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THE USE OF A WIRELESS SENSOR NETWORK FOR HIGH-RESOLUTION ENVIRONMENTAL MONITORING OF STONE MONUMENTS IN CONTEXT WITH INVESTIGATION OF SALT WEATHERING – EXEMPLIFIED FOR ROCK-CUT MONUMENTS IN PETRA / JORDAN

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Abstract

Salt weathering is known as a major cause of damage on stone monuments worldwide. Despite many years of intensive research, processes of salt weathering are still rather poorly understood. The overall aim of the research project 'petraSalt' is to improve knowledge of salt weathering on stone monuments. The project addresses salt weathering processes on stone monuments under real-time / real-scale conditions. It aims at reliable information on characteristic interrelations between stone properties, environmental influences (climate, salt load), salt weathering processes and the development of weathering damage. In order to ensure findings of high transferability, the rock-cut monuments of Petra / Jordan were selected for studies, since stone type and spectra of monument exposure regimes, environmental influences, salt loading and weathering damage are representative for a multitude of stone monuments worldwide.

Achievement of the project´s aims requires temporal and spatial high-resolution monitoring of environmental conditions affecting the monuments and acting as driving forces for salt weathering processes. An autonomously operating wireless sensor network (WSN) is applied as an innovative technology that can make this contribution.

Methodological approach - with focus on the WSN-system - and results of the 'petraSalt' research project are presented.

Keywords: stone monuments, salt weathering, weathering damage, wireless sensor network, environmental monitoring, impedance spectroscopy

1. Introduction

Stone monuments represent an important part of world heritage. All stone monuments are affected by weathering. Findings obtained from in-situ investigation, laboratory analyses and weathering simulation during the last decades have revealed salt weathering as a major cause of damage. Despite many years of intensive research, processes and mechanisms of salt weathering still cannot be explained satisfactorily. This is due to the heterogeneity of the systems "stone", "salt" and "environmental influences" and the complexity of their dynamic interaction. From experts´ point of view, better understanding of salt weathering deserves further comprehensive in-situ investigation jointly addressing active salt weathering processes and controlling factors. The 'petraSalt' research project – funded by DFG / Deutsche Forschungsgemeinschaft (German Research Foundation) – takes this approach. The project addresses salt weathering processes on stone monuments under real-time / real-scale conditions.

In order to ensure high transferability of methodological approach and findings, the rock-cut monuments of the ancient city of Petra in Jordan were selected for studies, since stone type (sandstone) and spectra of monument exposure regimes, environmental influences, salt loading and weathering damage are representative for a multitude of stone monuments worldwide. The Nabataean city of Petra with its more than 800 monuments carved from bedrocks about 2,000 years ago (tombs, sanctuaries, places of worship) represents outstanding world cultural heritage (Figs. 1 and 2). In 1985 UNESCO inscribed Petra on the list of World Heritage. In 2007 Petra was elected to represent one of the “New Seven Wonders of the World”.

Figure 1. Monastery (No. 462)

Figure 2. Corinthian Tomb (No. 766)

The project aims at weathering models that reliably depict characteristic interdependencies between stone properties, monument exposure regimes, environmental influences, salt loading and salt weathering damage. These models are expected to allow reliable rating and interpretation of aggressiveness and damage potential of the salt weathering regimes considering their variability under range of lithology, monument exposure, environmental conditions and time (Fig. 3).

