Developing a digital database of key factors responsible for natural fracture growth in the Theban Necropolis (Luxor, Egypt)

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1. Introduction

The Theban Necropolis is located on the West Bank of the Nile River in Luxor, south-central Egypt. During the Late Bronze Age (1500–1000 BC), many rock-cut tombs were constructed to host funerary chambers for members of the Egyptian elite, with hundreds uncovered to date. The site was listed by UNESCO as a World Heritage site since 1979 and many active archeological campaigns have strived to understand, document, and preserve the legacy of the ancient Egyptian civilization (Theban Mapping Project 2005). The area includes steep cliffs of marlstone and limestone from the Thebes Limestone Formation (Said 1990) and its morphology is continuously altered by erosional processes such as rock falls and infrequent recurring debris flows (e.g., Wilkinson & Weeks 2014).

The stability of the site is of interest in order to preserve ancient records and to protect the lives of tourists and workers in the area. The current state of the tombs is a result of both anthropogenic (e.g., fires, vandalism, tourists) and geological hazards (e.g., faulting, extensional fracturing, water infiltration and swelling, rock fall). For instance, an assessment of eight tombs constructed at Sheikh Abd El-Qurna (SAQ) showed that damage in pillars and ceilings of tombs are assisted by unfavorable tension cracks and faults and weak rock units (Ziegler et al. 2019). Likewise, in the Valley of the Kings (KV), persistent, subvertical joint sets and tension cracks in the rock cliffs of the valley have generated tall rock columns which could fail by toppling. One specific column above the entrance of tomb KV42 is in a poor state and thermo-mechanical weakening may drive it toward failure (Alcaino-Olivares et al. 2020).

Within this context, our research examines the most critical factors and processes impacting on the geological stability of tombs and cliffs in the Theban Necropolis. This paper intends to open the discussion for developing a method to tackle the collection, processing and archiving of data for use in machine learning analysis of the conditioning factors and driving processes promoting fracture growth in the rock. In particular, we focus on tomb TT95 (located in SAQ, 25°43'52.47"N, 32°36'24.58"E), which has been excavated by the German Archaeological Institute, Cairo, (1991-1996, 2003-2013) and which has become a major research focus of the University of Basel's archaeological project Swiss Mission at Sheikh Abd el-Qurna/Life Histories of Theban Tombs (LHTT) with permission from the Egyptian Ministry of Tourism and Antiquities since 2014/2015.

2. Case study: The rock-cut tomb chapel TT95A

The tomb chapel TT95A was constructed in the 2nd half of the 15th century BC. Its architecture consists of two large, pillared halls elongated in a South-North direction, with a first hall comprised of 6 pillars on each side, and a second unfinished western hall having four pillars, as shown in Fig. 1a. The rock unit is characterized as a massive limestone, cut by three joint sets (spacing 2 m, average length of 0.5 m, slightly rough, slightly weathered), and its Geological Strength Index (GSI) ranges between 55 and 75 (Ziegler et al. 2019). A large tensile fracture striking 50°E and dipping 50° that cuts through the southern part of the 1st pillared hall is believed to have played an important role in a pillar (Fig. 1b – label "H") and roof collapse (Fig. 1c). The collapse apparently occurred during the construction of the tomb (Loprieno-Gnirs 2018, 118-122).

