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# Geological and Geomechanical Properties of Abraha-Atsibha and Wukro rock-hewn churches and its surroundings, Tigray Region, Northern Ethiopia

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**ABSTRACT**

Globally well-known ancient rock-hewn churches are present in Ethiopia in general and particularly in the central and eastern parts of Tigray regional state. They are important sites of heritage and tourism. Most of them are facing destabilization problem in different degree due to natural and anthropogenic factors. Among the affected, two churches hewn into sandstone located near Abreha-Atsibaha and Wukro (Kirkos/Cherkos church) in Tigray region were chosen for detailed study in terms of geological and engineering geological condition of the rocks in to which they are hewn. Both of them are affected by weathering and seepage. Both are carved into Mesozoic Adigrat sandstone that occupy higher elevations in topography, red in color and with iron and silica-rich alternating bands. Petrographic data suggest that the rock is dominated by quartz followed by feldspars; opaque and heavy minerals; pore spaces and carbonate/iron/silica cement. The rock is characterized by low to medium unconfined compressive strength. The alternating bands with varying mineralogical composition differ in mechanical properties and are responding differently to weathering and erosion. This is resulting in the development of minor spalling, pitting etc in the pillars, walls and roofs of the churches. Keeping the geological condition in view remedial measures are to be planned to minimize deterioration with time.

**Keywords:** Geological, Geomechanical, Rock hewn-Church, Abraha-Atsibaha, Tigray, Ethiopia.

## 1. INTRODUCTION

Ethiopia is one of the few countries in the world, known for its ancient rock-hewn churches that are carved into rocks. Several of these churches are located in northern Ethiopia particularly in the central and eastern zones of Tigray Regional State. Though, no accurate date exists, most of them are assumed to be flourished during the Medieval Period, with only some exceptions probably dating back to the Axumite period (Gobezie, 2004; Asrat et al., 2009). Rock-hewn tradition in Ethiopia is supposed to be associated with the coming of the Nine Saints from Egypt and Syria in late fifth and early sixth centuries (Ethiopian Orthodox Church, 1997;Asrat et al., 2009).More than 100 rock-hewn churches of different ages, sizes, and with their own history are found around Atsbi, Hawzen-Ger'alta, Sinkata-Adigrat and Tembien (Asrat, 2002).

In Tigray, these rock-hewn churches are made by carving into the rocks or by converting the naturally developed caves. These are closely connected with the twin kings known as Abraha-Atsibaha, and are believed to have been constructed in 4th century AD (Ethiopian Orthodox

Church, 1997).One of the historical rock-hewn churches is Abreha-Atsibha church which is located 15km west of Wukro town. Most of the churches including the Abraha-Atsibahaare carved into sandstone belonging to either Adigrat orEnticho sandstone. However, recent geological and geomorphological studies (Gobezie, 2004; Asrat and Ayalew, 2011) have shown that the considerable numbers of churches are undergoing deterioration, some of them seriously, due to weathering, seepage, discontinuities, landslides etc. The degree of weathering and erosion in most of the cases is related to the discontinuities (cracks, fissures, joints) that facilitate seepage and weathering apart from landslides.

The geological structures being static in a given geological environment they are subjected to natural dynamic processes and rapid changes in the landscape evolution and urban developmental activities. Recent experiences indicate that many worldwide known rock-hewn churches, monuments and heritage landscapes were destroyed by geological and human induced factors (Lollino and Audisio, 2006; Asrat and Ayalew, 2011; Lee et al., 2011; Paolini et al., 2012; Bala'awi and Mustafa, 20017; Margottini et al., 2017).

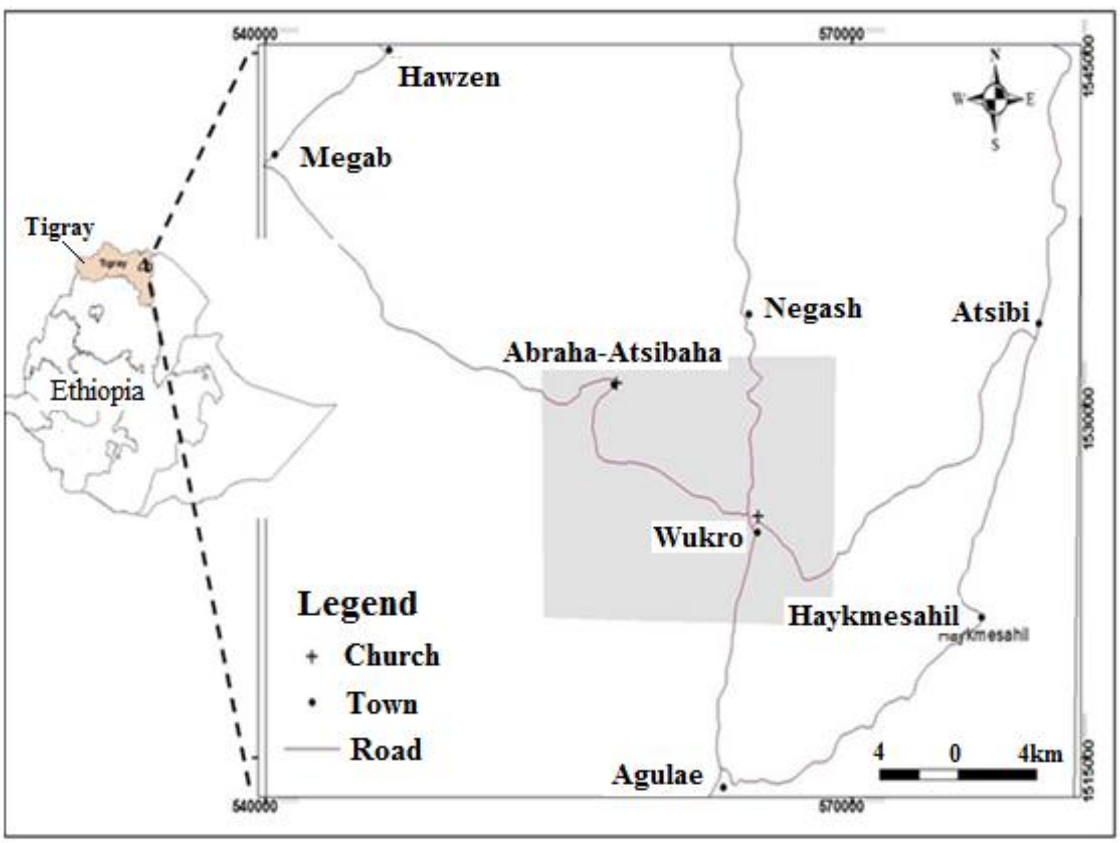


Figure 1. Location map of study area.