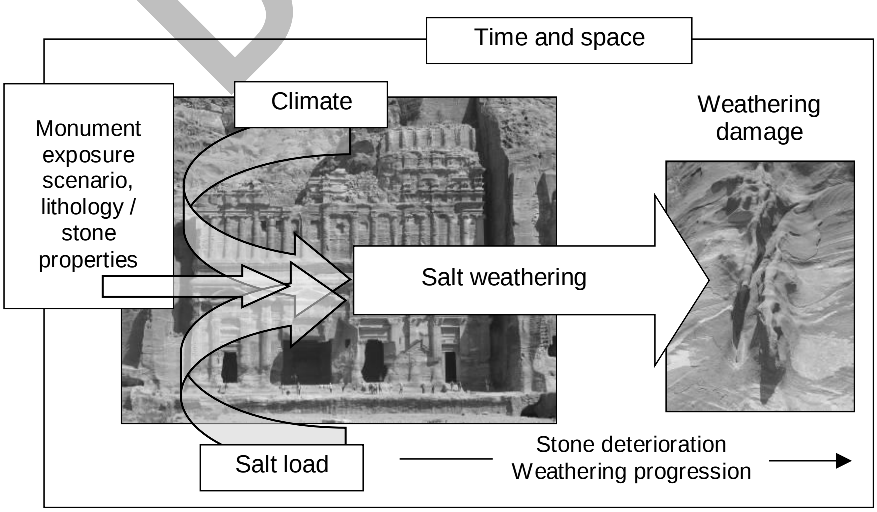


Figure 3. Dynamic weathering situation to be faced

In addition to precise assessment of characteristic monument exposure regimes, weathering damage and salt load regimes, achievement of the project´s aims requires temporal and spatial high-resolution monitoring of environmental conditions affecting the monuments and acting on the salt load as driving forces for salt weathering processes, considering diurnal, seasonal and spatial variation. An autonomously operating wireless sensor network (WSN) is applied as technology that can make this contribution. This innovative technology increasingly finds application in geosciences. In the framework of the 'petraSalt' research project it has entered the field of systematic salt weathering research.

2. Working program

The studies focus on the two main sandstone types which show considerable differences in their petrographic properties and in their weathering behavior as known from previous own research work in Petra (Heinrichs 2005, 2008):

- multicolored, fine-grained sandstone, Umm Ishrin Sandstone Formation – middle part / Cambrian,
- whitish, medium-grained sandstone, Disi Sandstone Formation / Ordovician.

Representative monuments were selected for studies, considering different architecture, monument exposure regimes and extent of weathering damage. The working program comprises five main activities:

- assessment of characteristic monument exposure scenarios (location, dimension and architectural composition / geometry of the monuments; orientation of stone surfaces, rain impact, water run-off situation, conditions of insolation and stone surface heating / cooling, etc.),
- assessment of weathering damage (type, extent, spatial distribution and progression of weathering damage),
- continuous high-resolution monitoring of micro-environmental conditions affecting the monuments (temperature, humidity, insolation, rain, wind),
- assessment of characteristic salt load regimes (type, concentration and spatial distribution of salts / salt mixtures; salt weathering profiles),
- integral evaluation.

These activities are explained in the following chapters with focus on the use of the wireless sensor network system for environmental monitoring.

3. Assessment of monument exposure regimes

As basic contribution to the assessment of characteristic monument exposure regimes, 3D terrestrial laser scanning (TLS) was made. In a first step, laser scanning was performed from longer distances with a resolution in the range between 2 and 6 cm, aiming at overview 3D sceneries of the monuments and their surroundings. For detailed investigation of the monuments, close-range scanning was carried out with a resolution in the range between 6 and 15 mm (Figs. 4 and 5). Evaluation of the laser scanning data by means of 3D models has provided precise information on dimension and stone surface exposition of the monuments under investigation (Heinrichs and Nguyen 2011). In addition to thorough visual inspection of the monuments, supplementary measurements and available information on the Nabataean architecture in Petra, the 3D models of the monuments served as basis for the assessment of the monuments´ original architectural composition including ground section (Figs. 6 and 7).

Figure 4. Bab el-Siq Triclinium (No. 34), Ordovician sandstone

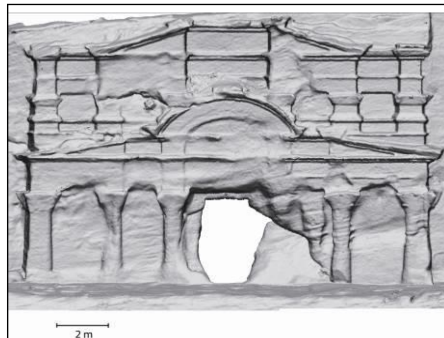
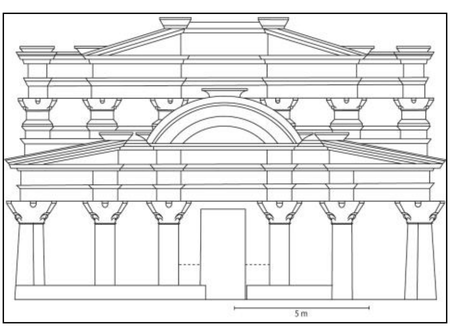


