis). In both churches the % increase in MI values between wet and dry seasons is generally higher at depth than on the surface. The error bars show that there is significant spatial variation in moisture content across the measured areas (both at depth and on the surface). At Bete Giyorgis there is a higher % increase

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in MI values at depth than the surface. This is likely due to the shelters that play a role in limiting the amount of moisture that enters the rock walls.

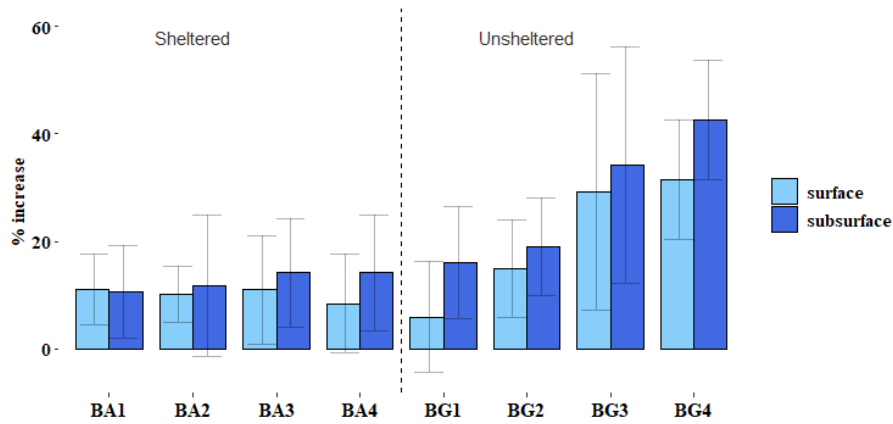


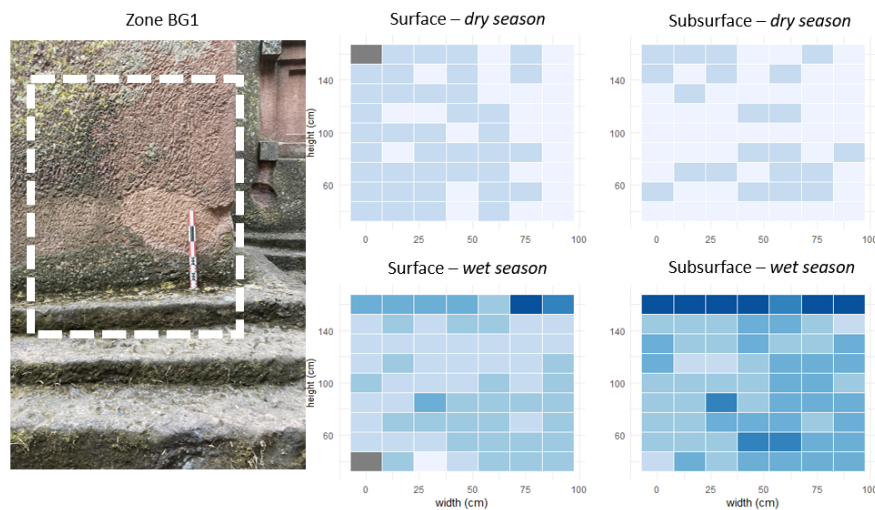
Figure 6.5: % increase from the dry to the wet seasons on the surface and subsurface of the zones measured at Bete Giyorgis (BG) and Bete Amanuel (BA).

6.1.3.3 Spatial variation

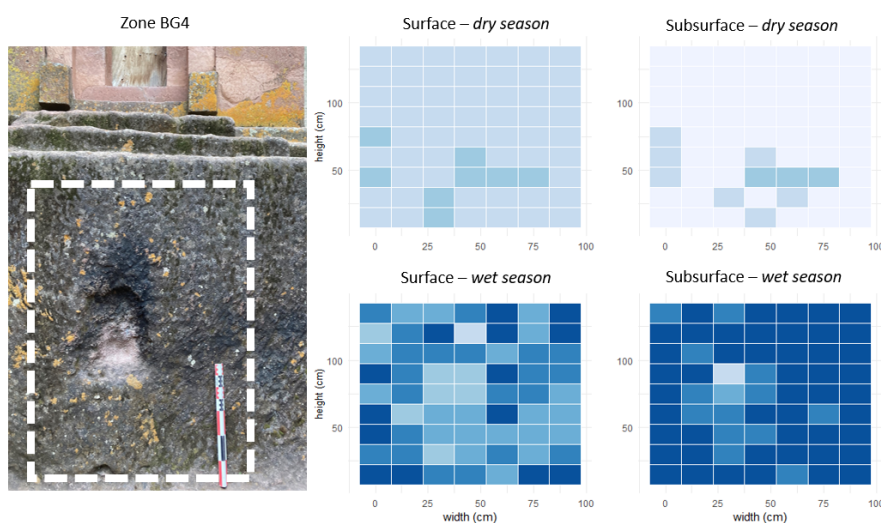
Spatial variations of moisture content on the surface and at depth in both the wet and dry season are presented as heatmaps of saturation (%) (see Fig 6.6). Of the eight zones measured at Bete Amanuel and Bete Giyorgis in the wet and dry seasons, four representative areas zones BG1, BG4, BA1 & BA4 (whose locations are show in figure 6.3) are presented for this discussion. The saturation (%) vary both in absolute terms and in the spatial distribution between wet and dry seasons. During the dry season the surface is more saturated than the subsurface in both churches, as depicted by generally darker blue coloration in the surface vs. subsurface heatmaps on the top rows within figure 6.6a, 6.6b, 6.6c and 6.6d. The surface probe of the MMMS measures moisture up to 3 cm depth, the reading is representative of the saturation (%) up to that depth. That is, the measurements are indicative of

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moisture present on and near the surface. Given the high rock-surface temperature and low relative humidity during the dry season at Lalibela, any moisture present on or near the surface is unlikely to be from capillary condensation. Rather, it is more likely that it is moisture transported near the surface by capillary uptake. Relatively low levels of moisture and inconsistent distribution in the interior of the rock wall during the dry season may reflect the disconnected hydraulic pathways typical of falling-rate drying.

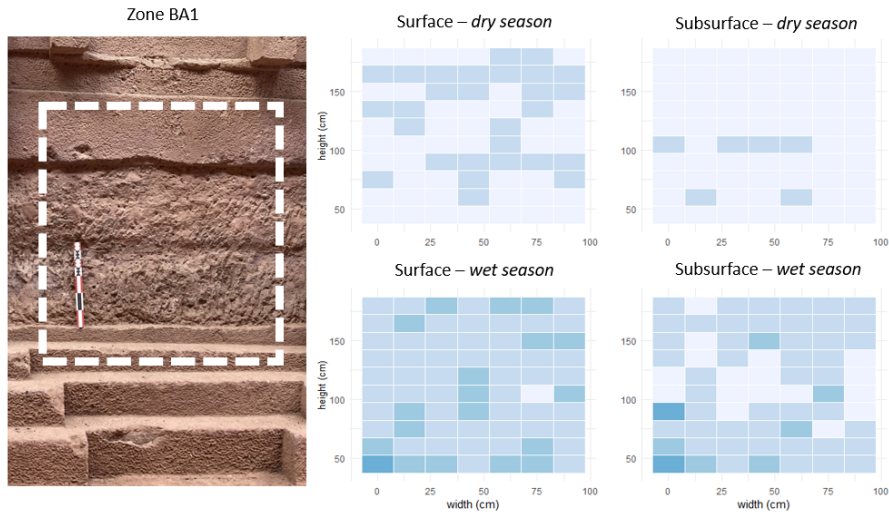


(a)

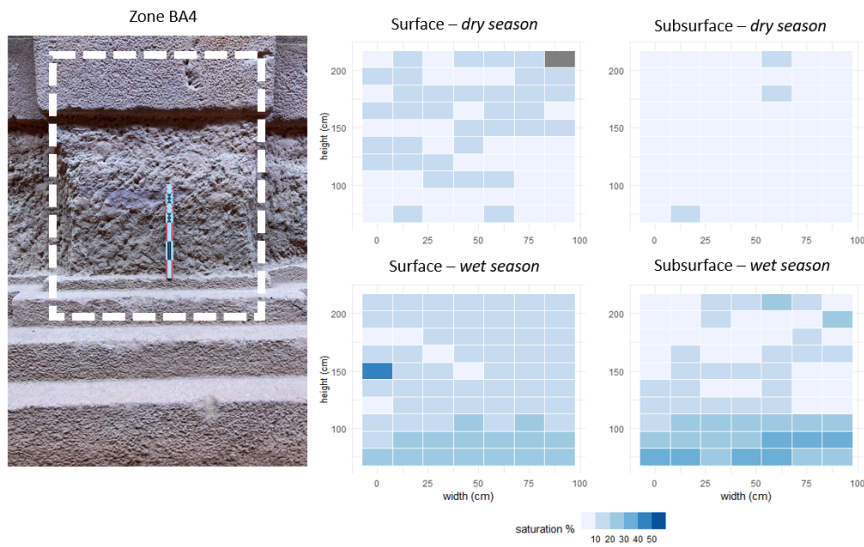


(b)

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(c)



(d)

Figure 6.6: An image of the measured zone and the surface and subsurface heatmaps are shown: (a) BG1, (b) BG4, (c) BA1 and (d) BA4. Heatmaps were generated by using the calibration function to convert moisture index values to percentage saturation. The axes on the heatmaps show the height and width (cm) of the measured areas.

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Conversely, in the wet season the walls are wetter at depth than on the surface, as depicted by generally darker blue coloration in the surface vs subsurface heatmaps in the bottom rows with in figure 6.6a, 6.6b, 6.6c and 6.6d. While the walls at Bete Amanuel (sheltered) are wetter during the wet season than the dry season, they are less saturated than Bete Giyorgis (unsheltered). The moisture content was higher at the base in Bete Amanuel (as shown by the darker blue coloration in the lower parts of the wet season heatmaps in figure 6.6c and 6.6d). While in Bete Giyorgis hotspots of saturation are less uniformly distributed (see random distribution of darker blue coloration in the wet season heatmaps in figure 6.6a and 6.6b). This is due to the exposure of the roofs of Bete Giyorgis to direct rainfall which leads to multiple sources of moisture ingress. It is unlikely that the churches, which are surrounded by trench walls, are hugely affected by wind-driven rain. Areas on the surface that have high saturation (%) values have a corresponding, but higher, saturation (%) value at depth. This indicates that connected hydraulic pathways are transporting moisture to the surface rather than moisture ingress from wind-driven rain. High humidity and low rock-surface temperature during the wet season are ideal for constant-rate drying.

6.1.4 Discussion

6.1.4.1 Advantages of the MMMS

This study reinforces other studies (Gartner et al., 2010; Kurik et al., 2017; Orr et al., 2020) finding that the MMMS can be usefully applied to cultural heritage settings to understand moisture dynamics. The calibration done in this study shows that the MMMS can be used on basaltic scoria. It also showed that this technique is particularly effective on rock-cut structures which are uniform in composition and ideally suited for the MMMS, which is sensitive to variation in physical properties. While directly interpreting the readings taken onsite is not straightforward, gravimetric calibration and representation of temporal difference in % increase allows for identification of key aspects of moisture dynamics in porous building materials, that is: (1) the percent saturation, (2) particularly high levels of saturation and (3) variation of moisture content over time. Comparing measurements taken at different depths is not straightforward either, as the MI values of different MMMS sensors are not measured on directly comparable scales. Nonetheless, it is possible to overcome this limitation of the device by instead using % increase in moisture index values, as a proxy for temporal variation in moisture content. Gravimetric calibration (Fig 6.2) showed that the range of MI measurements (dry to saturated) for the surface and subsurface probes, and the slopes of their regression model were comparable. Therefore, the two probes can be used to compare change in moisture content at surface and in depth and help to evaluate moisture gradients. Using the calibra-

tion function to convert MI values to saturation (%), it is possible to determine the surface to depth moisture gradient driven by seasonal fluctuation in environmental conditions.

6.1.4.2 Moisture regime in rock-cut structures

Moisture content is an important factor that influences rock weathering (Hall et al., 2011). Rock-cut structures are highly exposed to the environment because they do not have roofs or foundations to retard the uptake of moisture. Lack of adequate drainage systems and mortar joints means that these structures are susceptible to high seasonal variation in climate. At Lalibela the wet and dry season have variable amounts of rainfall and very different diurnal rock-surface thermal and humidity regimes. Due to the direct exposure of the roof to rain the moisture content of the walls at Bete Giyorgis (unsheltered) rises significantly during the wet season (Fig 6.5), especially at depth (up to 25 cm inside the wall). Lower change in moisture content between the wet and dry season in the sheltered (Bete Amanuel) vs unsheltered (Bete Giyorgis) church shows how important a sheltering system can be in limiting rain infiltration in the walls at rock-cut heritage sites that are exposed to heavy seasonal rains. Based on the measurements presented in this chapter, a conceptual model of moisture dynamics in the rock-cut walls at Lalibela is presented in figure 6.7. The sources of moisture and the rate of evaporation differ between the seasons. The main source of moisture during the dry season is groundwater uptake through capillary rise. Condensation of moisture in the micropores of the

rock surface is unlikely to occur because of low humidity during the dry season. Given the high rock surface temperature during this season, there is likely to be a steep gradient of moisture content near the surface and for the evaporation front to be in the subsurface. In the wet season, the moisture content is higher at depth than on the surface, which is likely due to the seepage of rainwater and groundwater uptake (Fig 6.7). Variation in the rock surface daily temperature range is common during the wet season at Lalibela. Sunny spells during the wet season cause spikes in rock-surface temperature that lead to variation in the diurnal thermal cycle. As the flow of moisture from the interior of the rock wall to the surface depends on the rock surface temperature, this variation might lead to a daily variation in moisture flux during the wet season.

The conceptual model presented in figure 6.7 may have wider application to other rock-cut structures and built stone structures (like Angkor Wat) in tropical areas that have long wet seasons, and which have their rock/stone roofs directly exposed to rainfall. These types of structures are more likely to experience deep wetting than those that have a sheltering system. Seepage of rainwater aided by gravity, to the base of the temples at Angkor Wat has been implicated as the primary means of salt transport to the base of the temples (Siedel et al., 2010). Another example is the Bingling Temple Grottoes in China where there are intense wetting periods have suffered from exposure of their roofs to direct rain (Chen et al., 2019). Heavy rains in exposed rock-cut roof structures should therefore be considered as a crucial factor that facilitates moisture related damage.

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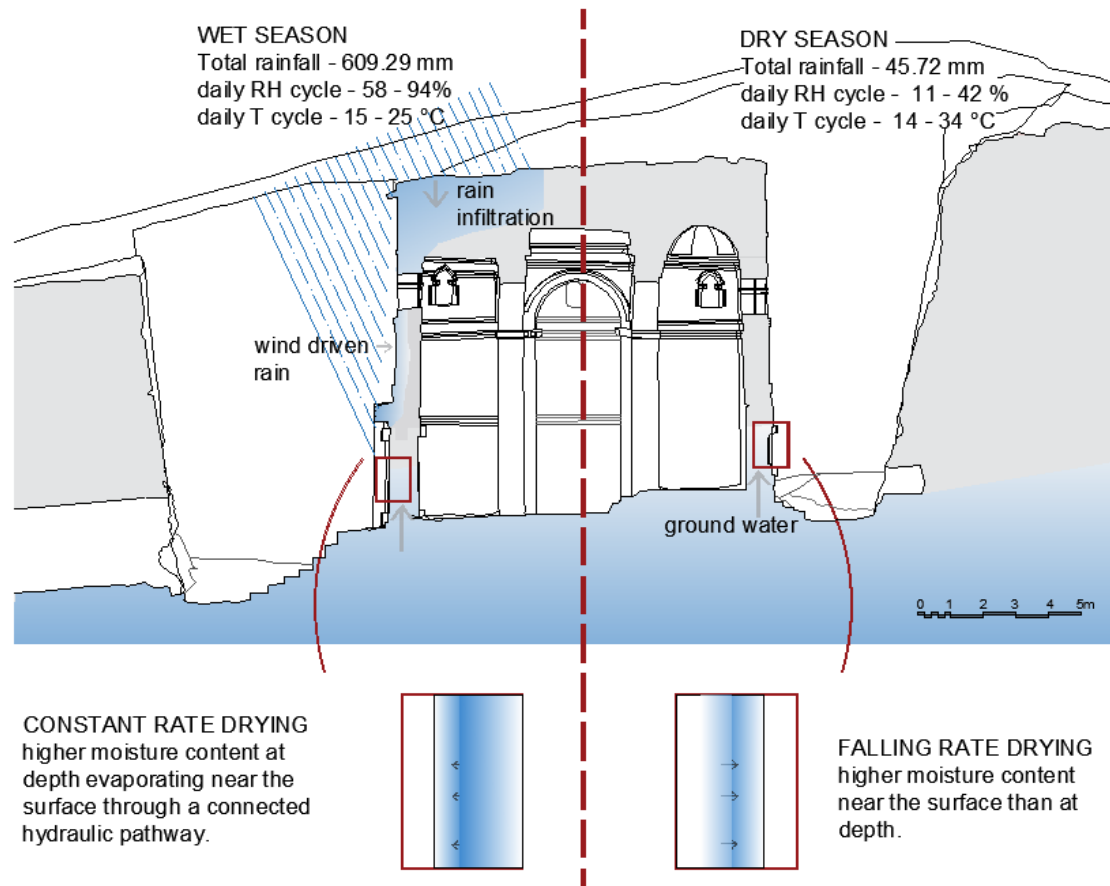


Figure 6.7: Conceptual diagram of moisture transport and dynamics at rock-cut monolithic structures during wet and dry seasons.

6.1.4.3 Seasonal variation in moisture dynamics

Seasonal variation in rainfall and rock-surface temperatures will lead to a significant difference in the presence and spatial distribution of moisture within walls which in turn will lead to a seasonal variation in moisture dynamics, as has been demonstrated by the data presented in this chapter. The moisture dynamics during the wet season, is likely to match constant-rate drying (stage I drying) whereas during the dry season it is likely to match falling-rate drying (stage II drying). During the wet season the two conditions that allow for a constant-rate drying to occur are met: (1) the increase in moisture at the surface and in depth (Fig 6.6) and (2)

controlled rate of drying (low ambient and surface temperature) which allows for well-connected hydraulic pathways capable of sustaining a steady flow of moisture to the surface. The rise in groundwater level during the wet season will play a huge role as a source of water, even in the absence of rain. The lack of semi-impermeable foundation to slow the rate of water transport at rock-cut sites will sustain the liquid pathway for constant-rate drying (Fig 6.7).