This has resulted in the destruction of innumerable historical properties and museums that hold the history of humanity within their walls. Typical examples of such hazards affecting cultural heritages are prolonged weathering of the stones in Petra monuments (Jordan), destruction due to earthquake in Bam in Iran in 2003, destruction of Bamiyan Buddhas by Talibans in Afghanistan in 2001, structural damages due to settlements to Angkor Temples in Cambodia, collapse of building in Pompei in Italy and many others worldwide (Lollino and Audisio, 2006; Paolini et al., 2012).

Keeping the importance of these heritage and tourist sites in view, a detailed geological and geomechanical study was conducted on the rocks of both Abraha-Atsibaha and Wukro kirkos/ Cherkos churches (Fig 1) and its surroundings and the results are presented in this paper.

## 2. METHODOLOGY

A reconnaissance survey was first carried out around Abraha-Atsibaha and Kirkos/Cherkos which are part of the Geralta Mountains, along Wukro-Negash - Sinkata and Atsibi areas to see the distribution and condition of 12 rock-hewn churches. Seven of them including Abraha-Atsibaha and Cherkos churches are carved into Adigrat sandstone while others into Enticho sandstone.

Detail fieldwork was conducted around Abraha-Atsibaha and Wukro Kirkos/Cherkos to assess the geological setting. Detail and systematic measurement of discontinuities (spacing, aperture, and orientation) is performed following ISRM (1981) recommendations at the surface exposures of both Adigrat and Enticho sandstones around both the churches.

Seven representative rock samples (4from Adigrat sandstone and 4 from Enticho sandstone) were selected for petrographic study. 752 Schmidt hammer measurements were taken at various localities in the study area to estimate the unconfined compressive strength (UCS) of rocks exposed within and around Abraha-Atsibaha and Wukro Kirkos/Cherkos churches. Out of these, 433 are for Adigrat sandstone, 257 for Enticho sandstone and 62 for Antalo limestone which is overlying Adigrat sandstone. The UCS of the rocks was estimated from Schmidt hammer rebound number following the methods suggested by ISRM (1978).

Geomechanical characteristics of the rock masses such as RQD and RMR were estimated using the measured discontinuity and Schmidt hammer data. Moreover, the rock mass engineering properties such as rock mass strength, deformation and permeability of the sandstones were also estimated. In the study area, RQD is estimated from the number of joints (discontinuities) per unit volume (Jv) collected in the field.

## 3. GEOLOGICAL SETTING

The geology of northern Ethiopia is comprised of low grade Neoproterozoic basement rocks followed by Paleozoic and Mesozic sedimentary rocks and Cenozoic volcanics. Mesozoic sedimentary succession is unconformably overlying the Paleozoic sedimentary rocks and at places the basement rocks, forming about 8000km$^2$areas around Mekelle (Beyth, 1972). The stratigraphic sequence of the rocks of northern Ethiopia is summarized as: Flood basalts, Amba-Aradom Sandstone Formation, Antalo Super Sequence, Adigrat Sandstone Formation, Edaga-ArbiTillites, Enticho Sandstone Formation, and metavolcanic & metasedimentary basement rocks. Among these, major geological units present in the study area include the low grade basement rocks followed by Edaga-Arbi Tillite, Enticho Sandstone of Paleozoic; and Adigrat Sandstone, Antalo Limestone, and Agulae Shale of Mesozoic age. Brief description of the sandstones and the overlying limestone and shale is given hereunder.

### 3.1. EntichoSandstone and Tillite

Enticho sandstone shows white color on fresh surface and grey to brown color on weathered surface. It is poorly sorted and consists of fine to coarse grain size texture (some places pebblesize), with silica cement and at places shows development of laterite. It is characterized by big cross-bedding sedimentary structures indicating paleo-current directions. Tillite on the other hand, is almost unsorted with the grain sizes varying from clay to boulder size. Presence of fine grained siltstone and clays tone layers together with coarse at places boulders of granite indicate fluvio-glacial depositional process. Striations present in minerals within the boulders further indicate the direction of glacial flow. The rock shows bands or layers of clays tones, mudstones, siltstones with different colors, varves are also common with variegated colors (Bosellini et al., 1997; Dow et al., 1971). Edaga-ArbiTilliteis inter-fingered with Enticho sandstone and underlies Adigrat sandstone. This rock unit covers very small area compared to other rocks and is mainly exposed in the northern part of the study area (Fig 2).

### 3.2. Adigrat Sandstone

Adigrat sandstone, Mesozic in age, underlies Anatlo limestone and overlie Tillite and Enticho sandstone rocks. The rock shows red color, massive, thickly bedded with ripple marks and cross-bedding structures. It shows fine to medium grained clastic texture with well sorted grains. The color generally varies from red at the bottom of the strata to grey color at the top with decreasing amount of iron and increasing amounts of silica with intercalated fine grained layers of siltstones/clay stones. The rock is dominated by quartz mineral over other clastic grains (Fig 3) and is exposed in north, northeast and southeast parts of the study area.