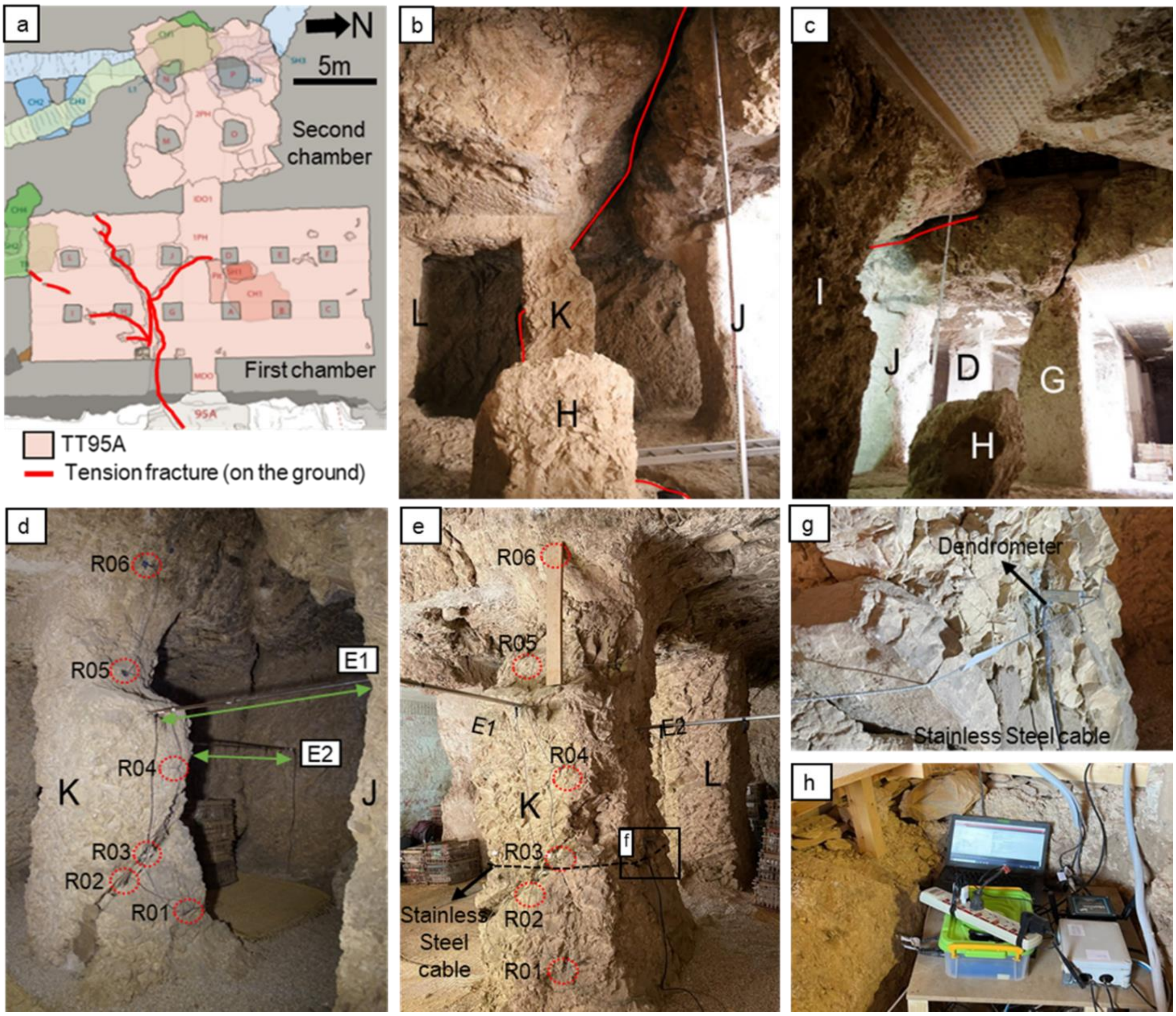

Figure 1: Case study of tomb TT95A, (a) the tomb's layout with two pillared halls (pillars A to O), showing the location of a tension fracture crossing the southern part of the first hall which has contributed to (b) the collapse of pillar H and (c) wedge formation which impacted pillar K in ancient times. To monitor the stability, (d, e) pillar K was instrumented with temperature sensors (R#; ID of each sensor) and two extensometers (E1 and E2) in 2019, whereas (f) in 2022 a dendrometer was installed to measure the radial expansion of the pillar by installing a stainless-steel cable around pillar K. All sensors are connected to (g) on-site data acquisition units. (images © LHTT, University of Basel)