Conversely, during the dry season the conditions for falling-rate drying are met. Unlike in the wet season, during the dry season, surface and subsurface hotspots of saturation (%) do not correspond (Fig 6.6). Due to the high rock surface temperature during this season, it is unlikely that a hydraulic pathway can transport moisture to the surface at the same rate as it is removed by evaporation. The sources of moisture during this season is for the most part limited to groundwater uptake. In this case, drying will mainly happen through vapour transport to the surface which is a less efficient process of drying. Salt forming ions will crystallise at the boundary (in the subsurface) where moisture transitions to a vapour state.

6.1.4.4 Implications of moisture dynamics for weathering at Lalibela

Long periods of sustained high flux moisture transport in the wet season and sub-surface drying in the dry season have implications for weathering of the rock-cut churches at Lalibela. High flux of moisture transport to the surface over a long period of time will facilitate accumulation of salts on the surface. In the dry season, the drying zone is in the subsurface which will lead to salts crystallisation below the

surface. Given the presence of swelling clay minerals in the basaltic scoria, surface to depth moisture gradients will be associated with stress due to tension and buckling (Gonzalez & Scherer, 2004). Seasonal variation in moisture dynamics will cause stress due to wetting and drying and crystallisation of salts to be concentrated near the surface in the wet season and in the subsurface in the dry season. The combined effect of this, as seen from onsite observation, is granular disintegration of surface material and scaling (due to subsurface crystallisation of salts and clay swelling) in areas exposed to moisture (Fig 6.4).

Higher saturation (%) at depth during the wet season suggests that deep wetting is likely to occur in the wet season, particularly in July and August which are characterised by heavy rainfall (Chapter 4). Rain infiltration and ground water uptake will increase the wetness of the walls during the wet season and lead to the redistribution of salts within the rock wall and the reduction of mechanical strength (Smith et al., 2011).

From visual observation and comparative analysis of the moisture distribution between the dry season and the wet season, the moisture related damage observed at Bete Giyorgis and Bete Amanuel is consistent with the rise and fall of the capillary rise at each church. The height of the capillary rise varies between the churches. This may be due to a difference in the ground water table and thickness of the church walls. Hall et al., (2011) using their saturated and unsaturated flow models have shown that the severe damage in El Merdani Mosque in Cairo was consistent with the seasonal variation in the rise and fall of the wetting front. The location

of the granular disintegration, contour scaling and coving observed at Bete Giyorgis (30 – 90 cm) and Bete Amanuel (60 -150 cm) corresponds well with the areas that showed a rise in moisture content during the wet season (Fig 6.6). These figures may be the lower and upper limit of rise and fall of the wetting fronts seasonally, but further investigation needs to be done to confirm this hypothesis.

6.1.5 Conclusions

This chapter showed that moisture dynamics in the rock walls at Lalibela varies seasonally. As would be expected, the walls are wetter during the wet season than the dry season. The moisture gradient from the surface to the depth was also different between the wet and dry seasons. During the dry season there was a higher concentration of moisture near the surface than at depth. Conversely, in the wet season the walls were more saturated at depth than near the surface. This suggests that constant-rate drying dominates in the wet season while falling-rate drying dominates in the dry season. The implications of the seasonally varying moisture dynamics for weathering are: (1) fluctuation of drying to the surface and subsurface will cause salts to efflorescence or subfluorescence to occur and (2) stresses induced by clay swelling/shrinking will occur at different depths seasonally. Seasonally shifting moisture dynamics will contribute to a complex and dynamic damage profile.

This study showed that the MMMS can be applied to assess spatial and temporal variations in moisture content in basaltic scoria. Percentage increase of moisture index can be used to assess temporal variation in moisture content. Gravimetric

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calibration was used in this study to determine the efficacy of the MMMS in measuring a range of unsaturated moisture contents (between oven dry and saturated) in basaltic scoria. The calibration function was used to convert field data to percent saturation. This allowed comparison of data collected with the surface (up to 2 - 3 cm) and subsurface (up to 20 - 30 cm) sensors as well as assessment of surface to depth moisture gradients.

Heritage sites having a similar architectural style to rock-cut structures i.e., exposed rock/stone roofs and semi-permeable foundations are likely to experience similar moisture related damage as shown in this chapter. As far as the authors are aware, this is the first study to investigate seasonal moisture dynamics in rock-cut structures in Ethiopia. Given that over 200 rock-cut structures that are located in northern Ethiopia having similar rainfall patterns to Lalibela, the finding of this study have implications beyond the site studied in this chapter. Seasonality in moisture dynamics is also relevant for other rock cut structures found in tropical climates such as Petra and Ellora.

This study also showed that protective open shelters at Lalibela are reducing the wetness of the walls during the wet season. Comparison of the sheltered (Bete Giyorgis) and unsheltered (Bete Amanuel) church shows that the walls at Bete Giyorgis were more saturated during the wet season than Bete Amanuel. Given the significance of the variation of moisture content between the churches, it is reasonable to suggest that the shelter is playing a role in reducing the amount of moisture in the walls.

6.2 Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-cut bas-reliefs at Bete Golgotha, Lalibela (Ethiopia)

Abstract

This study investigates the deterioration of carved bas-reliefs on the interior walls of a medieval rock-cut church in Lalibela, Ethiopia. Bete Golgotha is one of two church in the Lalibela church complex that has bas-reliefs of saints on the north and south walls of the church. The bas-reliefs on the north wall are affected by surface material loss due to flaking, while the bas-reliefs on the south wall, conversely, are in very good condition. The aim of this paper is to determine the cause of localised deterioration on stone structures using non-destructive techniques. Surface moisture content and salt distribution were measured along a vertical transect on the bas-relief to determine if moisture ingress and salt weathering were the main causes of the damage that was observed on the north wall. Moisture distribution was assessed

Published as: Taye Gemed, B, Viles, H., Giorghis, F. and Sifir, F. (2019) Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-hewn bas-reliefs in Bete Golgotha, Lalibela (Ethiopia) In, *Hyslop, E., Gerdwilker, C. and Gonzales., V (Eds). Monuments in Monuments. Historic Environment Scotland.* (pp. 43-52).

using a Protimeter Surveymaster, an Infrared camera and a Moist 350 B microwave moisture system (MMMS). Soluble salts were extracted from the bas-reliefs using paper pulp poultice and the concentration of soluble salts absorbed by the poultice was measured using a conductivity meter and an ion chromatography. The results from the IR camera and MMMS showed a similar distribution of surface moisture on the north and south walls. An overall higher Protimeter reading was measured on the north wall. This was due to the presence of salts, which are known to increase Protimeter readings on stone surfaces. This corresponds with the results of the salt extraction test, which showed that a higher concentration of soluble salts was present on the surface of the north wall. Therefore, we can conclude that the deterioration of the north bas-reliefs may have occurred as a result of salt weathering.

6.2.1 Introduction

In the built heritage environment localised deterioration is a common occurrence. Localised deterioration refers to the phenomenon of patchy ‘hot spots’ of deterioration in materials of the same age exposed to similar environmental conditions. Determining the cause of ‘hot spots’ of deterioration can be challenging because there are complex processes at play. Environmental factors, material properties, human intervention and other factors can contribute to localised deterioration. It is critical to correctly diagnose the causes of localised deterioration in order to carry out effective conservation treatments. In this paper, two sets of bas-reliefs found on opposite walls inside a rock-cut church are investigated to determine what has caused

one set to deteriorate badly when the other set appears to be in good condition. The bas-reliefs are found in Bete Golgotha, a rock-cut church in Lalibela, Ethiopia. The churches were carved into a basaltic scoria hill in medieval times. These groups of churches are an important religious and cultural heritage site and were inscribed on the UNESCO world heritage list in 1978. Bete Golgotha is one of two churches in the Lalibela church complex that has bas-reliefs adorning its southern and northern walls, and some of these bas-reliefs are under threat from rapid deterioration. There are six bas-reliefs, three each on the north and south walls in Bete Golgotha. Four of the bas-reliefs are found in the nave of the church: the rest are in the Holy of Holies and can only be accessed by priests and deacons of the church. Therefore, only four bas-reliefs could be studied in this research. Granular disintegration and surface flaking have significantly damaged the surface of the north bas-reliefs (N1 and N2). A lot of surface material has been lost and the reliefs do not appear as sharp and clear as the south bas-reliefs (S1 and S2) (Fig 6.8). The cause of this damage has not been investigated scientifically before. Whilst art historians have suggested that the north bas-reliefs were the first to be built, with the reliefs on the south being reproduced later (Gervers, 2003), there is no historical or physical evidence to suggest that the north set were built first. Through investigating the condition of the two sets of bas-reliefs it is possible to diagnose the cause of the deterioration and to determine if the difference in appearance between the two sets is a result of rapid weathering.



Figure 6.8: Bas-reliefs in Bete Golgotha: (a) N1 and (b) S1.

The basaltic scoria outcrop into which the churches are carved is very porous, contains swelling clays and has weak mechanical properties (Asrat and Ayallew, 2011; Gemedda et al., 2018; Renzulli et al., 2011; Schiavon et al., 2013). The north and the south set of bas-reliefs are found four meters away from each other in what appears to be the same rock type despite the spatial variability in the vicinity of this church. One of the main differences between the two sets of reliefs is the thickness of the walls on which they are carved; the north wall has a thickness of > 5 m and the south wall is 0.9 m thick. Moreover, the north wall separates the church from a trench that serves as a drainage channel in the rainy season, which could lead to higher moisture content in the north wall and could aid the transport of soluble salts. Understanding the impact of salt and moisture on the deterioration

of the bas-reliefs in Bete Golgotha is highly beneficial to future conservation efforts and studies on the rock-cut churches at Lalibela. Using multiple non-destructive testing (NDT) methods, the salinity and moisture content of the bas-reliefs could be determined on site without requiring invasive sampling.

6.2.2 Methods

6.2.2.1 Moisture measurement

In this study non-destructive handheld moisture measuring equipment was used to measure the surface and near-surface moisture content of the bas reliefs on the north (N1 and N2) and south (S1 and S2) walls of Bete Golgotha. Hand-held moisture measurement techniques are useful to scan large areas quickly and map the moisture distribution (Pinchin, 2008). The moisture distribution on the surface of the bas-reliefs was assessed by point measurements along a vertical transect. The Protimeter Surveymaster (GE), Moist 350 B microwave moisture system (MMMS) (hf sensor GmbH) and an Infrared camera (FLIR-T460) were used to map the moisture distribution. The Protimeter Surveymaster uses electrical conductance principles to measure the moisture level of the material between two electrodes. Unlike the MMMS, which measures the change in the dielectric constant of a material, Protimeter measurements are sensitive to the presence of salts (Eklund et al., 2013; Pinchin, 2008). Because of its response to salts, the Protimeter has been used to define damp/saline zones in buildings (Akiner et al., 1992; Mol, 2014). Moisture

measurements on the bas-reliefs were taken along a vertical transect in the middle of the reliefs to avoid measuring moisture content in areas with detailed carvings or protrusions. Measurements were taken 3 times every 5 cm using the Protimeter, and three times every 15 cm using the R1M V2 and PM V2 sensors of the MMMS. The R1M V2 (surface) and PM V2 (subsurface) sensors can detect moisture up to a depth of 2 - 3 cm and 20 - 30 cm, respectively. The IR camera was used to detect the source and distribution. Using multiple techniques to measure surface and sub-surface moisture content allows for a more accurate diagnosis of the cause of localised deterioration moisture distribution and building deterioration (Balayssac et al., 2012).

6.2.2.2 Salt extraction

The distribution of salts on the surface of the largest bas-reliefs from the north (N1) and south (S1) set was assessed using the paper pulp poultice protocol from Egartner and Sass (2016). Other methods of salt extraction are destructive or invasive, and the resulting concentration of soluble salts cannot be used to determine the spatial distribution of salts because the sampling method is not standardised. Field investigation was done using a commercially available poultice (Arbocell BC1000) and deionised water. For each point of extraction 4 g of poultice was soaked in 28 ml of water and applied on the surface of the bas-reliefs every 30 cm for a period of 60 min. The poultice was then soaked in 100 ml of deionised water in the laboratory and filtered to measure the cations and anions in the solution using Ion

chromatography. Egartner and Sass (2016) used a 1:20 ratio of poultice to water for their field experiment; in this study a 1:7 ratio was used because using a higher ratio resulted in the poultice not attaching to the surface of the stone. The contact area between the poultice and surface of the stone was roughly 28.27 cm². The poultice was placed every 30 cm on a vertical transect on the centre of the bas-relief; eight spots were sampled roughly in the same area where surface moisture content was measured.

6.2.3 Results

6.2.3.1 Moisture distribution

The moisture distribution measured using the electrical conductance and microwave technique showed different levels of moisture distribution in the two sets of bas-reliefs. The Protimeter readings showed a higher mean value for N1 and N2 as compared to the values measured in the south set (Table 6.2). In contrast, the microwave moisture meter measurements using the surface and subsurface sensors had comparable values of moisture content between the north and south sets. The surface sensor, which measures near-surface moisture distribution up to a depth of 2-3 cm, did not show a significant difference in the mean values of the measurements taken along the vertical transect between the north and south set of bas-reliefs. This contradicts with results obtained using the Protimeter, which also measures near-surface moisture content.

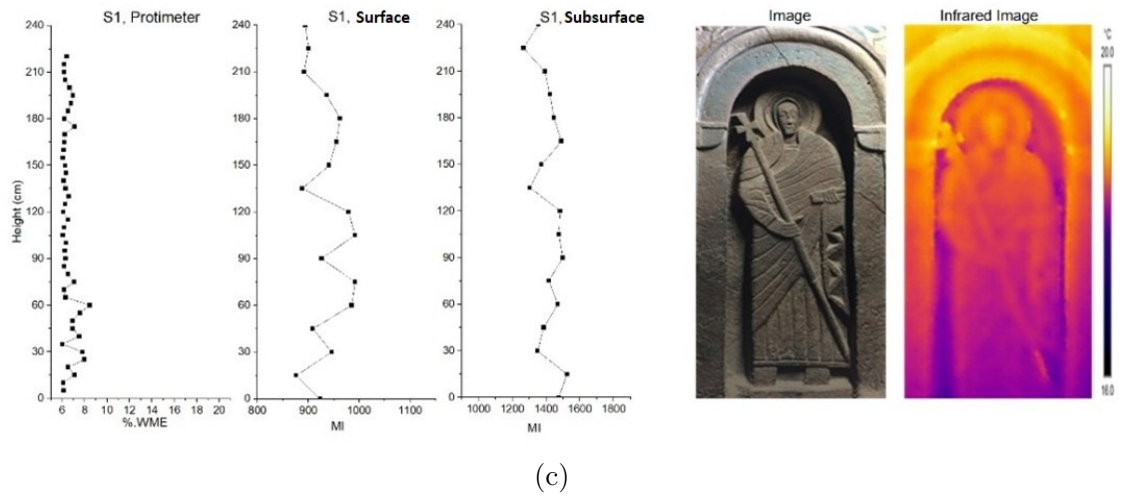
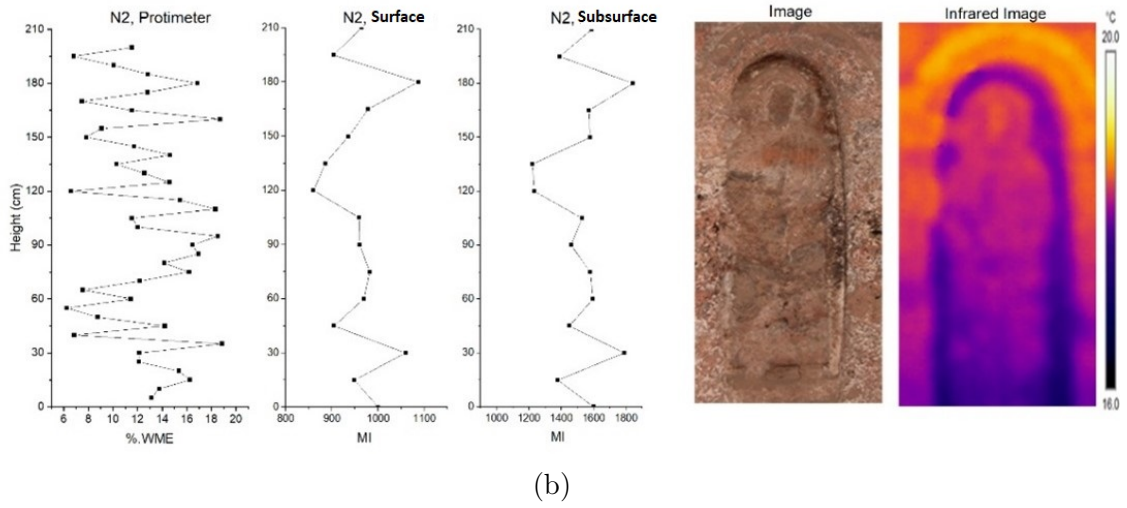
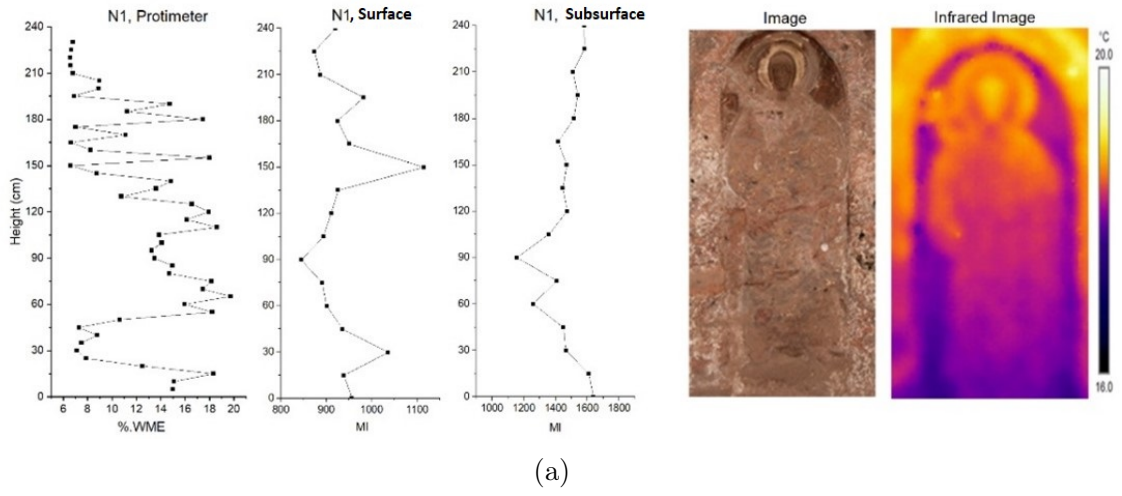
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Table 6.2: Mean and Standard Deviation (SD) of Protimeter, surface (MMMS) and subsurface (MMMS) measurements