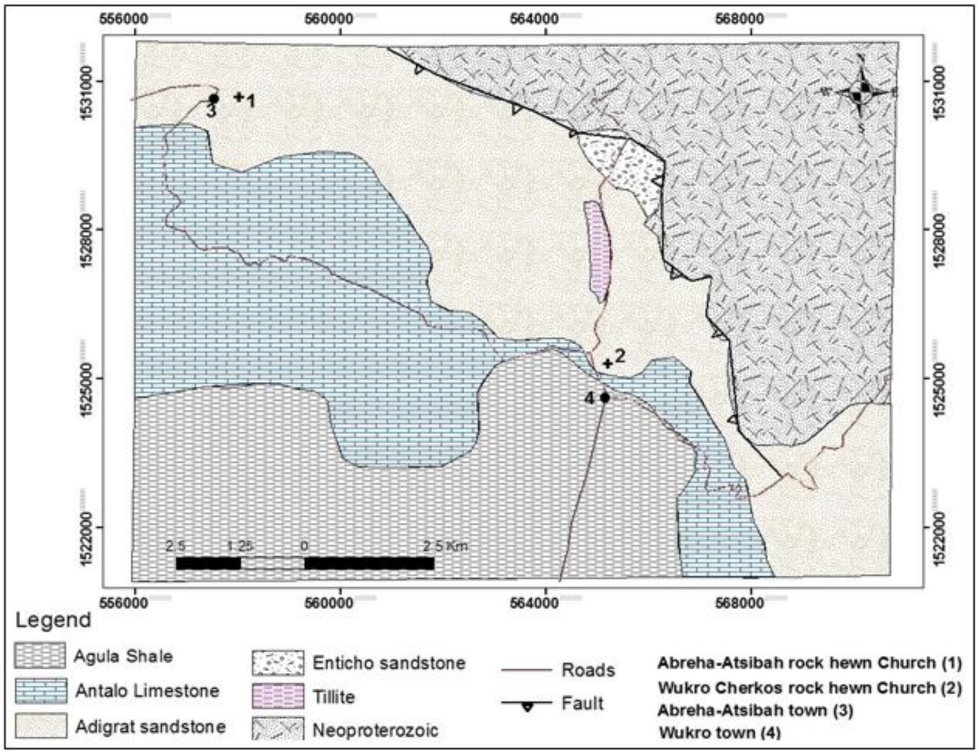


Figure 2. Geological map of the study area.

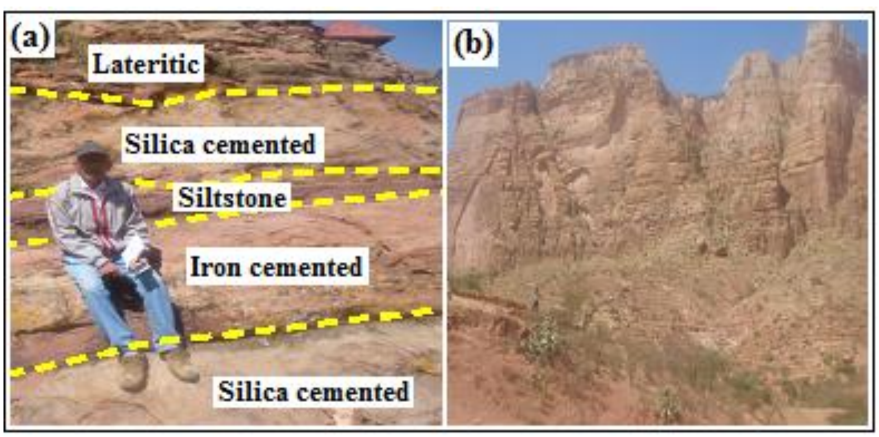


Figure3.Adigrat sandstone a) silica and iron cement dominated layers adjacent to Abraha-Atsibaha church; b) cliff forming Adigrat sandstone with well- developed fractures at Mariam Korkor area near Abraha-Atsibaha.


Figure 4. a) Microcrystalline limestone, and b) karst development in limestone.

### 3.3. Antalo Limestone

It covers northwestern part of the study area (Fig2) and is intercalated with shale and marl units. Its color varies from white to yellow, and shows micrtic to medium grain texture. Being dominated by calcite mineral, dissolution cavities and karsts topography development is common as a result rock-water interaction (Fig 3). Different types of limestone rocks are observed namely, microcrystalline, karstic and fossiliferous (e.g. gastropods, bivalves, brachiopods and coral reefs) (Bosellini et al., 1997).

### 3.4. Agulae Shale

Agulae shale overlies Antalo limestone and is widely exposed in the south and southwestern parts of the study area. It shows yellow color with fine grained texture and fissile nature. The loose and unconsolidated nature of the shale forms gentle slope topography. Marl and gypsum layers are also found associated with shale.

## 4. RESULTS

### 4.1. Petrography of sandstones

The rock-hewn churches under study though, are carved into Adigrat sandstone, both Adigrat and the Enticho sandstones were examined for mineral composition under transmitted light microscope. Petrographic details of Adigrat sandstone are shown in figure 5.

Petrographic data indicate that the Adigrat sandstone is composed of quartz (57-60%), orthoclase and plagioclase feldspars (12-20%), opaques and heavy minerals (~3%), and pore spaces (~5%).