Figure 5. Bab el-Siq Triclinium, 3D model (front view) derived from laser scanning

This step of evaluation is required for precise quantification of weathering damage on the monuments, especially loss of stone material. Furthermore, the 3D models of the monuments were used for the calculation of rock mass that was removed for the creation of the monument façades. Considering the huge mass of rock material removed, unweathered condition of the monuments´ rocks can be postulated for the initial phase of exposure. Thus, salt weathering processes can be clearly attributed to a period of approximately 2000 years. A next step of investigation has addressed the rainfall and water run-off situation at the monuments, considering rain as an important source of salt loading. Stone surface exposed to rain was identified. Statistical information on direction and inclination of rainfall was gathered allowing a differentiated calculation of rain water input at the monuments in dependence on orientation of their stone surfaces as well as the assessment of spatial variation of stone surfaces exposed to rain in the course of weathering progression. Furthermore, those parts of the monuments affected by water run-off during or after rain were mapped, considering short and long, respectively light and heavy rainfall (Fig. 8).



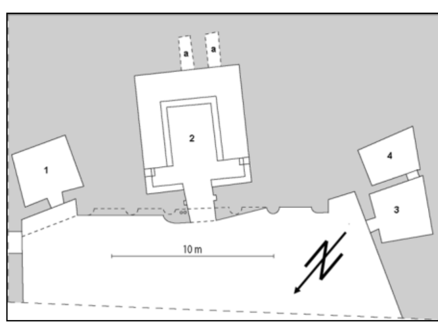


Figure 6. Bab el-Siq Triclinium, monument plan derived from reconstruction of the original architecture by use of the 3D model of the monument, approximately 700 m^3 of rock removed for creation of the monument

Figure 7. Bab el-Siq Triclinium, ground section, 1: chamber with three graves, 2: triclinium chamber with two graves (a), 3: chamber, 4: chamber with four graves

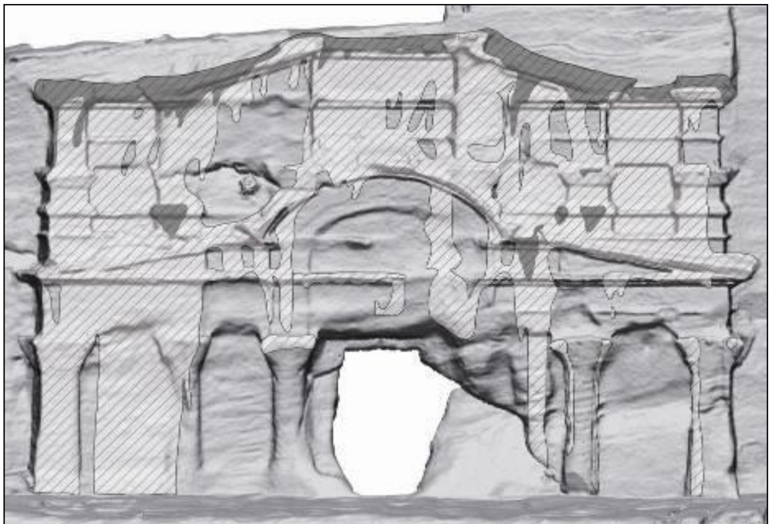


Figure 8. Bab el-Siq Triclinium, 3D image with documentation of water run-off, dark gray areas with hatching: water run-off after light / short rain, light gray areas with hatching: additional areas by water run-off after heavy / long rain

Measurements by means of infrared-thermography are performed for the assessment of the heating and cooling behaviour of the monument façades as further important contribution to identification of characteristic monument exposure scenarios. The measurements provide detailed information on parameters such as minimum, maximum, and average stone surface temperatures, insolation periods, variation of stone surface temperature, heating and cooling rates etc., considering diurnal and seasonal variation (Figs. 9 and 10).