	Protimeter (%WME)		Surface (MI)		Subsurface (MI)	
	N1	S1	N1	S1	N1	S1
Mean	12.18	6.56	934.65	935.06	1462.71	1419.29
SD	4.32	0.57	62.03	37.23	120.01	71.14
	N2		S2		N2	
	N2	S2	N2	S2	N2	S2
Mean	12.61	6.66	951.59	959.8	1502.35	1438.4
SD	3.59	1.05	59.35	34.83	164.57	152.6

Infrared Thermography (IRT) was used in this study to qualitatively assess the surface temperature/moisture distribution. IRT is extensively used for the detection of defects such as thermal bridges, air leaks or abnormally moist spots (Grinzato et al., 1998). The infrared thermography analysis showed a comparable heat distribution in all the bas-reliefs; the temperature range was between 16°C and 20°C and the lower parts of the bas-reliefs were cooler for all the reliefs assessed in the study (Fig 6.8). MMMS measurements did not show a trend in moisture distribution along the transect that was measured. MMMS and IRT measurements are not correlated (see appendix 5) but the results demonstrate that moisture/heat distribution are comparable between the north and south bas-reliefs. Conversely, Protimeter results showed a significant difference between the north and south reliefs. It should be noted that the Protimeter readings are affected by the presence of salts. Eklund et al. (2013) observed that the presence of salts may significantly increase the readings of Protimeter. The difference between the measurements taken with the MMMS/IRT and the Protimeter could be as a result of the salinity of the bas-reliefs on the north set which is severely damaged by scaling and granular disintegration. The north wall is also partially covered with salt efflorescence (Fig 6.8).

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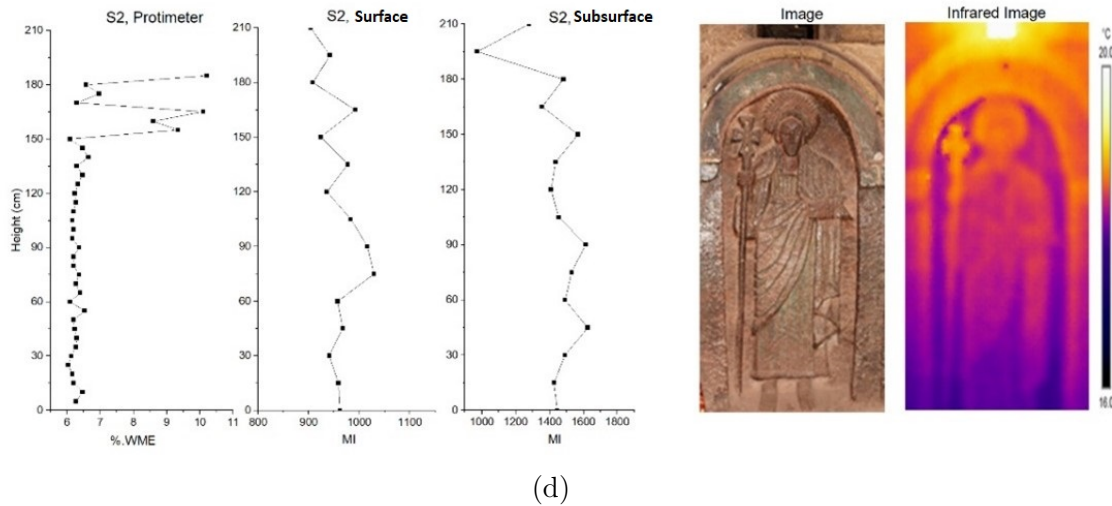


Figure 6.9: Moisture measurement results of bas-reliefs (from left) Protimeter, surface (MMMS), subsurface (MMMS), Image and IRT results of (a) N1; (b) N2; (c) S1; and (d) S2.

6.2.3.2 Soluble salts

The soluble salts extracted from the bas-reliefs using paper pulp poultice were soaked in deionised water and filtered. The conductivity (S/cm) and ion concentration (mg/l) of the filtered solution was then measured. The conductivity of the solution was very low, ranging from 11 to 144 S/cm, with the mean value for N1 samples being 49.62 (standard deviation = 44.55) and S1 samples 29.62 S/cm (standard deviation = 32.39). For the north bas-relief, the highest conductivity was recorded on the lower and upper parts (Fig 6.10 a); this corresponds with areas where salts could be seen on the surface of the reliefs. The Protimeter measurements of the upper and lower parts of N1 correspond with the conductivity and salt concentration values. Similarly, the conductivity of poultice sample from the lower parts of S1 (Fig 6.10 b) was significantly higher than the other areas sampled. Protimeter

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measurements were also higher on the lower parts of S1 as compared to the rest of the bas-relief; this corresponds with higher ion concentration and conductivity measurements. The conductivity of the poultice samples was found to be a good indicator of the salt concentration as the conductivity and salt concentration results correlate very well ($R^2 = 0.98$).

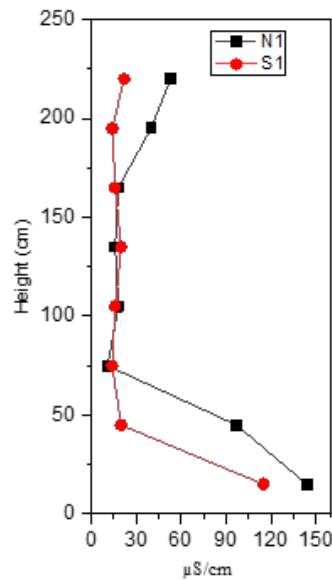


Figure 6.10: Conductivity ($\mu\text{S/cm}$) of poultices sample solutions of N1(black) and S1(red).

Low levels of soluble salts were detected overall despite the visible efflorescence of salts on the surface of the north wall. There were higher concentrations of Sulphate, Chloride, Potassium and Sodium ions on N1 samples as compared to S1 (Fig 6.11). Given the visible salt efflorescence on the bas-reliefs, the low levels of soluble ions measured may have been caused by the salt not diffusing into the poultice. In this church sub-florescence has been observed as the dominant form of salt weathering; therefore, the amount of water that was used (28 ml per poultice) may not have

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been enough to wet the subsurface and to allow the soluble salts to diffuse from the subsurface into the poultice. The dry condition would have further hampered this during the field experiment, which would have caused the water in the poultice to be evaporated before sufficiently wetting the surface.

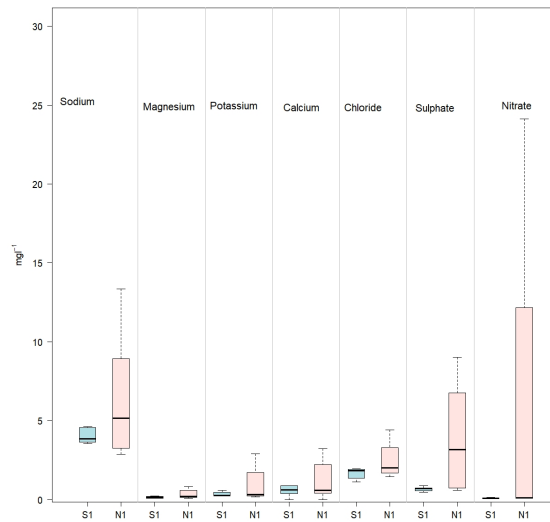


Figure 6.11: Sodium, Magnesium, Potassium, Calcium, Chloride, Sulphate and Nitrate concentration in mg.l-1 for S1 (blue) and N1 (pink) poultice samples.

6.2.4 Conclusion

Our aim with this study was to demonstrate the use of non-destructive techniques (NDT) to diagnose localised deterioration of stone. With the use of moisture measuring equipment, an IR camera and the paper pulp poultice technique we were able to determine that there is a higher concentration of soluble ions on the surface of the north bas-reliefs, which are the most deteriorated bas-reliefs in the church of Bete Golgotha. While we are not able to fully ascertain that the bas-reliefs carved on the north wall have been solely damaged due to salt weathering, our findings and observations suggests that the north wall is more susceptible to salt weathering

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than the south wall. This is beneficial for current conservation efforts being made in rock-cut churches in Lalibela and could serve as a simple methodology to diagnose localised deterioration in settings where destructive sampling or sophisticated laboratory equipment might not be available. Moreover, we have found that using paper pulp poultice to extract salts can be challenging when the dominant drying front is in the subsurface. The amount of water used to soak the poultice should be increased to speed up the rate of diffusion of the soluble salts to the poultice.

7. History of Conservation

Efficacy of traditional conservation methods for the protection of rock-cut heritage sites: Lessons from Lalibela, Ethiopia

Abstract

Lalibela, Ethiopia, is a World Heritage Site consisting of 11 medieval rock-cut churches carved into a basaltic scoria hill that have been severely damaged by natural weathering processes. In response to these deterioration threats, local communities have developed and used traditional conservation approaches, which have now been replaced by modern techniques to conserve this historic site. However, the effectiveness of the traditional conservation methods has not been properly investigated.

The aim of this study is to determine if traditional conservation techniques are

Published as: Taye Gemedo, B, Fusade, L. and Viles, H. (2020) Efficacy of traditional conservation methods for the protection of rock-hewn heritage sites: Lessons from Lalibela, Ethiopia. In, Siegesmund, S. and Middendorf, B. (Eds.).In *14th International congress on the deterioration and conservation of stone* (pp. 687-692).

adequate for the preservation of rock-cut heritage sites. To realise this aim, an initial assessment of traditional conservation methods of preventing water infiltration has been done. Using evidence from archival records, imagery and oral accounts of community elders, the most common traditional conservation methods used at Lalibela have been described, and their performance compared with similar modern techniques. The effectiveness of traditional techniques such as thatched shelters and mud plastering are assessed by comparing them with similar modern conservation techniques like lightweight open shelters and soft capping. The advantage of the traditional conservation approaches evaluated here is that they are non-intrusive, reversible and sustainable because they use natural, locally available materials and skills. Moreover, these methods have many commonalities with proven modern conservation techniques. Traditional conservation approaches should not be abandoned, they should instead be scientifically studied to determine their efficacy and to improve conservation strategies at Lalibela and other rock-cut sites.

7.1 Introduction

In conservation of the built environment, very little focus is given to traditional practices of maintaining and preserving heritage sites. Although the Venice Charter (ICOMOS, 1964) states that modern techniques for conservation should only be applied where traditional techniques have proved inadequate, this is rarely practised. The discipline of heritage conservation was formed in the first decades of the 19th

century CE, largely within a western European centred approach (Poulios, 2010). This is why western-based conservation philosophies and methods have dominated and shaped global heritage conservation perspectives. There is a consensus that the preservation and restoration of ancient buildings should be done within the framework of its own culture and traditions (ICOMOS, 1964), but in practice, this still remains a challenge. Clashing perspectives on methods of heritage conservation between international organisations and local communities have strained the relationship between the communities and heritage conservation practitioners. Much more work needs to be done to bridge this gap. The first step must be to determine the advantages of using traditional preservation techniques.

The medieval rock-cut churches at Lalibela, Ethiopia, which are the main focus of this study, are a good case study to investigate the potential benefits of local traditional efforts to conserve heritage buildings. The churches at Lalibela were carved between the 11th and 13th century CE and inscribed on the UNESCO world heritage list in 1978. These churches represent a unique architectural style and are a historically significant testimony of the medieval civilisation in Ethiopia (Fig 7.1).

Typically, rock-cut heritage sites are carved into ‘soft’ rock outcrops, chosen for the ease of sculpting. This property of the rocks makes them more susceptible to weathering and, therefore, more challenging to conserve. The rock-cut churches at Lalibela are carved into a basaltic scoria hill. The rock in which these churches are carved is very porous and contains a significant amount of swelling clays (Renzulli et al., 2011). Due to these intrinsic properties and exposure to the environment, the

rock churches at Lalibela have deteriorated considerably over time.

Traditional conservation techniques at Lalibela were developed with the aim of mitigating the deterioration of these churches and ensuring they can continue to serve the community. These churches are considered one of the holiest sites in Ethiopia and have maintained their original function for centuries. During the rainy season leaking roofs would not have allowed for the churches to continue to host service. In response to these conservation challenges, the community and members of the church developed and implemented preventive conservation treatments to maintain the use of the churches.

Tucked away deep in the Northern Highlands of Ethiopia, the churches at Lalibela remained largely inaccessible to the wider world until the beginning of the 20th century CE. Once roads and an airport were built and the site grew in popularity, modern conservation methods became the norm. The use of modern interventive conservation techniques has significantly altered the original design and the monolithic nature of the churches. The preservation and restoration campaigns were not done within the framework of the culture and traditions of the community in Lalibela (Ayalew, [2016](#)). Examining traditional conservation techniques using the tools and principles of modern conservation will be a good way to bridge the gap between modern and traditional conservation techniques.

7.2 Modern and traditional conservation techniques

Modern conservation efforts in Africa have often involved changes to the fabric of a site, its size, its use, its layout and or its hierarchy of spaces and rules of access (Joffroy, 2005). Lalibela has been saved from such large-scale changes, but restorations have become more frequent in recent years as tourism has increased and more international and local funding become available. The first non-local conservation and restoration work was done in Lalibela in 1919, it included significant changes to the monolithic aesthetic of the churches by replacing damaged parts of the walls with blocks of stone. In the course of the 20th and 21st century CE many conservation works were carried out by international organisations. These modern conservation efforts are distinctively different from the locally driven traditional conservation efforts that used to be practised before the 20th century CE.

Comparing the traditional and modern approaches to conservation works carried out in Lalibela the main differences between traditional and modern approaches to conservation are sourcing of material, community participation, frequency of works and intrusiveness. Materials used in traditional conservation methods are sourced locally, stones are taken from quarries nearby and the material is more likely to be compatible with the original. Modern approaches to conservation were more concerned with aesthetic compatibility and used materials like tar paints (Angelini, 1967). Traditional conservation efforts are led by leaders of the community and carried out by members of the community, whereas modern approaches have relied

more on foreign practitioners. Traditional conservation works are carried out periodically in preparation for or after a wet season. Modern approaches have not been done periodically, but rather as the need arises and are usually one-off treatments. Traditional conservation efforts are not intrusive i.e., the fabric of the structure being conserved is minimally altered. In contrast, more recent efforts to conserve the structures at Lalibela have been very intrusive; the walls have been chiselled and sand blasted as part of conservation treatments.

The aim of this study is to provide an initial assessment of traditional conservation methods used to prevent water infiltration and to determine if they are viable techniques that can be used for future conservation efforts in Lalibela and other rock-cut heritage sites facing similar conservation challenges.

7.3 Sources of Evidence

Traditional conservation methods that were used in Lalibela have not been well documented. There is no written evidence of the nature of the conservation works employed. Fortunately, knowledge of traditional conservation methods has been passed down from generation to generation through practice. The evidence that we now have of traditional conservation efforts is based on accounts of community elders who have either witnessed these methods being applied or participated in these efforts. Ayallew (2016) conducted interviews with local elders and has documented the methods used for conservation of the churches at Lalibela.

7 History of Conservation

Sketches and photos from travellers in the late 19th and early 20th centuries are also important resources. Detailed sketches by a traveller named Achille Raffray who visited the churches at Lalibela in 1882 are the first pictorial evidence we have of the churches (Raffray, 1882). Other travellers, such as Francisco Alvarez who visited Lalibela in the 16th century, described the churches at length (Alvarez and Stanley, 2010), but their descriptions are not accurate enough to convey a detailed sense of the appearance of the churches. The drawings of Achille Raffray are an important resource which illustrate the appearance of the churches and local preventive conservation methods before any modern interventions. Throughout the 20th century, other travellers have documented the state of the churches; from these resources, it is possible to see how the churches were transformed aesthetically due to modern interventive conservation efforts. Figure 7.1 shows the transformation that Bete Mariam underwent from the end of the 19th century to the beginning of the 21st century. The conservation campaigns that took place in the 20th century significantly altered the form and monolithic nature of this structure. Raffray's drawings of Bete Mariam (Raffray, 1882) (Fig 7.1 a) shows thatched shelters, made from locally sourced materials, were used to protect the roofs of the porticos. Photos taken in 1925 (McGrath, 1925, p.517) show that the thatched shelter was replaced with a gable roof made from concrete (Fig 7.1 b). Conservation works in the 1950's replaced the gable roof with flat roof made from mortar (Fig 7.1 c) (Ayalew, 2016). Currently the church of Bete Mariam (and other churches at Lalibela) are protected by a big open shelter (Fig 7.1 d).