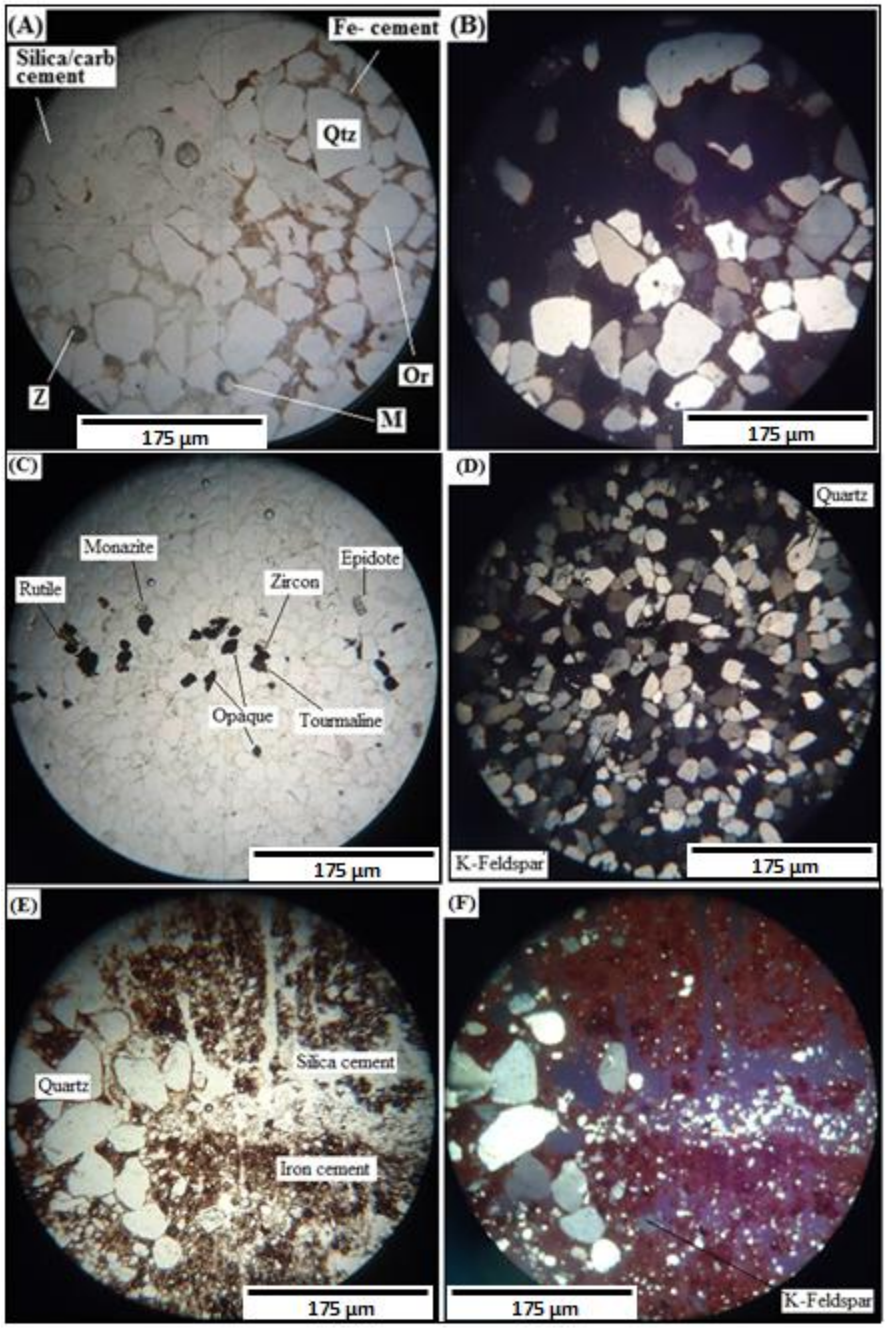


Figure 5. Microphotographs of Adigrat sandstone from Abraha-Atsibaha (40x); (A) red colored sandstone in PPL and (B) in XPL showing irregular to sub-rounded quartz (Qtz), irregular to rectangular orthoclase feldspar (Or), grains of monazite (M) and zircon (Z), and major part of the pore spaces are occupied by the iron (minor) and silica/carbonate (major) cement; (C) yellowish white sandstone in PPL and (D) in XPL, showing fairly sorted quartz dominated sandstone with K-feldspar and opaques and heavy minerals, rutile, zircon, monazite, epidote and tourmaline; (E) ferruginous sandstone with siltstone layer in PPL and (F) in XPL, showing iron oxide/hydroxide and silica cement with not well sorted quartz grains.

Its cementing materials include silica (2-15% and iron oxide (2 -10%). The Adigat sandstone also has thin layers of silicified siltstone which consists of iron oxide (~50%), quartz (~25%), orthoclase feldspar (~3%) and silica cement (~20%). Some of the siltstones layers are also present with iron rich cementing material.

Enticho sandstone on the other hand is composed of quartz (40-65%), K-feldspar and plagioclase (11-20%), lithic fragments (3-20 %), opaque and heavy minerals (0-5%), pore spaces (5-7%), silica and iron cement (15-20%). Mostly the rock is dominated by silica cement but at places by iron cement.

## 4.2. Geomechanical characterization of the rock mass

### *4.2.1. Discontinuity data*

The mechanical properties of the rock mass are obviously influenced by the presence of discontinuities and their characteristics. Discontinuity data such as joint spacing, opening, orientation, and their condition (infill material and roughness).The knowledge of joint characteristics is important to study the rock slope stability, water leakage and as an input for the calculation of rock mass rating values.

Table1. Discontinuity data measured at the various lithologies exposed around Abraha-Atsibaha and Wukro Kirkos/ Cherkos churches.

| *Lithology* | *Joint set* | *dip amount* | *Strike* | *Av. Spacing (cm)* | *Av. opening (mm)* | *Roughness* | *Persistence ( m)* |
|---|---|---|---|---|---|---|---|
| Adigrat sandstone | J1 (nearly N-S) | vertical-sub vertical | N-S | 223 | 1-5 | rough , undulating | 1-3 |
| | J2 (strike E-W) | vertical-sub vertical | E-W | 305 | < 1 | rough , undulating | 1-3 |
| | J3 (strike NW-SE) | vertical-sub vertical | NW-SE | 50 | < 1 | rough , undulating | < 1 |
| Enticho sandstone | J1 (nearly N-S) | sub vertical | N-S | 296 | >5 | rough | 1-3 |
| | J2 ( strike E-W) | sub vertical | E-W | 144 | <0.5 | rough | 1-3 |
| Limestone | J1 (strike N-NE) | sub vertical | N-NE | 49 | 1.6 | rough | 1-3 |
| | J2 (nearly E-W) | sub vertical | E-W | 98 | 2 | rough | < 1 |

Two to three major joint sets observed in different exposures in the study area were measured and the data is given in table 1 and their trends are shown in figure 6.It is common to see the rock falls of different sizes at the cliff forming Adigrat sandstone and Antalo limestone rocks units following the intersection of these joint sets. For example, wedge failure is common at the intersection of J2 and J3 at the sandstone cliffs (Fig 3b). Similarly, the characteristics of the major discontinuities (e.g. spacing, opening, joint condition) present in Adigrat sandstone, Enticho sandstone and Antalo limestone were collected and analyzed from the surface exposures and used in the RMR systems. These are the discontinuities that are facilitating mobility of rainwater or groundwater i.e. seepage into these churches.