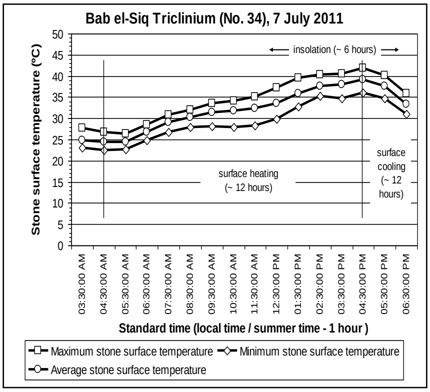


Figure 9. Bab el-Siq Triclinium, stone surface temperatures in high summer (example), façade exposed to NW

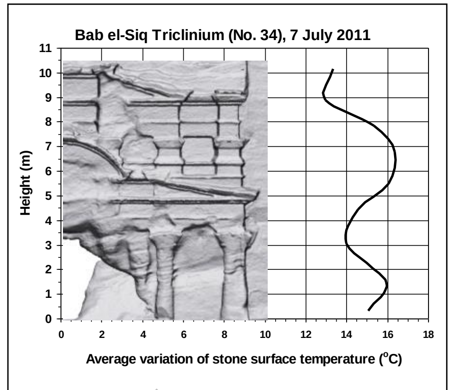


Figure 10. Bab el-Siq Triclinium, average diurnal variation of stone surface temperatures (vertical profile) in high summer (example)

4. Assessment of weathering damage

Weathering damage on the rock-cut monuments is assessed by mapping of weathering forms (apparent weathering phenomena at cm to m-scale) according to type and intensity. A classification scheme of weathering forms has been developed as basis for detailed mapping, specially tailored to use for the Petra monuments. It is accompanied by representative photo-documentation. Evaluation comprises:

- maps of weathering forms (separately for loss of stone material, deposits, current detachment of stone material, cracks),
- quantitative evaluation of all weathering forms and their combinations,
- identification of characteristic spectra and sequences of weathering forms (development of weathering damage, weathering progression) in consideration of the sandstone types and monument exposure regimes under investigation,
- rating of weathering damage by use of a correlation scheme "weathering forms – damage categories" (maps and quantitative evaluation of damage categories, calculation of damage index).

5. Environmental monitoring by use of a wireless sensor network (WSN)

An autonomously operating wireless sensor network system (WSN) has been developed in the framework of the 'petraSalt' research project for the temporal and spatial high-resolution environmental monitoring of the monuments selected for detailed investigation. Considerable advantages of this innovative technology compared to conventional measuring techniques are miniaturisation of sensors (high quality, low cost sensors), possibility of complex sensor setups, high-resolution monitoring, high durability of the system, little maintenance efforts, and remote access to system and data by the end-user. The WSN system is composed of several independent wireless nodes (motes), linked to each other by a short range radio communication link (2.4 GHz), hence building a wireless sensor network (Fig. 11).

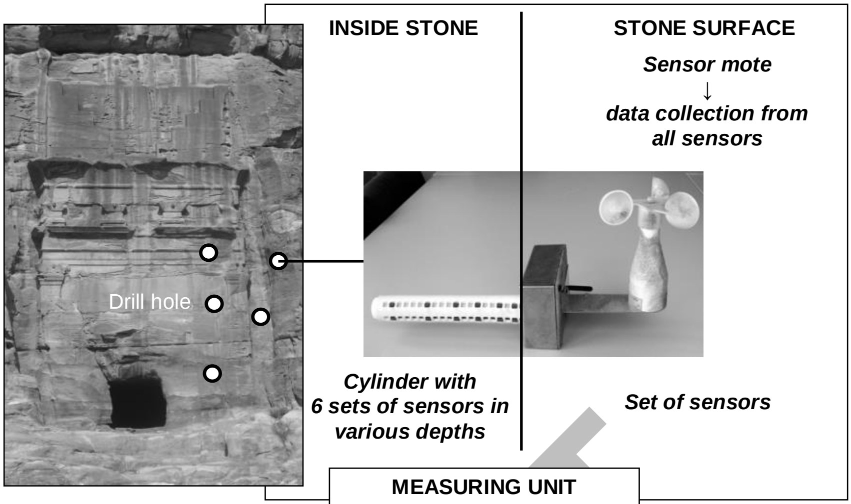


Figure 11. Configuration of the wireless sensor network, measuring unit with sets of sensors and sensor mote for data collection

Regarding measurements inside the stone, a cylinder was developed that is equipped with six sets of sensors, arranged in separate chambers in various depths (1, 3, 6, 9, 14, 19 cm). Each set includes sensors for the measurement of temperature, humidity and electrical impedance. The cylinder is inserted in drill holes (depth: 20 cm, diameter: 3.7 cm, dry drilling). A special spreading technique with closed cell foam made from silicone ensures proper sealing of the six measuring chambers against each other as well as tight and dense connection between cylinder and stone substrate. Reversibility of this technique will ensure that the measuring units can be easily removed at the end of the project without harming the stone substrate.