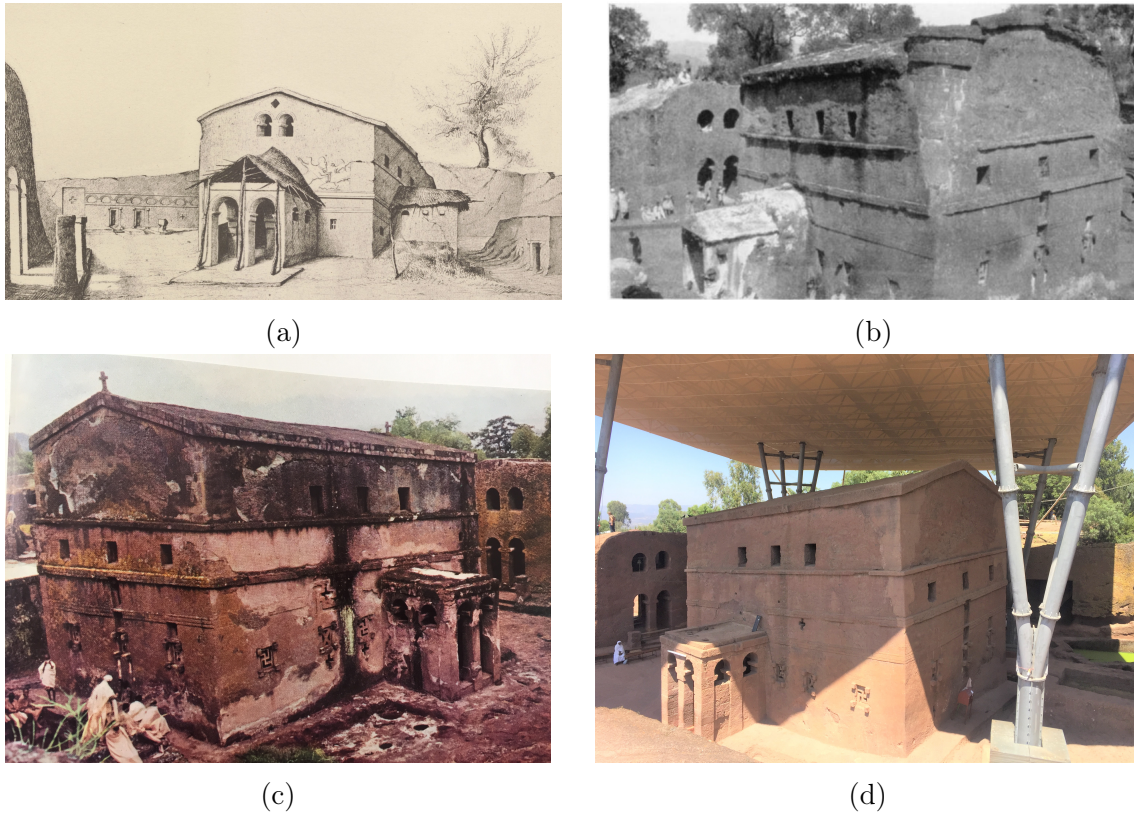


Figure 7.1: Drawing/photos of Bete Mariam (a) showing thatched roof in 1882 (Raffray, 1882, p.PL.6); (b) photo showing concrete gable roof in 1925 (McGrath, 1925, p.517); (c) photo of Bete Mariam in 1959 (Bidder, 1959, p.15); (d) photo showing open shelter in 2019

7.4 Modern conservation vs traditional conservation methods

From historical evidence and accounts of local elders, two traditional conservation methods that have been applied at Lalibela have been identified. Thatched shelters and a mud mixture were used to prevent water infiltration through the roof. These conservation methods were employed to tackle one of the major causes of deterioration of the rock-cut churches, that is, water infiltration through cracks in the roof of the churches. This deterioration mechanism continues to challenge the

conservation of the churches at Lalibela today. These methods are discussed below and compared with modern conservation techniques that apply similar principles (such as architectural shelters and soft capping).

7.4.1 Traditional methods to prevent water infiltration

Monolithic rock-cut structures have more vulnerable roofs than masonry structures and other building types. The roofs of rock-cut structures are directly exposed to rain and diurnal temperature fluctuations. Two traditional methods have been used to prevent the infiltration of water through the roof of these churches: thatched shelters and plastering the roof with a mud and animal fat mixture. Thatched shelters were used in the porticos at Bete Mariam (Fig 7.1 a) and as part of the roof at Bete Aba Libanos (Fig 7.2 a). These preventive conservation methods were deemed vital to reduce water ingress and thermal fluctuations, and allow the holy churches to be used properly. Much like the shelters made of modern materials that are now used in megalithic sites and ruins (Cabello-Briones and Viles, 2017), these shelters were put in place to protect the buildings from further damage. Open shelters have been used successfully to protect vulnerable structures from direct solar radiation and rain at megalithic sites (Becherini et al., 2016). Some of the churches at Lalibela have been completely sheltered from the 1990s onwards (Fig 7.2 b). This was done in order to protect the structure itself and to ensure that the churches could be used during the rainy season.

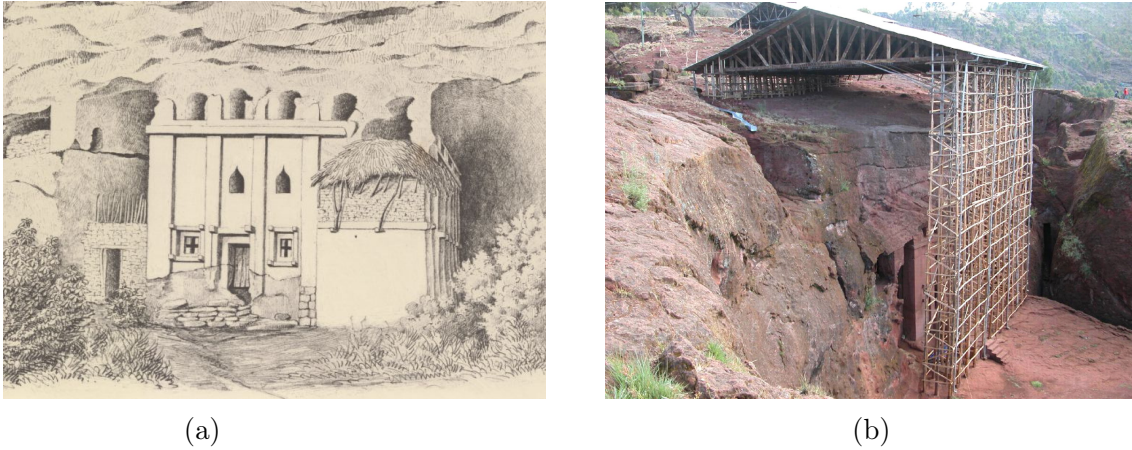


Figure 7.2: Bete Aba Libanos a) drawing showing thatched shelter in 1882 (Raffray, 1882 p.PL.17); b) photo of temporary shelter in 2010 (Delmonaco et al., 2010 p.15); c) photo of open shelter at Bete Aba Libanos in 2019

Other traditional method to protect the roofs of the churches involved plastering with mud treated with butter, and physically covering the roof with animal hide. From interviews with local elders, Ayallew (2016) has summarised the method used as follows: (1) mud collected from the surrounding area was plastered on top of the roof; (2) butter was then applied on the surface of the mud plaster to reduce absorption of water into the mud; and finally (3) animal hide was put on top of this layer to serve as a mechanical protection from direct rain. This non-invasive treatment was applied before the start of the rainy season to impede the infiltration of water through the roof. A similar method is used in Mali where the walls of the Grand Mosque of Timbuktu in Mali are plastered with mud before the start of the rainy season to protect the walls from the heavy rains (Sidi, 2012).

The mud that is applied on the roof of the churches also provides an ideal condition for the growth of grass and other plants. As this treatment is applied before the start of the rainy season, there will be plenty of water available to promote the

growth of plants. The result will eventually mimic soft capping techniques, which is the use of grass or other plants to protect horizontal rock surfaces (Cathersides et al., 2019). Figure 3 shows what Bete Amanuel looked like when it was soft capped with mud (Fig 7.3 a) and hard capped with a mortar and cement mixture (Angelini, 1967) (Fig 7.3 b). Field and laboratory trials have shown that soft capping can be a more effective method than hard capping in serving as a thermal blanket and slowing down the absorption of water on ruined walls in the UK (Viles and Wood, 2007).

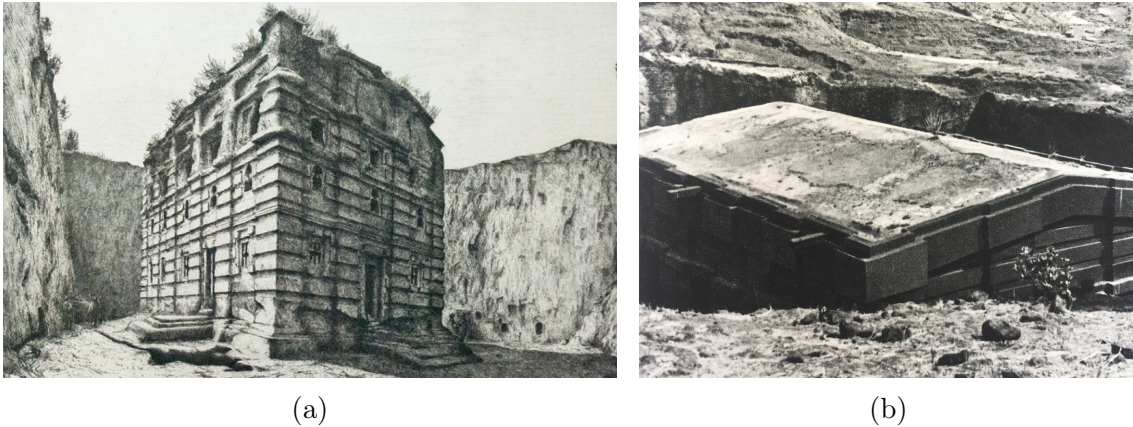


Figure 7.3: Bete Amanuel in a) drawing showing natural soft capping in 1940 (Manzato, 1988, p.56) and b) hard capped roof of Bete Amanuel in 1959 (Bidder, 1959, p.22)

7.5 Lessons from traditional conservation techniques

There are many advantages to using traditional conservation methods. Primarily, these methods are preventive solutions that are non-intrusive and reversible, aimed at making sites such as the churches at Lalibela more resilient to the environment. The materials used in traditional conservation are sourced locally and are likely

to be physically and aesthetically compatible with the structure being repaired. Traditional conservation efforts are funded locally and done with the participation of the community. Members of the community have a wealth of knowledge about the site, which in itself is a resource that needs to be used. Making the community more engaged and invested in the upkeep of their heritage site ensures that the conservation works are done within the framework of the culture of the community.

An initial assessment of thatched shelters and mud mixtures for protecting vulnerable rock-cut roofs shows many commonalities with proven modern conservation techniques of lightweight open shelters and soft capping. This demonstrates that traditional conservation methods are being replaced with modern ones without sufficient proof that traditional approaches to conservation are inadequate. To ensure the continuity of the authenticity of this and other sites of immense historical significance, it is essential to develop a new approach to conservation that respects and learns from local cultures and traditions.

However, more research needs to be done to investigate the efficacy of traditional conservation techniques. Modern conservation approaches have improved because of the efforts made to study their efficacy scientifically. If similar effort is made to improving traditional conservation methods, we would have more sustainable conservation approaches that would be in keeping with traditions and cultures of sites being preserved.

Part III

Towards a New Approach

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The outside is built from one rock, the inside is built from one rock. The work done on the outside is far greater.

(Acts of Lalibela, [2018](#), p. 201)

8. Discussion

This chapter discusses the results presented in chapters 4 to 7, synthesises the main findings and summarises the implications of this research. The review of literature on rock-cut architecture in chapter 2 showed that rock-cut architecture belongs in a semi-natural setting at the intersection of the built and natural environments. This section recounts the history of stress and weathering at Lalibela through a semi-natural site framework. The benefits of approaching the study of weathering through a semi-natural site framework will be shown by weaving together the components of the thesis that focused on Lalibela and demonstrating their broad implications. This chapter concludes by showing how the semi-natural sites framework and conceptualising the interaction of climatic and lithological factors as architectural forms can be usefully applied in other rock-cut sites.

8.1 Climate

Chapter 4 explored the impact of interannual, seasonal and diurnal variations in climate at Lalibela and their implications for the rate and nature of weathering. The implications of intense rainfall and high rock surface temperature fluctuations were identified as the most important climatic factors that affect the churches at Lalibela.

During Kiremt (main rains season), the climatic conditions are favourable for salt dissolution-crystallisation cycles, clay swelling/shrinkage, and biological weathering. Experimental analysis (Chapter 5) has also shown that given the high content of swelling clay minerals, the relative humidity fluctuations in Kiremt leads to significant swelling and shrinkage. Field observation clearly indicates that rainfall patterns significantly affect biological colonisation in Lalibela. Figure 8.1 shows the difference in biological cover on rock surfaces at Lalibela in Bega (the dry season) and Kiremt. Bega sees high temperature fluctuations that vary significantly depending on which cardinal directions the walls face. Belg (the small rains season) has milder climatic conditions in comparison to the other seasons. The temperature fluctuations in this season are low, and there are few rainy days. The rain in Belg is also predicted to decrease as a result of ongoing climate change. As a result, wetting-drying cycles driven by rainfall will occur less frequently.

The results of the climate analysis are useful for rock-cut sites located 10 to 20 km away from Lalibela like Bilbala Giyorgis, Genete Mariam, Asheton Mariam and Nakuto Le'ab and other sites in northern Ethiopia that experience heavy seasonal rainfall and high temperature fluctuations. Rock-cut churches further in the north in the region of Tigray (Fig 8.2) are exposed to a similar climate, that is, intense seasonal rainfall and mild variation of temperature throughout the year. The rainfall in Tigray varies spatially, with 260 mm/year rainfall in the north-eastern lowland and up to 1000 mm/year in the west (Gebrehiwot et al., 2011). Most of the rock-cut churches are located in the eastern part of Tigray in Atsbi, Hawzen-Ger'alta

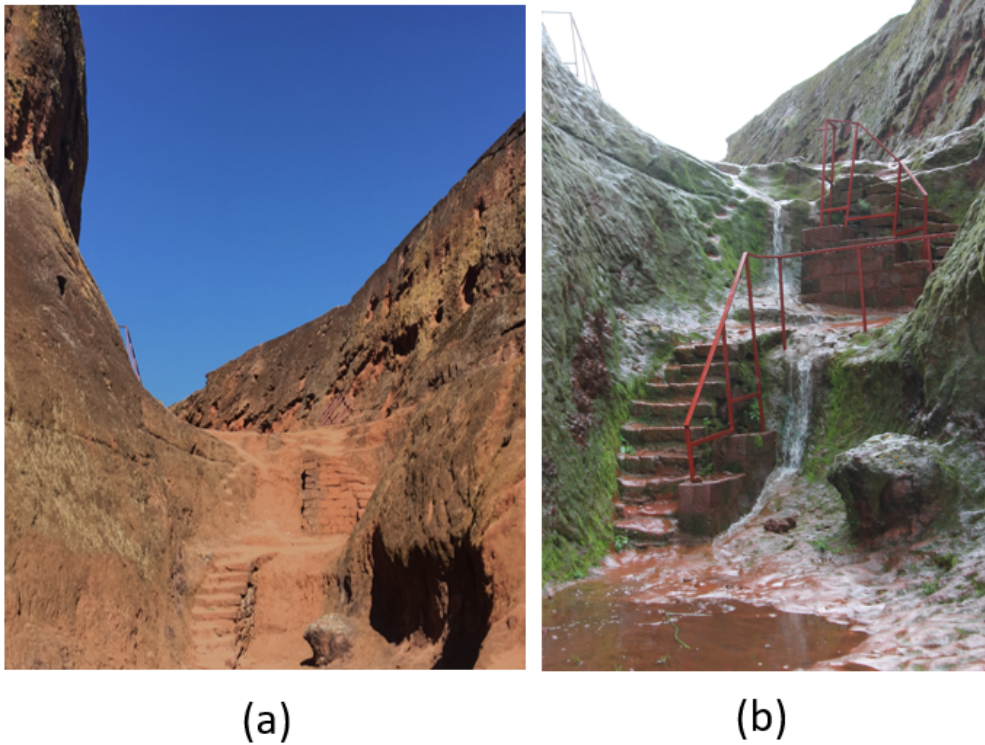


Figure 8.1: Image of trench that leads from Bete Amanuel to Bete Aba Libanos taken in (a) Dec 2018 (Bega) and (b) July 2019 (Kiremt). During Kiremt small the trench that is used as a foot path become a drainage channel. *Source: Author's own*

and Sinkata-Adigrat. The UNESCO world heritage site of Axum, which has large rock-cut steles and numerous rock-cut tombs, is located in central Tigray. The eastern (260 – 425 mm/year) and central (500 – 600 mm/year) part of Tigray has less annual rainfall than Lalibela, but similar to Lalibela, most of the yearly rainfall occurs during the rainy season (Kiremt) with July and August accounting for most of the annual rainfall. Given the similarity in rainfall patterns, rock-cut architecture in Tigray is likely to be affected by wetting-drying cycles and surface and deep wetness. Biology is likely to proliferate during Kiremt as there are ideal conditions for organic growths (i.e., moisture and sunlight). The temperature range in eastern Tigray is slightly higher than Lalibela, which might make it more prone to thermal fatigue.