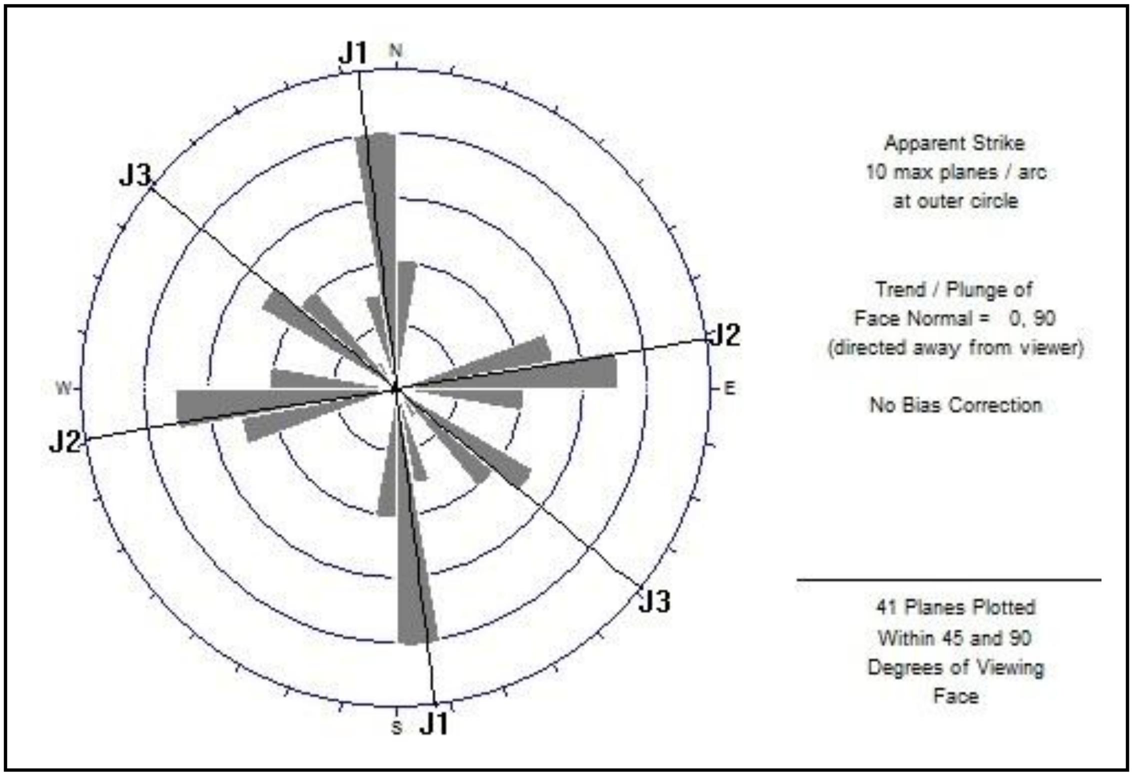


Figure 6. Rose diagram showing the trend of joints in the rock exposures (n = 41).

### *4.2.2. Uniaxial compressive strength (UCS)*

Schmidt hammer rebound test is used to measure where a number of readings were taken in the field. As suggested by ISRM (1978), the readings were ordered in increasing order of magnitude and the first five minimums dropped, and the mean of the last five maximums is taken as representative of the Schmidt hammer rebound test. The UCS is taken from the established correlations of the hardness number against uniaxial compressive strength chart. The value of compressive strength is obtained from the Deer-Miller graph showing its dependence on the rock strength found from the Schmidt hammer measurements as shown in figure 7.Based on the above procedure, the UCS for Adirat sandstone, Enticho sandstone and Antalo limestone were calculated and results are given in table 2.