Exterior system components of the measuring units – densely connected with the cylinder inside the drill hole – comprise sensor mote with rain-proof enclosure, long-life batteries, processor board, radio module and sensors for the measurement of air temperature, air humidity, stone surface temperature and light (insolation).

In addition, several measuring units have been equipped with wind and rain sensors. In this way, a measuring unit can be equipped with 24 sensors at maximum. The sensor motes act as data collector and are programmed to collect data from all sensors in periodic intervals of 15 to 30 minutes over a period of at least one year.

Additional elements of the wireless sensor network system are solar powered gateways, which relay the measurement data to a long-distance network (GSM) for remote access, and a database to save data for later retrieval and optional post-processing. The database is a MySQL database located in Germany. The possibility of remote access to the data allows their continuous evaluation (Fig. 12).

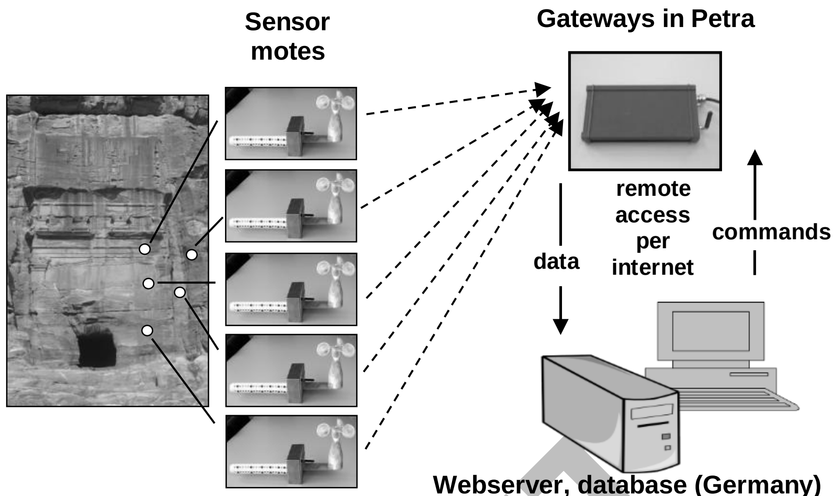


Figure 12. Configuration of the wireless sensor network, data transfer from the sensor motes via gateways per internet to remote webserver / database

All the hardware is optimized to work under harsh environmental conditions. Different kinds of sensors could be attached to a wireless mote simultaneously that is various MEMS (Microelectromechanical systems) sensors with digital output, e.g. for the acquisition of temperature, humidity, solar radiation etc.

Additionally analog sensors like electric impedance sensors are connectable by using especially developed electric circuits for the signal conditioning. This modular concept allows for customization and optimization for specific monitoring objectives as they are apparent in Petra. While sufficient techniques and sensors are available for the measurement of temperature and relative humidity of the air, the determination of moisture content of natural stone is of high complexity. All porous materials could contain various amounts of moisture that depends on the specific material, especially its chemical composition and porosity, and on the surrounding environment and exposition. The hygroscopic moisture content of a material is driven by absorption and desorption functions of both relative humidity and temperature and represents the amount of water absorbed from the air at a standing environmental level. A lot of attempts have been made to monitor the equilibrium moisture content by just measuring the relative humidity in boreholes. Although such measurements can give some indications on material moisture and moisture change over time, the determination of absolute moisture by this method could be source of severe error, because the equilibrium moisture content strongly depends on hygroscopic substances inside the material, to which many chloride and hydroxide salts belong.