In order to examine the current stability of TT95A and its potential degradation related to natural perturbations (i.e., weather conditions, ground vibration), a monitoring system was deployed inside the tomb chapel in April 2019 and upgraded in March 2022. Pillar K (Fig. 1d) was instrumented with two extensometers (E1 and E2), a temperature string measuring the rock temperature (RT) at ten locations from the hall's ground to the roof across pillar K (Fig. 1d), as well as temperature and relative humidity sensors for monitoring the indoor conditions of TT95A. In March 2022, our team decided to install a sensor (dendrometer) to measure the circumferential deformation of pillar K (Fig. 1e), along with a rock temperature (RT) sensor inserted in pillar J within a fracture of the same set of the long tension fracture crossing pillar K. These sensors send their readings to a Libelium data acquisition system. All the data acquisition equipment is located inside TT95A (Fig. 1g).

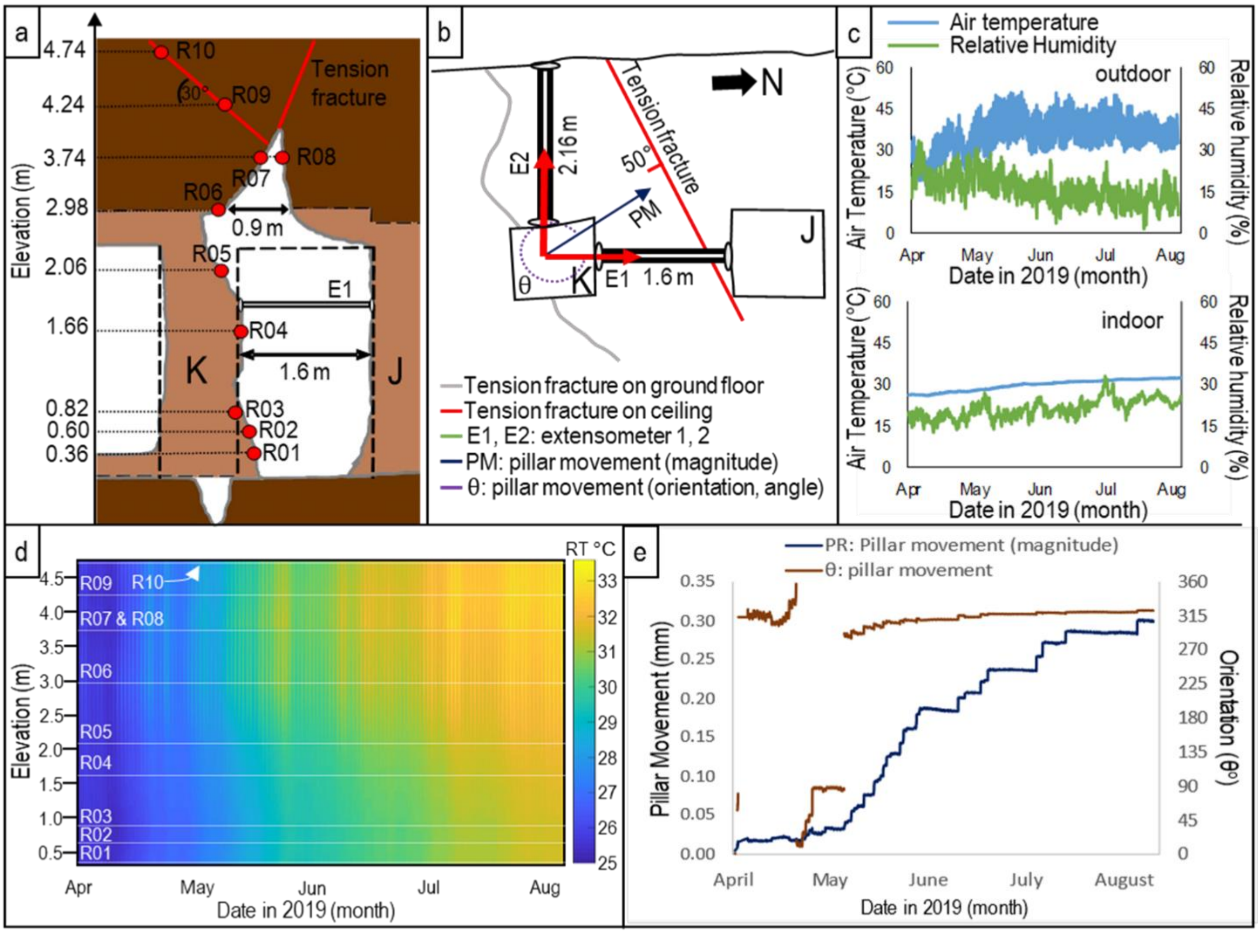

Figure 2: Preliminary data acquired in TT95A from April to August 2019, from (a) rock temperature measured at different elevations above the ground floor across pillar K and following the trace of the tension fracture, and (b) extensometers monitoring the displacement and orientation of the pillar movement vector given by both E1 and E2 data (floor plan). The ambient conditions for the tomb chapel are shown in terms of (c) rock temperature and relative humidity for the interior and exterior of TT95A. Rock temperature values displayed as a (d) time-series color map with elevation from April to August 2019, whilst displacements are reported as a (e) time-series of relative pillar movement in mm and angular orientation (from North).

A NS cross section of the monitored pillar (K) is shown in Fig. 2a indicating the location of the RT sensors, whereas the floorplan in Fig. 2b illustrates the orientation of E1, E2, and the tension fracture. Since E1 and E2 are orthogonal to each other, the resulting vector indicates the horizontal displacement of pillar K. Ambient outdoor temperature (Fig. 2c) ranges between 25°C and 46°C for during the recorded period, with diurnal fluctuations reaching up to 10°C in a single day. The indoor AT has daily fluctuations no larger than 3°C, and ranges from 27°C to 35°C. However, the RH seems to increase in the interior of TT95A from 15% to 27% with increasing AT, whereas outdoor RH drops from 25% to 10% as AT rises, even though it fluctuates more.