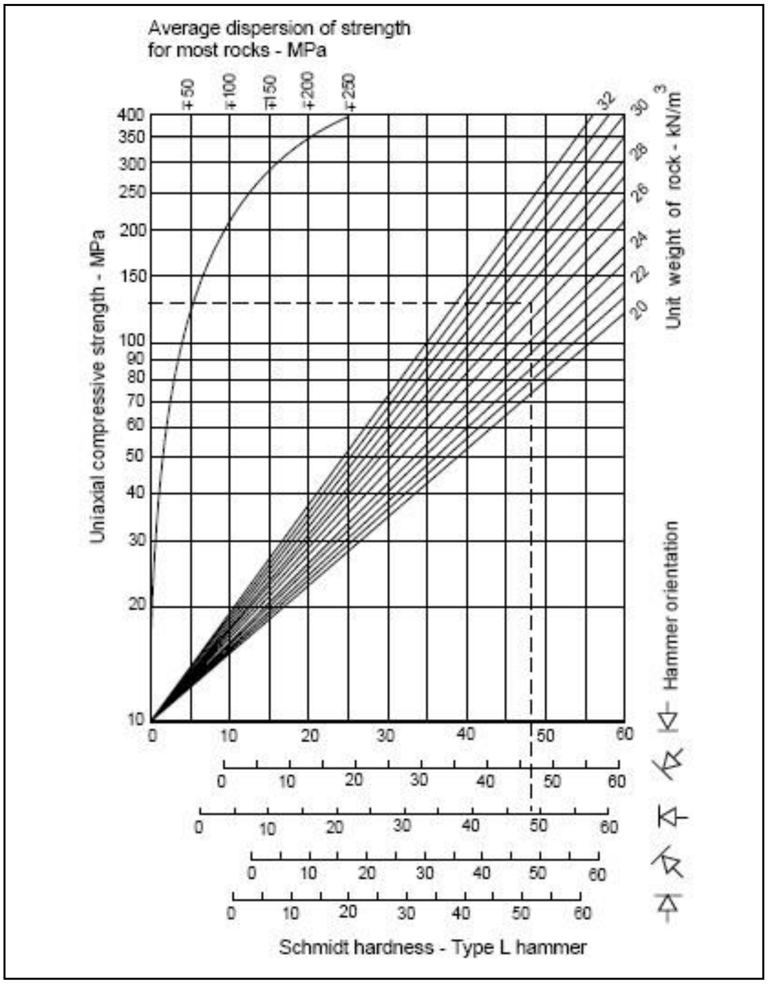


Figure 7. Graph used to convert the Schmidt hammer rebound number to UCS of rocks.

Table 2. L-typeSchmidt hammer reading VS corresponding UCS (MPa).

| ***Lithology type*** | ***Schmidt hammer reading*** | | | ***UCS (MPa)*** | | |
|---|---|---|---|---|---|---|
| | ***Min.*** | ***Max.*** | ***Average*** | ***Min.*** | ***Max.*** | ***Average*** |
| Adigrat Sandstone (red color with iron cement) | 30 | 47 | 35.5 | 38 | 86 | 51.2 |
| Adigrat Sandstone (red color, fine silica cement) | 32 | 46 | 39.4 | 42 | 85 | 57.9 |
| Adigrat Sandstone (white) | 28 | 47 | 32.6 | 35 | 90 | 45.2 |
| Enticho Sandstone | 26 | 45 | 36.8 | 33 | 82 | 53 |
| Antalo Limestone | 53 | 60 | 56.2 | 150 | 240 | 195.8 |

Table 3. Volumetric joint count (Jv) measurements from joint sets observed in a rock surface.

| ***Rock type*** | ***Joint sets*** | ***Variation of joint set spacing and frequency*** | | | | ***Average spacing (m)*** | ***Average frequency (m)*** |
|---|---|---|---|---|---|---|---|
| | | ***Min. spacing (m)*** | ***Max. spacing (m)*** | ***Max. frequency*** | ***Min. frequency*** | | |
| Adigrat sandstone | J1 | 1.3 | 4.2 | 0.77 | 0.24 | 2.75 | 0.36 |
| | J2 | 0.2 | 4.6 | 5 | 0.22 | 2.4 | 0.42 |
| | J3 | 0.3 | 0.7 | 3.33 | 1.43 | 1 | 1 |
| | 3 random joints | 5* | | 0.6 | 0.6 | - | 0.6 |
| | **Jv = Σfrequencies** | | | **9.7** | **2.5** | **-** | **2.4** |
| Enticho sandstone | J1 | 1.15 | 2.2 | 0.87 | 0.46 | 1.675 | 0.67 |
| | J2 | 0.7 | 5 | 1.43 | 0.2 | 2.85 | 0.815 |
| | 2 random joints | 5* | | 0.4 | 0.4 | - | 0.4 |
| | **Jv = Σfrequencies** | | | **2.7** | **1.1** | **-** | **1.9** |
| Limestone | J1 | 0.35 | 0.6 | 2.9 | 1.7 | 0.48 | 2.3 |
| | J2 | 0.4 | 1.05 | 2.5 | 0.95 | 0.725 | 1.725 |
| | 3 random joints | 5* | | 0.6 | 0.6 | - | 0.6 |
| | **Jv = Σfrequencies** | | | **6.43** | **3.25** | **-** | **4.84** |

***Note***: 5* (spacing of random joints).

### *4.2.3. Rock quality designation (RQD and Rock Mass Rating (RMR) system*

RQD is estimated from the number of joints (discontinuities) per unit volume (Jv) collected in the field survey as there is no core drill data. The relationship used to convert Jv in to RQD for clay-free rock masses is (Palmstrom, 1982) as per equation 1.1 and results are summarized in table 5.

$$RQD = 115 - 3.3J_v \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1.1$$

(RQD = 0 for $J_v > 35$, and RQD = 100 for $J_v < 4.5$)

Where $J_v$ represents the total number of joints per cubic meter or the volumetric joint count

$$J_v = \frac{1}{S1}+\frac{1}{S2}+\frac{1}{S3}+\cdots\frac{1}{Sn}+N_{r}/(5\sqrt{A}) \dots\dots\dots\dots 1.2$$

Where:

- $S_1$, $S_2$ and $S_3$ are the average spacing for the joint sets
- Nr is the number of random joints in the actual location and A is the area in m²

Accordingly the volumetric joint count (Jv) of Adigrar sandstone, Enticho sanstone and Limestone are calculated from the field joint observations and measurements using equation1.2 and results are provided in table 3.

The degree of jointing of the rocks can be described following that of Palmstrom (1982) classification of the volumetric joint count (Table4). The average calculated Jv values of Adigrat sandstone, Enticho sandstone and limestone are 2.4 and 1.9 respectively and that of limestone is 4.84. Accordingly, RQD values of the both sandstones are 100 because their Jv values are less than 4.5 while that of limestone is 98.8. This high value of RQD is attributed to weakly jointed nature of the rocks (low Jv values) (Table 4).