The determination of moisture content becomes even more complex if the overhygroscopic area is concerned. In excess of the hygroscopic moisture, additionally free (or capillary) moisture is filling the pores of the material. The free moisture content could vary significantly between different stone varieties because of their different permeability and porosity and therefore moisture carrying capacities as well as different salt content. This is why in addition to the measurement of the equilibrium moisture content impedance measurements will be conducted simultaneously. Due to the given restrictions of the measurement hardware it was decided to use a two-point electrode setup, although it is known that electrode effects (e.g. double layer) influence the measurement results (Barsoukov 2005). The electrodes used are made from conductive silicone and are pressed onto the stone surface inside the small boreholes. In general the measured impedance is dependent on the amount of water and the salt concentration within the water as well as temperature. The parameters influence the real and imaginary part of the impedance in a different way. Therefore, only measuring both parts in combination with the equilibrium moisture content and temperature allows conclusions about the moisture and salt concentration in the stone. However, the impedance value is also frequency dependent. Thus, the impedance sensor board is capable of assessing the impedance over a frequency range of 10 Hz to 100 kHz. Impedances starting from a few Ohms up to approximately 15 MΩ can be measured. For Petra the system used for the impedance measurements was set to measure logarithmic full-frequency sweeps from 10 Hz to 100 kHz with 10 points per order of magnitude.

6. Assessment of salt load regimes

The drill cores obtained from installation of the wireless sensor network system are taken for segment-wise ionic analysis of soluble salts (0 - 0,5 cm, 0,5 – 1,5 cm, 1,5 – 2,5 cm,...18,5 – 19,5 cm). This ensures detailed information on the spatial distribution of the salt / salt mixtures (depth profiles). The ECOS program (ECOS - 'Environmental Control of Salt Damage)'will be used as an expert thermodynamic model for the prediction of the crystallization behaviour of the salts / salt mixtures (salt phases, amount of salt, salt volume) under changing climate conditions (Price 2000).

Application will be made via RUNSALT (user interface to the ECOS-program) (Bionda 2002-2005). In addition, efflorescences on the stone surface of the monuments under investigation, detritus (loose material) from the base of the monuments and water (precipitation, water run-off) are planned to be included in geochemical analysis in consideration of composition, concentration and origin of salts.

7. Integral evaluation

All results obtained from measurements with the wireless sensor network, supplementary in-situ investigation and laboratory analysis will get combined for overall comprehensive information on salt weathering and its effects on the Petra rock-cut monuments. The integral evaluation will comprise:

- statistically reliable information on correlations between monument architecture, monument exposure scenarios, climatic regimes (stone surface, stone interior, diurnal and seasonal variation) and effects of salt weathering (state / development of weathering damage),
- characterization and quantification of salt loading (type and extent of salt contamination, spatial distribution of salts, main zones of salt accumulation, individual salts / salt mixtures, degree of pore space filling etc.) in consideration of the monument exposure regimes, salt uptake mechanisms and states of weathering / weathering progression,

- detailed numerical analysis of potential salt dissolution / salt crystallization cycles according to frequency and depth, based on joint evaluation of salt loading and microclimate acting on it,
- comparison of salt loading (depth profiles) and potential salt dissolution / crystallization cycles (frequency, depth) in consideration of seasonal variation
- correlation of salt regimes and weathering phenomena in the course of weathering progression,
- comparative characterization of the two sandstone varieties under investigation with respect to their weathering behavior / susceptibility to salt weathering in consideration of the differences in their petrographic properties,
- conclusive rating and interpretation of aggressiveness and damage potential of salt regimes in consideration of stone type, monument exposure characteristics, environmental influences, salt loading and salt weathering processes.

8. Conclusions

The overall aim of the 'petraSalt' research project is to improve knowledge of salt weathering on stone monuments. For reasons of representativeness the rock-cut monuments of the ancient city of Petra in Jordan were selected for the investigation. The methodological approach of the research project combines the application of a wireless sensor network system (WSN) as an innovative technology for high-resolution temporal and spatial monument environmental monitoring with systematic, well-directed laboratory analysis and supplementary in-situ investigation of the selected Petra monuments.

The wireless sensor network will provide an extraordinary information output for the analysis of interrelations between exterior and stone interior environmental conditions at the stone monuments considering diurnal, seasonal and depth-dependent variation.

Moreover, it will provide the basis for detailed analysis of depth-dependent salt crystallization-dissolution processes in dependence upon monument exposure characteristics, salt load, environmental influences, state of weathering and stone properties. In this way the application of the wireless sensor network will make an important contribution to rating of aggressiveness and damage potential of salt regimes in consideration of their variability.

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