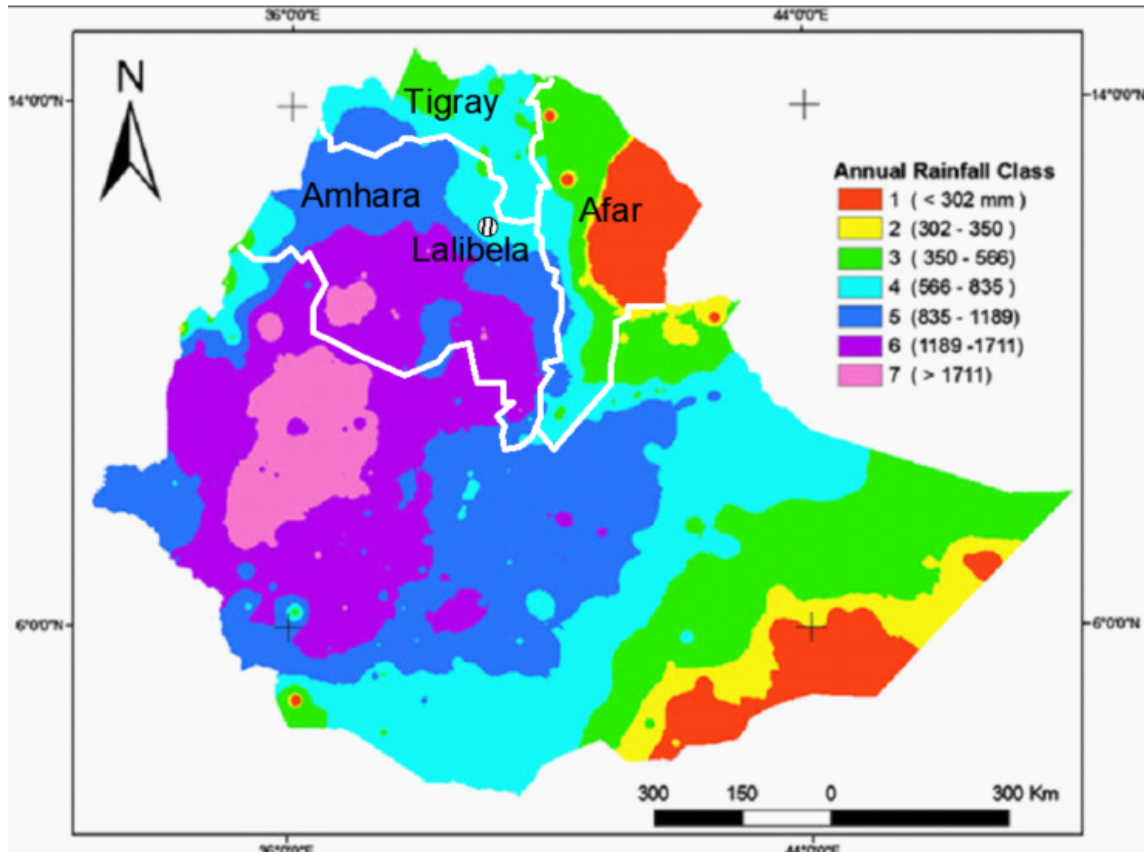


Figure 8.2: Rainfall map of Ethiopia (*Source: Berhanu et al., 2013*) with the location of Lalibela and regional borders of Afar, Amhara and Tigray regions superimposed.

The 29-year climate data analysis showed a statistically significant increasing trend in minimum temperature ($p\text{-value} = 4.7e-5$) and a nearly significant decreasing trend in annual rainfall ($p\text{-value} = 0.051$). Coarse spatial resolution and variability of the climate in Ethiopia make it challenging to have any certainty about future trends in rainfall in Lalibela. There is a high probability of exacerbation of hydro-meteorological extremes in the Horn of Africa (Betts et al., 2018). While it is challenging to determine the outcome of such extremes to the nature and rate of weathering at Lalibela, intense rain events may lead to flooding of trenches, tunnels, and courtyards at Lalibela. A study of the hydrology of the church complex would be beneficial to understand moisture dynamics at a larger scale than that covered

in chapter 6. The climate in northern Ethiopia is already changing and is expected to change further. Driven by a changing climate, it is highly likely that the rate and nature of weathering will alter as well. Conservation and management of these sites are made more difficult by uncertainties on future climate conditions.

8.2 Lithology

A broad review of the lithology of rock-cut architecture showed that rock-cut sites are often carved in outcrops that have low strength (Chapter 2). Soft limestone, sandstone, tuff and basalt outcrops are the most common places rock-cut structures are found. Low strength of rocks is associated with lithological properties such as low density, high porosity, presence of secondary minerals, and poor mechanical properties. Smectites, which occur as secondary minerals that form through hydrothermal weathering, are present in significant amounts in other well-studied rock-cut sites. Examples include the rock-cut dwellings in Meymand, Iran (Hashemi et al., 2018), the fairy chimneys in Cappadocia, Turkey (Topal and Doyuran, 1998), sandstone rock-cut structures in Petra, Jordan (Heinrichs, 2008) and the Moai monolithic carved sculptures in Chile (Gioncada et al., 2010). Experimental studies on the hygric and hydric behaviour of the clay-rich basaltic scoria showed that it has a high swelling potential (Chapter 5). The introduction of salt to a clay-rich rock accelerated the decay of the samples. The results demonstrated that salts in clay-rich rocks like those found in several rock-cut sites can significantly ac-

celerate the loss of material. This is particularly concerning in semi-natural settings where moisture can be transported throughout the structure more efficiently than in masonry structures. Areas with architectural detailing such as reliefs and friezes can be rapidly lost through exposure to salts from human activity (conservation and pollution).

Experimental studies on the synergistic effect of swelling clays and salt resulted in the samples developing decay features such as contour scaling. This decay feature is quite common on internal and external rock surfaces at Lalibela (Fig 8.3). Wetting and drying conditions determine the thickness of scales in clay-rich building stones (Wendler et al., 1990). A seasonally fluctuating drying front (evaporation zone) (section 6.1) moves the damage profile from the surface to the depth seasonally. This may explain why contour scaling is very common at Lalibela. The rock-surface temperature and relative humidity vary greatly seasonally, but they can also vary in the short term as a result of sunny spells in the wet season. These dynamic wetting and drying patterns can shift the evaporation zone frequently. During drying, the evaporation zone experiences the stress generated from crystallisation pressure of salts in a clay-rich substrate that is brittle and prone to failure. Shifting the location of this stress profile is likely to manifest as contour scaling.



Figure 8.3: Contour scaling on (a) a trench wall Bete Aba Libnos and (b) in the interior Bete Gabriel Rufael

8.3 Architectural Form

Architectural form was presented as a new way to conceptualise the interaction between lithological and climatic controls at semi-natural sites (Part I). The role architectural form plays in weathering of rock-cut structures was shown in chapter 6. Analysis of moisture dynamics on the exterior walls of Bete Giyorgis and Bete Amanuel showed that seasonality highly influences moisture content and distribution. Moisture dynamics in semi-natural settings is influenced by three factors: homogeneity of the rock mass, absence of impermeable foundation or roof and thick load-bearing walls. The combination of these factors leads to a high flux of moisture at semi-natural sites. Field observation of newly carved rock-cut churches 30 - 35 km away from Lalibela showed a similar wetting pattern as discussed in section 6.1. Figure 8.4 a and b shows Dagmawi Lalibela and Debre Tsion churches in the rainy season with the upper and lower parts of the structure completely saturated. The

images of Lalibela shown in figure 8.4 c and d show the lower part of the structure saturated, likely from groundwater absorption. The results presented in section 6.1 and figure 8.4 demonstrate the impact of homogeneity in material composition and the absence of roofs and foundations. Semi-natural sites have an efficient system for moisture absorption and transport; this is an ideal scenario for soluble salts to be distributed throughout the structure. Therefore, understanding moisture transport is an important component of managing rock decay at Lalibela.

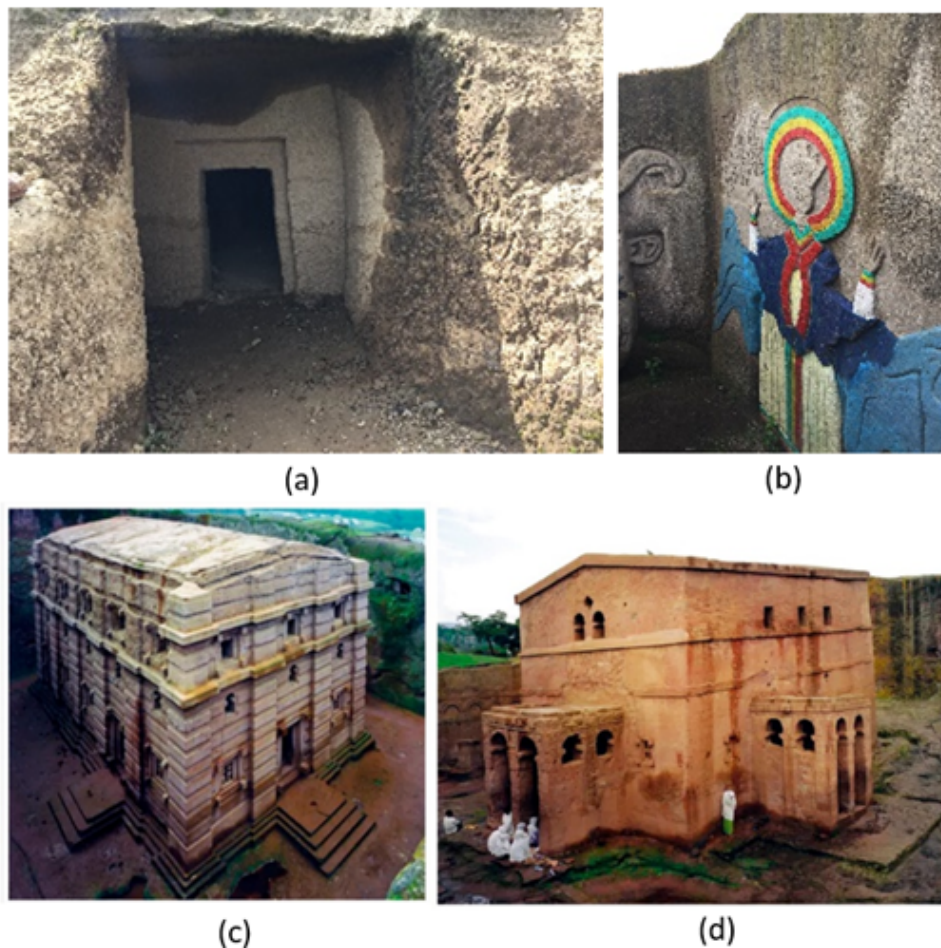


Figure 8.4: Images of newly built rock-cut churches (a) Debre Tsion and (b) Dagmawi Lalibela, and churches at Lalibela (c) Bete Amanuel and (d) Bete Miriam taken during the rainy season. The darker areas on the top and bottom images indicate areas that are wet. *Source of images c and d: Woldeyes, 2019*

Analysis of moisture and salt distribution in the interior walls of Bete Golgotha (section 6.2) showed an interesting relationship between the thickness of walls and the state of preservation. The north wall in Bete Golgotha is more deteriorated and has a higher concentration of soluble salts than the south wall. Field observations also show that the north wall is covered with salt efflorescence (Fig 6.8). The north wall is several meters thick (> 5 m) while the south wall is 0.9 m thick (Fig 8.5). The amount of moisture in walls is associated with evaporation rate, material properties and thickness (D'Agostino, 2013; Hall et al., 2011). The evaporation rate and material properties are unlikely to be significantly different between the two walls, given that these walls are carved in the same rock mass 6 m across from each other. The moisture reading presented in section 6.2 (Paper IV) were collected in the dry season; they showed that the saturation state was comparable between the north and south walls. Table 8.1 shows mean values of moisture content (% saturation) measured in the wet and dry seasons on the surface and at depth. Comparing the saturation state of the north and south walls between the wet and dry seasons, it is evident that the north wall is more saturated at depth during the wet season (Table 8.1). The increase in saturation at depth is greater for the north wall than the south wall. This demonstrates that the north wall is relatively more saturated than the south wall during the wet season.

Higher moisture content in the north wall may be explained by assessing not only the thickness of the wall but their exposure to moisture. A sectional view of Bete Golgotha (Fig 8.5) shows that the north wall is more exposed to rain infiltration and

Table 8.1: Mean saturation (%) of the north and south walls in Bete Golgotha during wet and dry seasons. Data presented in percentage saturation. Moisture Index values was converted using the calibration function presented in section 6.1. Moisture data taken in the wet season at Bete Golgotha is presented fully in appendix 6.

Sensors	North		South	
	dry season	wet season	dry season	wet season
R (surface)	8.9	17.9	9.0	16.3
P (subsurface)	8.3	22.9	4.2	13.2

is adjacent to a drainage channel. As the evaporation surface for higher amounts of moisture, the north wall will be more exposed to soluble salts than the south wall.

Localised deterioration in Bete Golgotha is linked to aspects of the architectural form such as the thickness of walls and exposure.

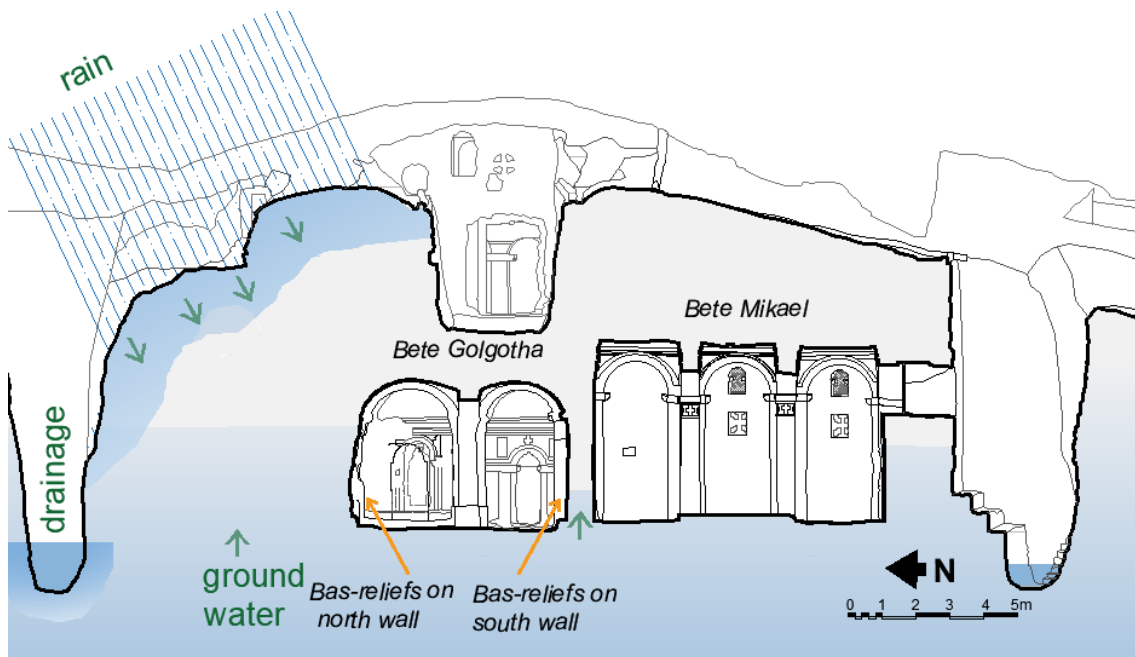


Figure 8.5: Conceptual model of moisture distribution at Bete Golgotha. Height of moisture rise are likely to be higher on the thick north wall and much lower on the south wall. Source of original drawing: Archeovision 2019

Rocks generally have low tensile properties and are prone to cracks and creep when subjected to excessive loading for an extended period of time. The ceilings of several of the churches exhibit hair cracks that go across the structure (Fig 8.6).

Recent studies on the decay processes of sandstone at Petra (Rihosek et al., 2016) and elsewhere (Bruthans et al., 2014) have questioned the role of gravity-induced stresses in increasing weathering rates. Rihosek et al. (2016) and Bruthans et al. (2014), using numerical modelling, laboratory experiments and field observations, concluded that the stress field is the primary control of the shape of sandstone landforms and that increased stress decreases the decay rate of monuments like Petra. While these studies were done on sandstone, studies at Lalibela have implicitly credited the stress field as a stabiliser of an otherwise weak structure; Delmonaco et al. (2005) credited the ‘arch effect’ for the stability of Bete Aba Libanos. The structural problems at Lalibela has so far been studied independently of the weathering behaviour of the basaltic scoria. Future studies should focus on the synergistic relationship of exposure to climate (e.g., cyclic loading from saturation and drying of roofs), material loss due to weathering and stress fields.

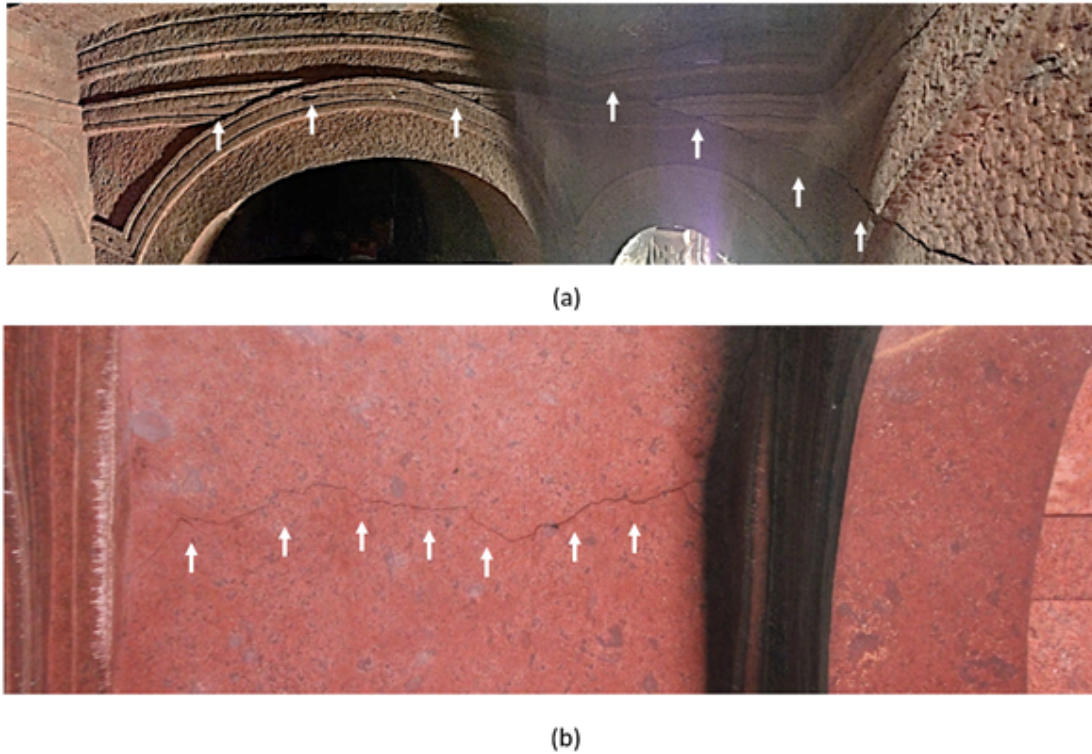


Figure 8.6: Cracks on on the ceiling of (a) Bete Mikael and (b) Bete Giyorgis. White arrows pointing to cracks.