Table 4. Classification of the volumetric joint count (JV) (after Palmström, 1982).

| ***Terms for jointing*** | ***Terms for JV*** | ***JV*** |
|---|---|---|
| massive | extremely low | < 0.3 |
| very weakly jointed | very low | 0.3-1 |
| weakly jointed | low | 1-3 |
| moderately jointed | moderately high | 3-10 |
| strongly jointed | high | 10-30 |
| very strongly jointed | very high | 30 - 100 |
| crushed | extremely high | > 100 |

Table 5. Summary of results of UCS, RQD and RMR values.

| ***Lithologies*** | ***Average UCS (Mpa)*** | ***RQD*** | ***RMR*** | ***Rock mass class as per Bieniaswki (1989)*** |
|---|---|---|---|---|
| Adigrat Sandstone | 51 | 100 | 67 | Class II (Good quality) |
| Enticho Sandstone | 53 | 100 | 82 | Class I (Very Good quality) |
| Antalo Limestone | 195 | 98.8 | 74 | Class II (Good quality) |

Rock mass classifications form the back bone of the empirical design approach and are widely employed in rock engineering (Singh and Goel, 1999). Among many of the geo-mechanical systems, Rock Mass Rating (RMR) system proposed by Bieniawski (1989) is used to characterize the rock mass nature rocks of the study area. In this work the six input parameters of RMR namely UCS of intact rock, RQD, spacing and condition of discontinuities, groundwater condition and orientation of discontinuities were readily collected and determined in the field using Schmidt hammer, Geological compass and meter tapes. In calculating the RMR values of the rocks, the joint characteristics with worst scenario are considered. Accordingly, the RMR values of Adigrat and Enticho sandstones and Antalo limestone is calculated (Table 5).

## 5. DISCUSSION

According to Bieniaswki (1973), a rock is said to be very low strength if its UCS value is <25MPa; between 25 to 50Mpalow strength; 50 to 100 MPa medium strong; if its value lies between100 and 250 Mpa high strength; and>250Mpais very high strength**.** From this perspective, the strength of both Adigrat and Enticho sandstones vary from very low strength to medium strength (Table 2). Statistically, 45 % and 55% of the Adigrat sandstone falls in the low and medium strength ranges while 33 % and 67% of the Enticho sandstone lies in the low and medium strength value ranges respectively. Similarly, analyzed strength results of limestone showed that its UCS varies from 160 to 240, which is of high strength rock as it is very crystalline rock. The strength of the limestone is three times higher than that of the sandstones (Table2) and Enticho sandstone relatively shows higher strength than Adigrat sandstone (Fig 8). From excavation point of view, it is relatively easier to manually excavate in the two sandstones than in the limestone. This could be one of the reasons why all rock churches in the study area are found in both sandstones but none in other rock out crops.

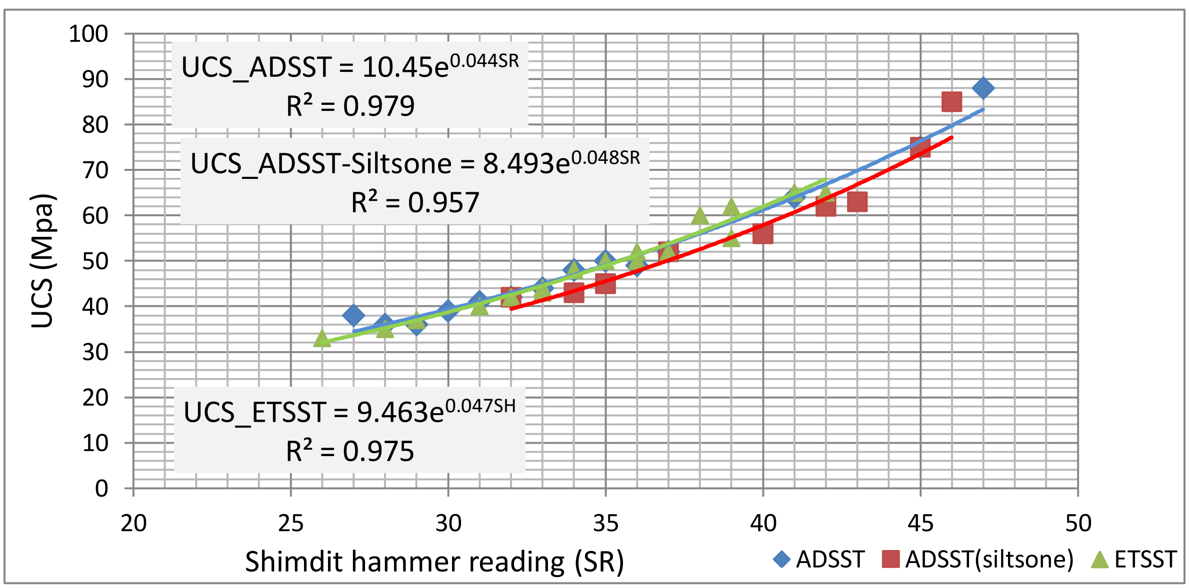


Figure 8. Relation of UCS to Schimidt hammer rebound test for rocks of the study area.
***Note***: ADSST =Adigrat sanstone; ETSST = Enticho sandstone.

Refering to the calcuated Jv values (Table 3), Enticho sandstone has the lowest Jv value (1.9) followed by Adigrat sandstone (2.4) and limestone (4.84) .This according to table 4 suggests that bothe the Adigrat sandstone and Enticho sanstone fall in the low range (between 1-3) and limestone falls in the moderately high Jv value ( between 3-10) . That is, both sanstones are more massive (least fractured) than that of limestone. Similarly, the calculated RQD values of Adigrat sandstone (RQD =100%), Enticho sandstone (RQD =100%) and limestone (98.8) put them in the range of excellent rock quality as per Deere (1968). According to Deere (1968), high RQD idicates that the spacing of discontinuities is wider while low RQD values indicate that the rock is characterized by itensive and close fracture. RMR values indicated in table 5 also suggests that the Adigrat and the limestone are characterized as good rock quality while that of Enticho sanstone is very good quality rock mass behavoiur.

Enticho sandstone is characterized by a) by quartz and nearly uniformly cemented by silica (15%); (b) low strength (~33%) to medium strength (~ 67%) unconfined compressive strength; and c)excellent RQD values and very good RMR values. Data suggest that the rock-hewn churches excavated in Enticho sandstones are relatively in a better position weathering and spalling.