The RT data across pillar K is plotted as a color map of the integrated time-series in Fig. 2d, which shows that the upper sensors (i.e., above 2.5 m, R06 to R10) can reach higher RT values than those installed at the bottom part of the pillar. The resulting displacement vector of pillar K is shown in Fig. 2e, with a total displacement of 0.3 mm in 4 months and orientation approximately opposite to that of the dip direction of the tension fracture (320° or 40NW), although during the first month the extensometers likely adjusted and settled (i.e., experienced erratic orientation and movement magnitude). The largest rate of displacement was observed in May, aligning with the larger temperature contrast in the pillar. RT likely plays an important role in pillar K displacements.

3. Other influencing factors: developing a methodology for assessing their impact

Acquiring time-series of displacements and temperatures allow to link the rock mass response to other factors that normally are not accounted for in underground construction, particularly for long-term stability assessment of ancient structures. For instance, in a span of a few millennia, climatic conditions can widely vary, implying that fracture growth rate under ancient ambient conditions are different from the current rates. Similarly, anthropogenic factors (e.g. tomb's use, construction method) could also play a role in assisting fracture growth. Therefore, there is a need for interdisciplinary collaboration, with contributions from archaeological and egyptological studies, to first develop a digital database which contains records of such paleoclimate information and history of human activity in the tomb that can be coupled with geo-spatial, environmental, and geological process information. Additionally, understanding and modelling the physical processes behind the influence of climatic parameters on the pillar displacement is not a trivial task. However, data acquisition through the monitoring system installed in TT95A enhances the opportunity of using data-driven methods and exploratory data analysis to understand the rock mass response to environmental variables. The application of machine learning algorithms to develop a data-driven model representation of the system will be examined.

4. Conclusions

TT95A is an example of a pillared tomb constructed in the Theban Necropolis between 1500–1000 BC. A geotechnical assessment and the installation of sensors can guide the long-term monitoring of the tomb's stability and inform public safety measures. The collected data show that both extensometers generate a movement vector which aligns with the dip direction of the tension fracture. Data-driven methods of analysis are proposed to understand and predict the future movement of this critical pillar in TT95A that is likely related to fluctuations in climatic parameters. This research will not only contribute to the preservation of TT95A, but also to other tombs in the Theban Necropolis.

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