8.4 History of conservation

‘The properties of stone derive from the process of rock formation millions of years ago, and govern both the suitability of the material for different purposes and its long-term performance’ (Odgers & Henry, 2012, p.34). To understand the present state of the churches, it is essential to understand the geological formation, the history of construction and conservation at Lalibela. ‘A rock possesses inherited properties according to its composition and genesis’ (Warke et al., 1996, p. 296). In a semi-natural setting, the pre-exposure stress history significantly influences the post-exposure behaviour. Geological discontinuities, differential weathering and lithological properties are inherited properties that affect the durability

and behaviour of rock-cut structures post exposure. The basaltic scoria was formed in the Oligocene and has gone through a process of hydrothermal weathering over millennia (Fig 8.7). This has led to lithological properties such as high content of secondary minerals like zeolite and swelling clay minerals that contribute to how the rock weathers. During the excavation of the site, new surfaces were exposed by the removal of parts of the rock mass. As a result of these processes, the gravity-induced stress in the rock mass was redistributed to columns and load-bearing walls. Increasing human activity in the form of urbanisation, tourism and conservation has introduced additional complexity to the post-exposure stress history.

Figure 8.7 outlined the post-exposure stress history of Lalibela and the intensification of human activity starting from the 20th century CE. In the last century, Lalibela underwent several restoration campaigns that were very intrusive and visibly altered the architectural form of the churches. Revising both traditional and modern conservation efforts shows that these efforts were mostly focused on repairing roofs. Leaking roofs, fractures and cracks in the churches have been an issue in the churches at Lalibela (Angelini, 1967) and continue to be a problem (Asrat et al., 2012; Steel, 2016). As a result, soft capping, hard capping, grouting and shelters have been extensively used in Lalibela. Currently, four churches are sheltered in Lalibela (Table 3.2). The results presented in section 6.1 indicate that the shelters are somewhat effective in limiting moisture infiltration. A study on the structural impact of the shelters has suggested the pillars are resting on weathered rock that is not able to sustain the weight of shelters in the long-term (Asrat and Gebrey-

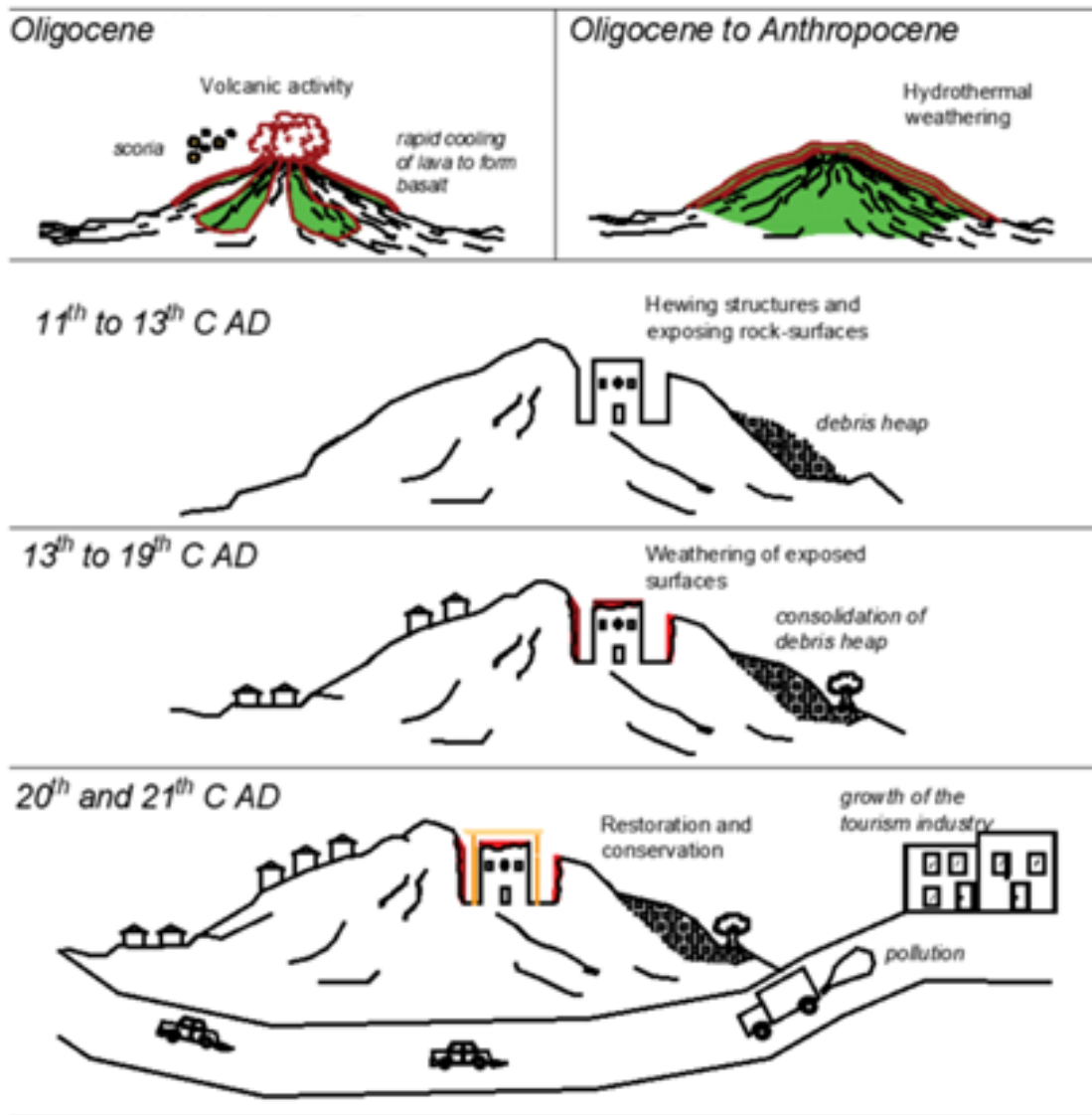


Figure 8.7: Conceptual diagrams showing the pre-exposure and post-exposure histories from the genesis of the rock outcrop to the present day. *Source: Author's original diagram.*

ohannes, 2014). Another disadvantage of the shelters is that they severely disrupt the cultural landscape of Lalibela (see Fig 8.8). In chapter 7, soft capping (green roofing) was identified as a traditional conservation method that could be improved for future use in Lalibela. There are several advantages to applying soft capping. It is cost-effective and shields the roof from rain infiltration and insolation. It would require maintenance to prevent roots from entering the rock substrate and managing

the species of plants that grow (Cathersides et al., 2019). While additional studies would have to be done to assess the positive role of soft capping in tropical climates, it is also important to determine if it is a suitable solution in the current social, religious and cultural context of Lalibela.



Figure 8.8: Aerial view of the churches showing how the shelters disturb the cultural landscape. *Source: Archeovision 2019*

8.5 Implications and summary of findings

8.5.1 Summary of findings

This thesis focused on identifying and studying the drivers of weathering at Lalibela. While the studies on micro-climate, moisture dynamics and salt distribution at Lalibela focused on individual churches, many of the results are broadly applicable across the whole site. A study of the micro-climatic conditions at Bete Mariam

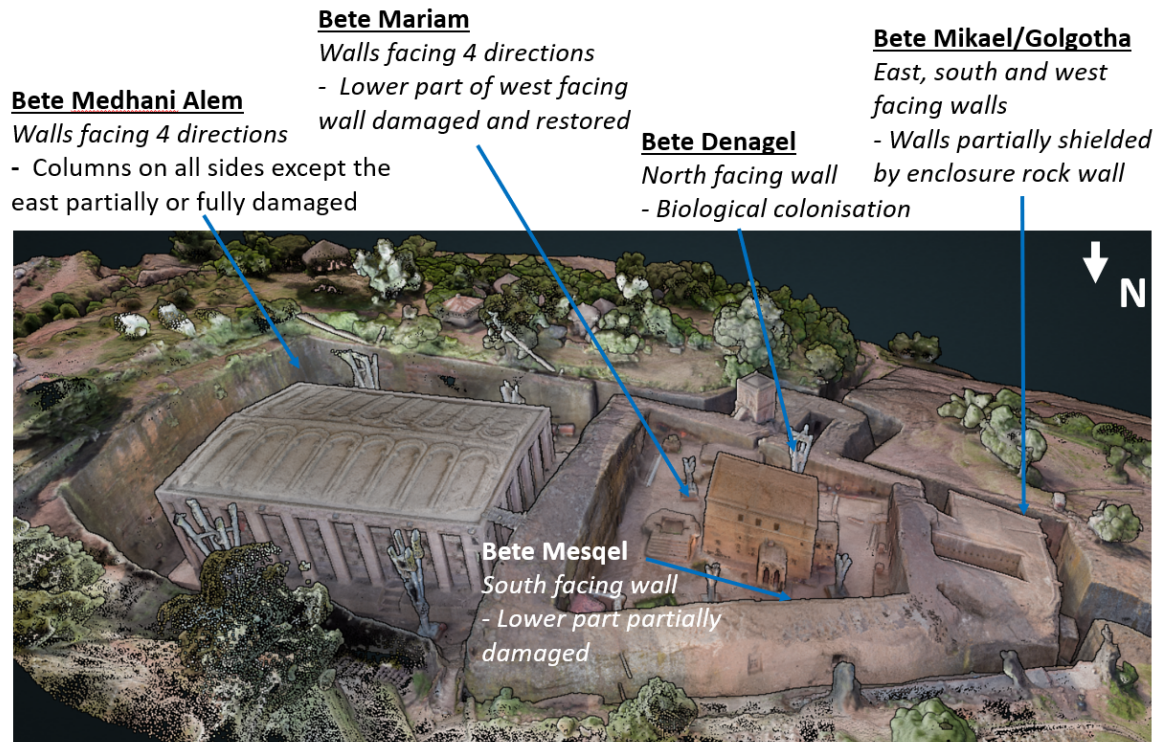
(Chapter 4) showed the importance of aspect in controlling insolation at Lalibela. Seasonality in moisture dynamics was assessed at Bete Giyorgis and Bete Amanuel (Chapter 6), and the results showed that the drying front was on the surface in the wet season and at depth during the dry season. The moisture dynamics in the interior walls were also assessed in Bete Golgotha (Chapter 6). The influence of wall thickness and exposure on salt loading was shown. Ambient climate, lithological properties and history of conservation were studied in a wider selection of churches. Using quarry samples with the same mineralogical composition as the churches, it was possible to assess the role of swelling clay minerals (smectite) in weathering (Chapter 5) at Lalibela. The history of intervention, conservation and restoration of many of the churches was summarised in section 3.3, and the traditional conservation techniques were examined in the context of their efficacy in chapter 7.

The key findings of these studies can apply to the site as a whole. The seasonality in rainfall has an impact on the amount of moisture in the walls and the drying rate. Low relative humidity in the small rains and dry seasons means capillary condensation is unlikely to occur. Moisture-driven decay in these seasons is likely to occur through groundwater uptake on the lower parts of the walls. The amount of moisture absorbed and the height of moisture rise in the walls depends on the thickness of the wall and its exposure to rainfall. The wet season has high relative humidity and frequent wetting-drying cycles are likely to occur throughout the structure. Near-surface environmental conditions also influence the nature of salt-driven decay. Variation of the drying front seasonally contributes to con-

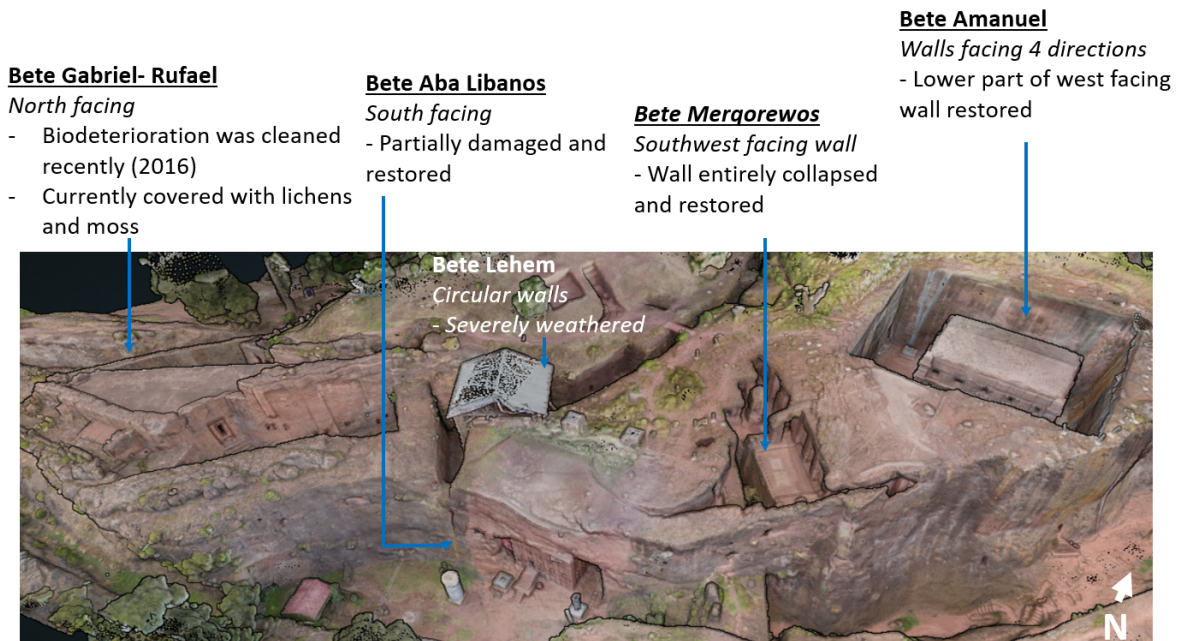
tour scaling. Based on these findings, some trends associated with micro-climate, conservation history and exposure are made. North-facing walls tend to have biological colonisation; for example, Bete Gabriel-Rufael and Bete Denagel (Fig 8.9) are covered with lichens and moss. Biological colonisation on north-facing walls is common because it has higher relative humidity during the driest period of the year (Bega) (Fig 4.6). The lower part of the west-facing wall of Bete Mariam, Bete Amanuel and Bete Giyorgis have been partially or fully restored (Fig 8.9). Damage seen on the lower parts of the west-facing wall may be associated with higher rock-surface temperature (evaporation rate) throughout the year, contributing to a higher flow of moisture and salt loading on the west-facing walls. These trends in the preservation state of the walls are likely associated with the significant variation in micro-climatic conditions on walls facing different cardinal directions. Long-term monitoring of the micro-climate and moisture content on different aspects in combination with an assessment of lithological differences may explain the significance of aspect in weathering at Lalibela.

8.5.2 Current and future risks

The risk to the preservation of the historic fabric at Lalibela stems from naturally occurring weathering processes that are augmented by human activity and socio-political threats like tourism and conflict. Threats to the conservation of Lalibela from naturally occurring weathering processes can be broadly classified into two scales of interaction of climate and lithology:



(a)



(b)

Figure 8.9: Aerial view of a 3D photogrammetry model of (a) the northern group and (b) south western group of churches with indication on which direction they face and some the weathering features they have. *Source: Archeovision 2019*

1. Rock surface/mass scale (architectural form): the impact of micro-climate (and aspect) on the frequency of salt crystallisation/dissolution and wetting-drying cycles as well as the role of swelling clay minerals on rock decay was presented in section 8.1 and 8.2. The role of architectural form on micro-climatic conditions (aspect) and the distribution of moisture and salts in the interior and exterior of the structure as well as on the structural integrity was discussed in section 8.3.
2. Landscape scale (landform): the impact of heavy rainfall on moisture dynamics has been discussed from a rock mass scale approach. Given the topography of the landscape around the churches, intense rainfall will impact the hydrology of the site. The church complex has drainage channels that were built along with the churches that take advantage of the topography of the site. Some of these channels have been disrupted by natural and human-made debris. The topography of the site will also control which areas are more exposed to surface runoff and the level of the groundwater table. These are essential factors that will affect which areas have higher exposure to surface runoff or groundwater. Heavy rainfall in July and August (Chapter 4) will likely induce significant surface runoff on the steep slopes of the church complex. The studies carried out in this thesis did not cover the landscape scale moisture transport in the complex. Future work is needed to understand the nature of the hydrological dynamics in Lalibela and its role.

The growth of the tourism industry around Lalibela poses a new challenge to the intangible and tangible aspects of the heritage site. Pollution, vibration from trucks and an increasing number of visitors affect the physical fabric of the site. Attempts to protect the sites have involved resettlement of the people that live near the churches out of the UNESCO buffer zone (Odiaua, 2010). Such measures alienate the local community (Ayalew, 2016) and negatively impact the preservation of the intangible heritage.

Lalibela has recently been at the centre of a conflict that broke out in northern Ethiopia between a rebel group and government forces. The conflict started in November 2020 in the Tigray region, less than 200 km from Lalibela (Fig 8.4). The conflict was mainly isolated in the Tigray region until later in 2021, when it started spreading outward to other regions in northern Ethiopia. Rebel forces took control of Lalibela briefly two times between September and December of 2021. Communities in northern Ethiopia have been severely affected by the ongoing conflict; it has had an immense impact on lives and livelihoods. Based on media reports (ENA, 2022), it seems that there hasn't been a significant impact on the physical fabric of the churches as a result of this conflict. Unfortunately, other lesser known heritage sites have been damaged (ENA, 2022). Because of the religious and historical importance of the churches at Lalibela, it would seem that both government and rebel forces took great care not to impact the physical fabric of the churches. Sadly, as the conflict is ongoing, communities in northern Ethiopia continue to face threats of displacement or attack. Regarding the threat of the destruction of the churches, the

restraint shown by both sides of the conflict during operations in Lalibela indicate that there are social drivers that contribute to the conservation of the churches.

8.5.3 Recommendations and future work

The findings of this thesis lay the foundation for understanding weathering at Lalibela. Studies on the micro-climate, ambient climate, moisture dynamics and lithological characteristics are useful contributions to the body of work on Lalibela. Based on the review of the literature and the findings made in field and lab studies in this thesis, some recommendations are presented.