Petrographic analysis of both Enticho and Adgrat sandstone though shows more or less similar mineralogical composition except in their cementing material and intercalated fine grained layers. Adigrat sandstone is characterized by (a) alternating bands of iron and silica cementing material (Figs 3 and 5); and (b) low to medium unconfined compressive strength. This means that the layers having different mechanical strengths respond differently to the surface processes i.e. the leaching of the cement. It is generally observed that iron is stable in the surface environment as iron hydroxide and produced lateritic layers. While silica is mobile in alkaline environments and remain stable in the normal pH conditions. Further, the response of thin layers of siltstones will be different from the sandstone as such. So, the iron rich siltstones layers and sandstone with iron cement seems to be relatively more liable to weathering compared to the silica cemented ones. Because of this it is common to see differential weathering in the cliffs and ridges of Adigrat sandstone exposed around Abraha Atisbaha and Wukro areas (Figs 1 and 2). Abraha-Atsibaha and Wukro Kirkos/Cherkos rock-hewn churches are carved into the Adigrat sandstone with both the iron cemented and silica cemented beds. Thus, it is common to observe different degree of spalling, pitting and discolorations in the interior parts of the pillars, walls and roofs of the churches (Fig 9a and b). This clearly suggests that the continuity of weathering of this nature if continues for long periods of time will deteriorate the rocks in the walls etc and ultimately affect these churches.

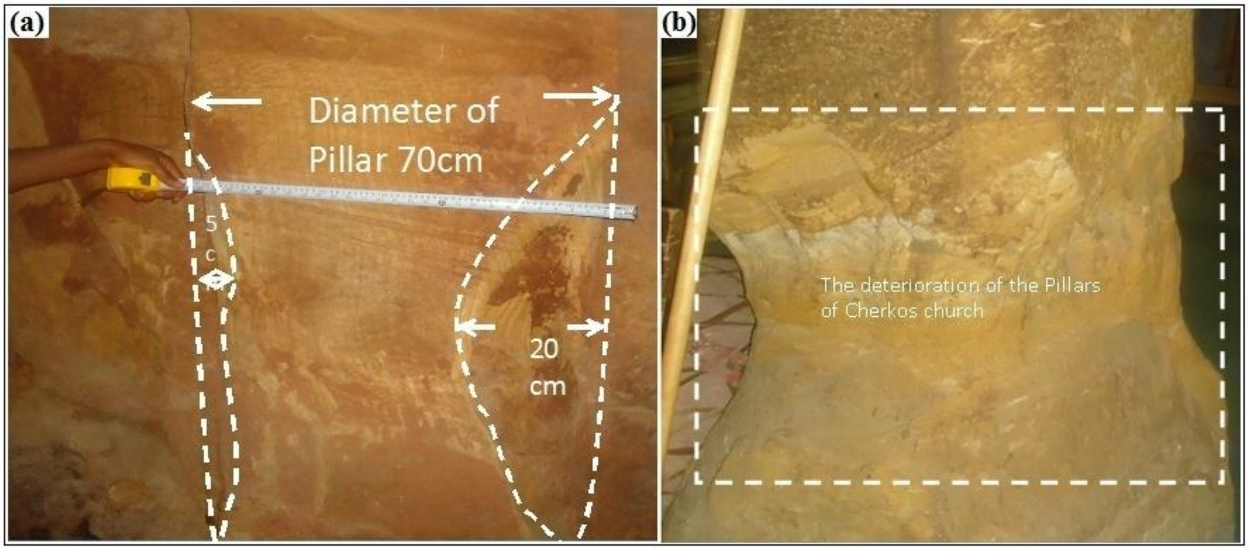


Figure 9. Showing (a) deterioation of one of the pillars of Abraha-Atsibah church; and (b) deterioation of one of the pillars of Wukro Kirkos/Cherkos.

Finally, the petrographic and geomechanical results suggest that the churches carved in the Enticho sandstone are relatively better than those carved in the Adigrat sandstone due to the reason that the Enticho sandstone has a wider discontinuity spacing and uniformly cemented and also mainly by silica which relatively increases the resistance to weathering of the rock.

## 6. CONCLUSION AND RECOMMENDATIONS

### 6.1. Conclusion

In Tigray region the rock-hewn churches are carved into either Adigrat sandstone or Enticho sandstone. The geological and geomechanical behavior of rocks exposed in the AbrahaAtsibaha - Wukro areas in relation to the rock-hewn churches are assessed. The rock-hewn churches at AbrahaAtsibaha – Wukro (Kirkos/Cherkos church) are carved into Mesozoic Adigrat sandstone.

From petrographic and geomechanical point of view both Adigrat and Enticho sandstones have nearly similar behaviors which is suitable for manual excavation of the rock-hewn churches. However, they have minor differences in the nature of the cementing material, structure and nature of discontinuities which are affecting their engineering properties. Adigrat sandstone is characterized by the presence of alternating bands of iron and silica-rich cementing material and intercalated thin layers of iron- rich and silicified siltstone; and by low to medium UCS, excellent RQD and good RMR. Low-medium strength, presence of discontinuities and presence of alternative bands are contributing towards differential weathering patterns and causing deterioration of the rocks in the churches resulting in spalling, pitting and discoloration. This will inevitably with time results in the negative impact on the churches and tourism industry.

### 6.2. Recommendations

The rock-hewn churches in Tigray are one of the major sources of income for the tourism industry for the country in general and the region in particular. However, significant numbers of churches are under threat due to seepage, weathering of the rocks and landslide.

To minimize the seepage of water, weathering and landslides etc, proper measures are to be devised and implemented. The measures to be taken includes, but not limited to diverting the flow direction of surface water, filling or sealing of fissures and joints by cement etc.

Further detail geological and engineering geological investigation and applied research works that seeks strategic remedial measures are crucial.

## 7. ACKNOWLEDGMENTS

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