Salt attack

Salt attack is one of the most significant challenges to the conservation of the churches at Lalibela. The poultice-derived samples presented in chapter 6 hint at the types of mixed salts likely found more widely at Lalibela. It would be challenging to remove the salts or apply treatment on a large scale. Wedekind et al. (2006) tested a sprinkling method to desalinate the rock-cut walls in Petra. They managed to reduce the salt concentration but also transported some of the salts to the base of the structures. Desalination using poultice and salt crystallisation modifiers (Lubelli and van Hees, 2010; Rivas et al., 2017) are commonly used in masonry walls, but large scale application would certainly be challenging. While these methods are partial solutions to salt efflorescence, they might not be sufficient for the removal of sub-efflorescence, which is most common at Lalibela. Newly developed consolidants

may offer a solution to moisture-driven decay processes, but their efficacy for large scale application is still unknown (Xie and Zhang, 2020). Efforts to reduce salt-driven decay at Lalibela should be focused on areas such as the bas-reliefs at Bete Golgotha, the frieze in Bete Mariam and the ceilings of many of the churches because of the threat of permanent loss of these architectural features. Identifying the source of salts, testing the salinity of groundwater and rainwater, and assessing the type of salts are essential to having a robust plan to manage decay at Lalibela.

Protecting the roofs

The roofs of the churches have been the focus of many conservation efforts (Chapter 7). Heavy rainfall during the wet season and thermal cycling during the dry season has severely weathered the roofs. The shelters were implemented as a temporary solution, and there haven't been any efforts thus far for a sustainable method to protect the roofs from rain infiltration and thermal cycling. Given the obtrusiveness of shelters to the cultural landscape of Lalibela (Fig 8.8), other methods of protecting the exposed roof, such as soft capping, may offer a more aesthetically compatible solution. The residents of Lalibela believe the shelters that are currently in place are harming the churches because they are massive structures. This has led to protests and condemnation of the federal authority that oversaw the project (Woldeyes, 2018). As such, in developing a strategy to protect the churches, it is essential to consider both social and environmental factors. Soft capping may be perceived as an aesthetically unappealing solution. A mechanism to protect the

churches from thermal cycling and rain infiltration while respecting the cultural landscape at Lalibela is desperately needed.

Hydrology

The climatic processes investigated in this thesis mainly dealt with ambient and micro-climatic conditions. The implications of heavy rainfall on the structures have been assessed in terms of its impact on the structures. Hydrology is an important factor for rock-cut sites that experience heavy rainfall. In Petra, Theban tombs and Mogao, for instance, flooding has been noted as a challenging issue (see section 2.2.4). Given that many rock-cut heritage sites are carved in cliff faces where they might experience surface runoff or are located underground level where they might be flooded, the hydrology of rock-cut sites is an important factor that should be considered in the management of these sites.

Biological colonisation

Some of the churches at Lalibela are covered in lichens most of the year and moss in the rainy season. A study on the impact of the lichens has suggested that the lichens are leaching minerals from the surface (Schiavon et al., 2013). In light of the studies in this research that have highlighted the high diurnal temperature fluctuation on the rock surface at Lalibela, the role of biological colonisation should be reexamined to determine if it can protect the churches from temperature fluctuation.

8.6 Towards a holistic approach for preservation of rock-cut architecture

The overarching aim of this thesis was to develop a holistic approach to diagnosing the deterioration of rock-cut structures through a case study of the churches in Lalibela, Ethiopia. By synthesising the insights gained from the literature review, field, laboratory and archival research, a holistic methodology is developed. The methodology is meant to help in identifying spatial patterns and causes of decay features that are common in rock-cut structures. A crucial component of the methodology is the semi-natural sites framework. This framework incorporates processes in the natural and built environment to understand weathering processes in semi-natural settings. The processes that drive weathering in the semi-natural context can be broadly classified into two sets of interactions between climate and lithology: landform and architectural form. Rock-cut sites are influenced by processes that created the landform (pre-exposure history), and the architectural form influences the post-exposure history. Rock-cut structures are often carved in limestone, sandstone and volcanic rock outcrops that have low strength. This inherent property makes rock-cut structures particularly vulnerable to rock decay. Pre-exposure history encompasses the inherited properties that the rock outcrop has as a result of its genesis. For example, the monuments in Petra are carved into sandstone with a bedding structure. This has resulted in large scale heterogeneity and differential

weathering as a result of significant variation of grain sizes and related properties (Heinrichs, 2008). Geological discontinuities, joints, fissures and rockfall are all part of the inherited history that contribute to rock decay at rock-cut sites. Topography and slope determine whether surface runoff, flooding or wind erosion will occur in semi-natural settings.

Architectural form controls the interaction of climate and lithology at rock-cut sites in various ways. The form of rock-cut sites can influence micro-climatic conditions, moisture dynamics, the extent of exposure and structural integrity. Common features of architectural form in rock-cut structures are thick load-bearing walls, permeable roofs directly exposed to rain and insolation, low ventilation (few windows in load-bearing walls) and poor structural integrity. The amount and distribution of moisture in stone structures hugely influence weathering patterns. In rock-cut architecture, architectural form plays an important role in moisture dynamics. In Petra, for instance, an assessment of the damage on rock walls showed that damage was concentrated in the lower and upper parts of the structure as a result of exposure to rainfall and groundwater moisture (Heinrichs, 2008). The spatial scale of salt weathering and biological weathering is also influenced by architectural form.

Table 8.2 outlines landform and architectural form features that influence the interaction of lithology and climate in semi-natural settings. It lists a range of factors that influence weathering and the factors that cause them. This can be used as a guideline to identify decay features and to determine their cause by understanding landscape processes and exposure to climate (architectural form). This is

a broad classification that can be used to describe commonalities in rock-decay in semi-natural settings. Micro-scale decay processes will be influenced by relative humidity and temperature fluctuation as well as mineralogical composition. Given the variation of mineralogical properties in rock-cut sites, larger scale rock properties that are shared across sites, such as geological discontinuities and low rock strength, are presented as a basis to diagnose deterioration in rock-cut structures.

Table 8.2: List of landform and architectural form features that influence the interaction between climate and lithology in a semi-natural setting.

	Landform	Architectural form
lithological controls	<ul style="list-style-type: none"> • geological discontinuities • joints and fissures • slope • topography • tectonics • rockfall 	<ul style="list-style-type: none"> • exposed roofs and walls • no means to slow water absorption • poor structural integrity • thick walls and roofs
climatic controls	<ul style="list-style-type: none"> • hydrology • wind 	<ul style="list-style-type: none"> • direct rainfall • wind driven rain • relative humidity fluctuation • temperature fluctuation
rock decay processes	<ul style="list-style-type: none"> • differential weathering • wind erosion • flooding • surface runoff 	<ul style="list-style-type: none"> • localised deterioration • infiltration of rain • groundwater absorption • high humidity and condensation

8.7 Conclusions

The findings of this research highlighted that weathering of rock-cut structures is influenced by large scale natural processes and building scale processes that are largely driven by human activities. By using a semi-natural sites framework and focusing on the rock-cut churches at Lalibela, this thesis outlined some of the common threats to the preservation of rock-cut architecture. Low strength rock outcrops that are often chosen for carving rock-cut sites contribute to their vulnerability to decay. The architectural form of rock-cut sites determine the degree of exposure to the environment. Exposed roofs and thick load bearing walls facilitate moisture driven decay processes such as salt weathering. At the landform scale, geological discontinuities and topography influence the vulnerability of these sites to climate driven processes such as rainfall ingress, surface runoff and flooding. A multi-scale approach that identifies the drivers of weathering in the landform and architectural form scale, is crucial for a holistic understanding of the processes that lead to deterioration of rock-cut sites.

9. Conclusions

This thesis has achieved the primary aim of developing an approach that can be used to holistically diagnose the deterioration of rock-cut structures (Fig 1.2). By identifying key drivers of weathering of rock-cut sites and their synergistic relationship, a multi-scale methodology for understanding weathering of rock-cut sites was developed. A semi-natural sites conceptual framework underpins this thesis and integrates the natural and anthropic factors that influence weathering of rock-cut structures (Fig 2.1). This is a crucial component of studying rock-cut sites as the scale of weathering processes that occur in these settings are influenced by landscape scale environmental processes as well as human scale activities such as carving.

There are four objectives that were outlined in this thesis (section 1.2.2) that were deemed essential to a holistic understanding of weathering of rock-cut structures. Each objective and its contribution to a broader understanding of deterioration at rock-cut sites are discussed in this chapter.

9.1 Implications of climatic trends for weathering

- **Objective 1:** to characterise the ambient and micro climatic trends at Lalibela and their implications for weathering.

9 Conclusions

Analysis of long-term ambient climate data and short-term micro-climate data allowed the characterisation of trends in climate that influence weathering at Lalibela. The climate at Lalibela is warming, mainly driven by a statistically significant increasing trend in minimum temperature. Annual rainfall also shows a decreasing trend (p-value = 0.051) in the 29-year climate data set analysed in Chapter 4. Lalibela has three climatic seasons: main rains season (Kiremt), small rains season (Belg) and dry season (Bega). The main difference in climatic conditions seasonally that are relevant for rock weathering at Lalibela are the following:

- intense rainfall in Kiremt with July and August having > 250 mm rainfall each;
- frequent and rapid fluctuation in temperature and relative humidity occur in Kiremt driven by rain and sunny spells;
- the relative humidity is high during Kiremt (>60% RH) and fluctuates at a range where wet-dry cycles may occur;
- south and west facing walls experience high rock-surface temperature fluctuation during Bega;
- Belg is the warmest season (highest minimum and maximum ambient temperatures);
- aspect plays a role in controlling the range of temperature and humidity fluctuation seasonally, west facing wall experiences high temperature fluctuation

in all seasons.

The key weathering-related impacts of the diurnal seasonal and inter-annual variations in climatic variables will influence surface and deep-seated wetness, wetting-drying cycles and thermal cycling. The duration of surface wetness is at its highest in Kiremt. This creates a suitable condition for organisms to grow on the surface, as evidenced by the seasonality of moss and grass growth on the church walls and roofs at Lalibela. Deep-seated wetness is also likely to occur only in Kiremt as a result of the intense rains. Moisture measurements done in Kiremt at Lalibela (Chapter 6) have shown that there is a large increase in subsurface moisture during Kiremt. Wetting and drying cycles will occur at varying frequencies throughout the year. Both Kiremt and Belg experience rainy and sunny spells that are suitable for wetting-drying cycles and, in turn, salt crystallisation-dissolution cycles. Experimental studies in chapter 5 have shown that the range of RH fluctuation in Kiremt can have a significant impact on hygric dilatation behaviour of the clay-rich basaltic scoria. Thermal fatigue will be dominant in Bega as rock-surface temperature fluctuations are high during this season. Flaking and contour scaling that are common across the churches are likely driven by a combination of wetting and drying cycles in Belg and Kiremt and thermal cycling in Bega. Characterising the climatic conditions sets the background to understanding the nature and rate of weathering at Lalibela.

9.2 Lithology

- **Objective 2:** to assess the role played by lithology on weathering at Lalibela.

The basaltic scoria churches at Lalibela are carved from contains significant amounts of secondary minerals such as swelling clay (smectite) and zeolite minerals. They also contain pyroxene, K-feldspars, hematite and ilmenite, but they are less abundant. The hydration of clay inter-layers with water leads to expansion forces that manifest as swelling. An experimental investigation was carried out to assess hydric and hygric behaviour of a clay-rich (basaltic scoria) rock to determine the synergistic role of swelling clay and salt (NaCl) in the decay of rocks. The experimental setup involved measuring the hydric and hygric dilatation of the rocks before and after salt contamination. Quarry samples that matched the mineralogical composition of the rocks used to carve the churches were chosen as representative samples for this study. In saturated (hydric) conditions, the salt-free samples had a higher dilatation than the salt-contaminated samples. When salt-free samples are contaminated with salt, swelling and shrinkage phases in wetting and drying cycles (hygric) are reversed. The pressure created by crystallisation of salts during drying leads to a higher dilatation than swelling of the salt-free samples during wetting. Salt contamination also led to frequent phasic changes in volume that correspond with both crystallisation/dissolution of salts and hydration/dehydration of clays. Clay minerals are plastic when wet and brittle when dry; this is why dilatation due

to clay swelling is to a large degree reversible. The introduction of salts to a clay-rich system means that during the brittle phase (during drying), salts will crystallise, causing non-reversible deformation. This experimental study demonstrates the synergistic role salt (NaCl) and swelling clays (smectite) play in rock decay. Where salt forming ions and swelling clays are present, wetting and drying cycles are likely to cause accelerated decay. Future work should focus on the impact of a range of salt concentrations and combinations in clay-rich rock types to learn more about this synergistic decay processes.

9.3 Architectural Form

- **Objective 3:** to determine the role of architectural form on moisture dynamics and localised deterioration at Lalibela.

Rock-cut heritage sites have different types of exposure to the climate. A review of literature on rock-cut structures (see section 2.2.4) has shown that infiltration of rain through the roofs of rock-cut structures, groundwater uptake and flooding are some of the most common moisture-related issues at these sites. The study done in Chapter 6 reinforces these observations with quantitative measurement of moisture in the field. A non-destructive microwave moisture measurement system (MMMS) was used to measure the spatial and temporal variation in moisture during the wet (Kiremt) and dry (Bega) seasons on the surface and subsurface of the rock walls. Comparative assessment of moisture distribution in the wet and dry seasons showed

that both surface and subsurface moisture increase in the wet season (Kiremt). During the dry season (Bega), there is a higher moisture presence near the surface than at depth. These characteristics of the moisture dynamics at Lalibela suggest that the drying front will shift seasonally, which leads salts to crystallise near the surface during the wet season and in the subsurface during the dry season. Swelling and shrinkage of clays will also shift seasonally along with the drying front. A complex multilayered decay profile is likely to occur as a result of these processes.

The exposure of the roofs to direct rainfall and lack of semi-impermeable foundation to retard the flow of moisture from groundwater uptake facilitates wetting of rock-cut structures during intense seasonal rainfall. Comparing a sheltered and unsheltered church in this study, it was possible to assess the efficacy of the shelters in preventing moisture ingress on the walls at Lalibela. The results showed that the unsheltered church had a higher moisture content. This study also showed that microwave moisture sensors are particularly well suited to investigate moisture distribution in homogeneous structures like rock-cut architecture and can be effectively applied to measure moisture in basaltic scoria.

In the church of Bete Golgotha, there are two sets of life-sized bas-reliefs on the north and south walls of the church. The bas-reliefs on the north wall have deteriorated and lost some of their surface details. Conversely, on the south wall, the carvings can be seen very clearly and are in a very good preservation state. Art historians have hypothesised that the reliefs are in different states because of poor workmanship or different date of carving. The bas-reliefs are in a similar lithological

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and environmental setting. To determine the cause of varying preservation states of the north and south walls, moisture distribution and salt distribution was measured non-destructively. Moisture distribution was measured using a combination of moisture measuring systems such as an electrical conductance technique that is sensitive to salts and a microwave system that is negligibly sensitive to salts. Salts were extracted via wetted paper pulp poultice and the salinity was measured in the lab. The electrical conductance readings and the concentration of salts was higher on the deteriorated bas-reliefs on the north wall. This suggests that the north wall has been damaged as a result of higher concentrations of salts. The source of salts for both the walls is mainly groundwater absorption throughout the drier periods and rain infiltration during the wet period. The north wall is > 5 meters thick, while the south wall is about 0.9 meters thick. Moisture content is higher in the north wall during the wet seasons as a result of higher absorption of groundwater through the thick wall and rain infiltration through the north wall. A higher flux of moisture on the north wall has led to a higher concentration of salts than on the south wall.

The investigation led to the conclusion that the localised deterioration at bas-reliefs in Bete Golgotha is driven by a higher presence of salts rather than as a result of the workmanship or age of the reliefs. Given the accelerated decay that is caused by contamination of salts in clay-rich substrates, high concentrations of salts will lead to significant deterioration of rock surfaces, as evidenced both by laboratory and field studies. Long-term monitoring of moisture and relative humid-

ity in the interior of the churches that have reliefs and mural paintings is essential to get a clearer understanding of the threat of moisture-driven decay processes on architectural ornaments at the threat of permanent loss.

9.4 History of Conservation: Lessons from Lalibela

- **Objective 4:** to conduct archival research on the history of conservation at Lalibela and assess the efficacy of traditional conservation techniques.

The present state of the churches at Lalibela is the result of historical weathering and various restoration efforts. Modern (20th and 21st century) restoration works at Lalibela have favoured one-off treatments that are not followed by monitoring campaigns. This is largely due to restorations being driven more by the availability of funding rather than a comprehensive strategic management plan. Traditional (before the 1920s) conservation techniques to restore the churches had a more sustainable approach. The church roofs were plastered with a mixture of mud and butter right before the start of the rainy season to prevent rain infiltration. During the rainy season, this layer of plaster would be fertile ground for plants such as grass to grow. This process would inadvertently create a soft cap which, as recent studies have shown, is an effective technique that serves both as a thermal blanket and prevents moisture ingress. At present, some of the churches have hard caps, and others have open shelters. So far, the efforts to preserve the churches have relied on a trial and error methodology that has significantly and negatively impacted the

churches. Reevaluation of traditional conservation techniques through a scientific lens may offer sustainable approaches to conservation at Lalibela. Based on the holistic understanding of the climatic, lithological, architectural and historical context set out in this study, a methodology to conserve the churches that builds on existing traditional knowledge is the best way forward.

9.5 Final remarks

This thesis explored various aspects of weathering of the rock-cut churches at Lalibela with the aim of paving a path toward a holistic methodology to understand weathering of rock-cut architecture. An approach based on a semi-natural sites framework can be effectively applied to identify the multi-scale processes that contribute to weathering of rock-cut structures. The landform scale environmental processes rock-cut structures are exposed to lead to more complex and dynamic contributors to weathering, such as geological discontinuities, surface runoff and flooding that are less common in built structures. The extent of exposure of the rock-cut structures or architectural form influences moisture-related weathering. The absence of impermeable roofs and foundations facilitates a higher flux of moisture, especially in tropical climates that experience intense seasonal rainfall. Vulnerability to moisture ingress and salt attack is exacerbated by conservation approaches that are not well suited for a low strength monolithic structures. Future work is needed to consolidate the knowledge on the management of rock-cut architecture that is at the

moment siloed geographically.

The insights presented in this research which benefits from field, laboratory and archival research can be applied to improve the management of the rock-cut churches at Lalibela. The study has shed light on the climatic drivers of weathering, moisture dynamics, lithological controls and response and the importance of re-evaluating traditional conservation techniques at Lalibela. It is hoped that the outcome of this research will benefit the development of a strategic plan for the conservation of these magnificent churches that embody the culture and spirituality of the community that protects them.

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Until the day of Your revelation Saint Lalibela's churches will not be lost nor quiver.

(Acts of Lalibela, [2018](#), p. 202)

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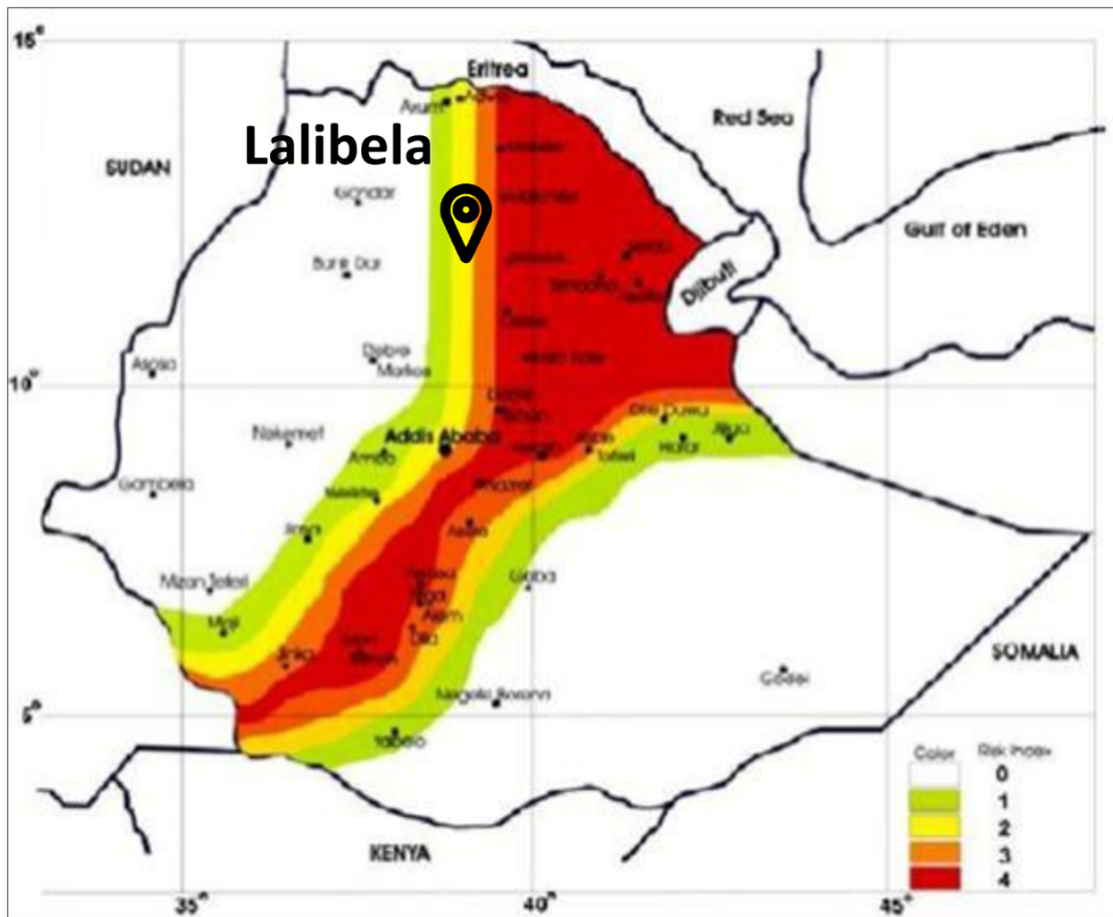
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Appendices

Appendix 1: Earthquake zones

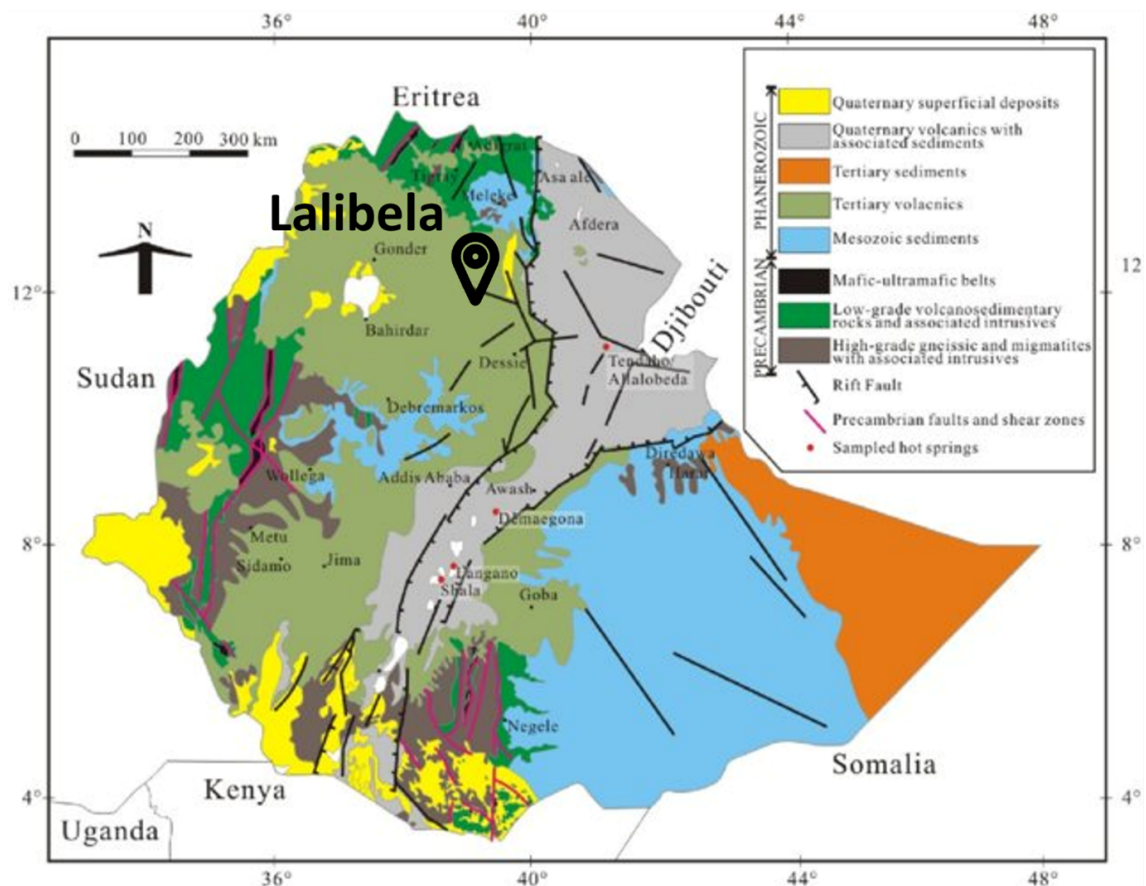
Earthquake hazard zone map of Ethiopia indicating that Lalibela is located in a grade 2 zone.



Source: Ethiopian Roads Authority

Appendix 2: Geological map of Ethiopia

Geological map of Ethiopia showing the Tertiary volcanic zone Lalibela is located in.



Source: Moon, D.-H., Kim, E.-J., Koh, S.-M. (2013). Occurrences of Hot Spring and Potential for Epithermal Type Mineralization in Main Ethiopian Rift Valley. *Economic and Environmental Geology*. The Korean Society of Economic and Environmental Geology. <https://doi.org/10.9719/eeg.2013.46.3.267>

Appendix 3: Supplementary material to Paper I

	Minimum			Maximum		
	P-value	R square	Slope	P-value	R square	Slope
Annual	0.00000476*	0.5287	0.037622	0.7514	-0.03312	-0.003338
Jan	0.002282*	0.2885	0.04061	0.139	0.04887	-0.02204
Feb	0.0008182*	0.3413	0.05247	0.3625	-0.005398	-0.01751
Mar	0.008296*	0.2026	0.04065	0.4733	-0.01711	-0.01576
Apr	0.003825*	0.2435	0.05161	0.3288	-0.000394	0.02551
May	0.07536	0.07957	0.02850	0.3815	-0.007503	-0.02169
Jun	0.04538*	0.1084	0.03485	0.4981	-0.01924	-0.01994
Jul	0.003224*	0.2523	0.03342	0.24	0.0156	0.02609
Aug	0.05204	0.1006	0.019264	0.5461	-0.02288	0.008333
Sep	0.09567	0.06862	0.02217	0.3059	0.003354	-0.01598
Oct	0.00004899*	0.4556	0.047897	0.4283	-0.01323	0.01249
Nov	0.004617*	0.2337	0.03919	0.2561	0.01222	-0.02881
Dec	0.003928*	0.2504	0.030306	0.003051*	0.2638	-0.04099

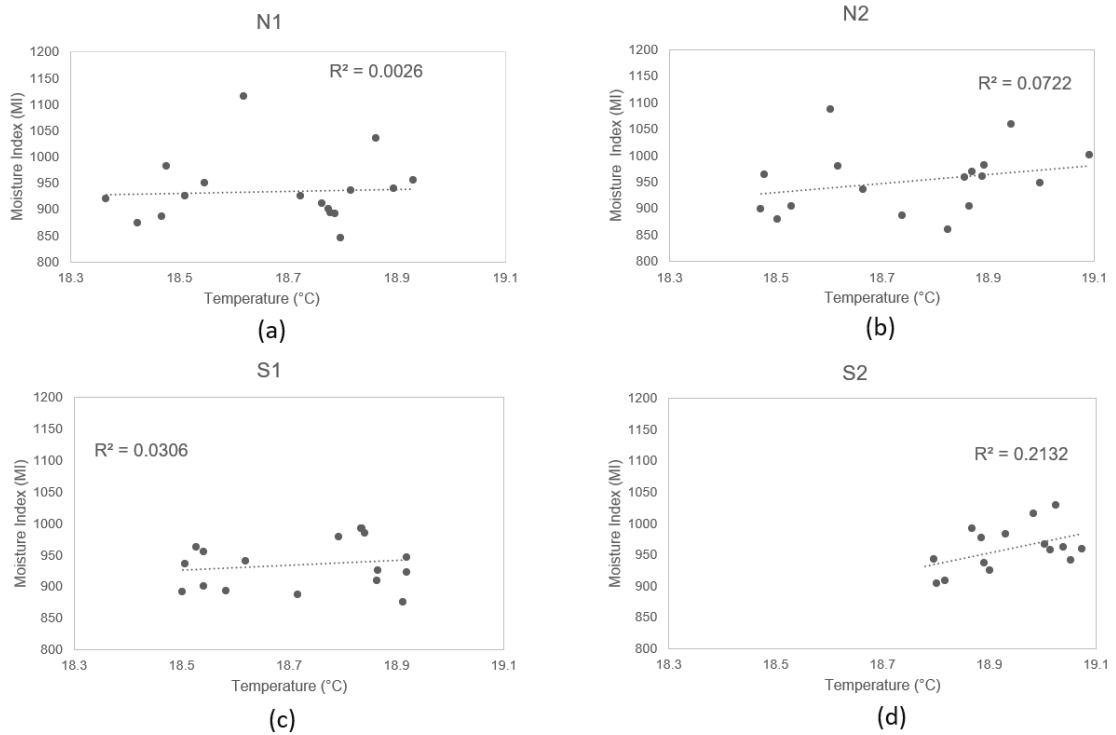
Linear regression analysis of 29-year of trends in minimum and maximum temperatures. Asterix indicate significant p-values.

Appendix 4: Supplementary material to Paper II



Rock outcrop from which samples Type A and Type B were extracted. Yohannes Amba quarry located near the church complex in Lalibela.

Appendix 5: Supplementary material to Paper IV



Correlation of MMMS and IRT measurements taken on the north and south bas-reliefs in Bete Golgotha. There isn't a strong correlation between surface moisture (MMMS) and heat distribution (IRT) in the north or south reliefs.

Appendix 6: Additional moisture measurement data

Height	Surface				Subsurface			
	North		South		North		South	
	wet	dry	wet	dry	wet	dry	wet	dry
cm								
15	911	956	914	923	1437	1637	1223	1475
30	905	939	995	876	1486	1610	1493	1524
45	860	1036	941	946	1555	1464	1494	1349
60	1064	936	1021	909	1547	1449	1475	1386
75	994	901	1040	985	1620	1257	1524	1468
90	981	891	1027	992	1623	1409	1494	1417
105	931	845	992	926	1617	1155	1489	1499
120	1010	894	983	992	1641	1357	1389	1477
135	1017	911	1047	979	1619	1472	1578	1484
150	1152	926	1101	888	1604	1445	1656	1304
165	1138	1115	1089	941	1760	1470	1575	1373
180	1126	951	1070	955	1697	1415	1520	1490
195	1056	925	1061	962	1590	1516	1651	1447
210	1108	982	1089	936	1671	1539	1576	1422
225	1170	887	1025	892	1650	1509	1647	1393
240	1074	874	895	900	1666	1583	1446	1266
255	1024	920	1038	894	1767	1579	1500	1354
mean (MI)	1030.65	934.65	1019.29	935.06	1620.59	1462.71	1513.53	1419.29
% saturation	17.29	8.97	16.30	9.01	22.98	8.27	13.00	4.22

Moisture measurements taken on the bas-reliefs at Bete Golgotha during the wet and dry seasons. Moisture measurements taken using the Moist 350 B (hf Sensor GmbH) surface (3 cm) and subsurface probe (25 cm).

Appendix 7: Co-author statements

Professor Heather Viles

As a co-author on the publications (published or in preparation) listed below, I confirm that the first author **Blen Taye Gemed**a has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Taye Gemeda, B. & Viles, H. (2022) Implications of climatic variability for the nature and rate of weathering of rock-cut churches in northern Ethiopia. In Review

Taye Gemeda, B., Viles, H. & Orr S.A. (2022) Seasonality in moisture dynamics in the walls of rock-cut churches at Lalibela, Ethiopia: Implications for weathering. In Review

Taye Gemeda, B., Viles, H. & Zhang, H (2022) Influence of salts in hydric and hygric dilatation of clay-rich rocks. In Review

Taye Gemeda, B., Fusade L. & Viles, H. (2020) Efficacy of traditional conservation methods for the protection of rock-cut heritage sites: Lessons from Lalibela, Ethiopia. In, Siegesmund, S. and Middendorf, B. (Eds.). 14th International congress on the deterioration and conservation of stone (pp. 687-692).

Taye Gemeda, B., Viles, H., Giorghis, F., & Sifir, F. (2019). Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-cut bas-reliefs at Bete Golgotha, Lalibela (Ethiopia). In, Hyslop, E., Gerdwilker, C. and Gonzales, V (Eds). Monuments in Monuments. Historic Environment Scotland. (pp. 43-52).

<https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-aabc00ab0e4e>

Heather Viles, Professor of Professor of Biogeomorphology and Heritage Conservation,
University of Oxford

Signature:



Date:24/3/2022.

Associate Professor Fasil Giorghis

As a co-author on the following publication, I confirm that the first author **Blen Taye Gameda** has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Taye Gameda, B., Viles, H., Giorghis, F., & Sifir, F. (2019). Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-cut bas-reliefs at Bete Golgotha, Lalibela (Ethiopia). In, Hyslop, E., Gerdwilker, C. and Gonzales., V (Eds). Monuments in Monuments. Historic Environment Scotland. (pp. 43-52). <https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-aabc00ab0e4e>

Fasil Giorghis, Associate Professor at the Ethiopian Institute of Architecture, Building Construction and City Development, Addis Ababa University

Signature:  Date: *March 31, 2022*

Hong Zhang

As a co-author on the following publication, I confirm that the first author **Blen Taye Gemed** has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Taye Gemed, B., Viles, H. & Zhang, H (2022) Influence of salts in hydric and hygric dilatation of clay-rich rocks. In Review

Hong Zhang, Research Technician, School of Geography and the Environment, University of Oxford

Signature: *Hong Zhang* Date: *24.03.22*

Fkereselase Sifir

As a co-author on the following publication, I confirm that the first author **Blen Taye Gemed** has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Taye Gemed, B., Viles, H., Giorghis, F., & Sifir, F. (2019). Using portable moisture meters and paper pulp poultice to investigate moisture and salt distribution in rock-cut bas-reliefs at Bete Golgotha, Lalibela (Ethiopia). In, Hyslop, E., Gerdwilker, C. and Gonzales., V (Eds). Monuments in Monuments. Historic Environment Scotland. (pp. 43-52). <https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-aabc00ab0e4e>

Fkereselase Sifir (co-author)

Signature:



Date:

24/03/2022

Dr Scott Allan Orr

As a co-author on the publications (published or in preparation) listed below, I confirm that the first author **Blen Taye Gemed**a has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Taye Gemeda, B., Viles, H. & Orr S.A. (2022) Seasonality in moisture dynamics in the walls of rock-cut churches at Lalibela, Ethiopia: Implications for weathering. In Review

Scott Allan Orr

Lecturer in Heritage Data Science

UCL Institute for Sustainable Heritage

Signature: 


Date: 4 April 2022

Dr. Lucie Fusade

As a co-author on the following publication, I confirm that the first author **Blen Taye Gemed**a has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Taye Gemeda, B., Fusade L. & Viles, H. (2020) Efficacy of traditional conservation methods for the protection of rock-cut heritage sites: Lessons from Lalibela, Ethiopia. In, Siegesmund, S. and Middendorf, B. (Eds.). 14th International congress on the deterioration and conservation of stone (pp. 687-692).

Dr Lucie Fusade, (Conservation officer; Dorset Council)



Signature: ..

.... Date: ...29/03/2022.....