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Origin and Environmental Role of Negative Air Ions in the Ravne Underground Complex, Bosnia-Herzegovina: A Multidisciplinary Geological, Hydrological, and Microclimatic Analysis

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Abstract: The Ravne Underground Complex near Visoko, Bosnia-Herzegovina, has attracted scientific attention due to unusually high concentrations of NAIs (negative air ions) measured within its tunnel system over a fifteen-year period. Measurements conducted between 2010 and 2025 frequently recorded NAI concentrations exceeding 20,000 ions/cm³, with peak values substantially higher than those commonly reported in forests, caves, mountain environments, or urban settings. To investigate the possible origin of these elevated concentrations, environmental measurements were evaluated together with geological, petrographic, hydrological, and microclimatic observations collected throughout the tunnel network. The underground system is developed within quartz-bearing conglomerate formations overlying marl and sandstone deposits. Petrographic analyses identified quartz, quartzite, calcite, chert, sandstone, shale, schist, and basalt within the conglomerate matrix. Permanent underground water circulation, stable humidity, relatively constant temperatures, and limited atmospheric disturbance characterize the subterranean environment. These conditions may favor ion generation through water-air interactions and contribute to the long-term persistence of ionized air within confined underground spaces. The combined evidence suggests that elevated NAI concentrations in the Ravne Underground Complex result from the interaction of geological composition, hydrological activity, and stable microclimatic conditions. The site represents a valuable natural laboratory for future research in environmental science, hydrogeology, cave atmospheres, geophysics, and atmospheric ionization processes.

Key words: Negative air ions, Ravne Underground Complex, subterranean environment, conglomerate geology, underground water flow, microclimate, environmental ionization, quartz-bearing conglomerate, cave atmosphere, Bosnia-Herzegovina, hydrogeology, atmospheric electricity.

1. Introduction

NAIs (negative air ions) are electrically charged molecules or molecular clusters naturally present in the atmosphere. They are generated through several environmental processes, including atmospheric electrical activity, cosmic radiation, ultraviolet radiation, friction between airborne particles, and interactions involving water, minerals, and vegetation. Elevated concentrations of negative air ions have been documented near waterfalls, forests, mountain environments, ocean coastlines, and certain subterranean systems. Environmental studies have shown that flowing and aerosolized water may contribute significantly to ion generation through charge separation processes commonly referred to as the Lenard effect [1].

Interest in negative air ions has increased in recent decades within the fields of environmental science, atmospheric physics, cave climatology, hydrogeology, and environmental medicine. Previous investigations

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have examined the relationships among NAIs, airborne particulate reduction, aerosol dynamics, atmospheric chemistry, and selected biological responses [2-4]. Although some reported physiological and environmental effects remain debated, multiple studies have confirmed that elevated NAI concentrations are characteristic of highly dynamic natural environments involving moving water, stable humidity, and reduced atmospheric pollution.

The Ravne Underground Complex is located near the town of Visoko in central Bosnia-Herzegovina (Fig. 1). The documented underground network comprises multiple tunnel branches and interconnected passages distributed across the Ravne Valley (Fig. 2). Environmental measurements conducted within the tunnel system over multiple years consistently documented concentrations of negative air ions that substantially exceeded those commonly measured in urban environments and many natural outdoor locations.

The Ravne tunnel network is developed primarily within horizontally layered conglomerate formations resting above marl and sandstone deposits (Fig. 3). The geological structure contributes to relatively stable subterranean conditions characterized by constant temperatures, elevated humidity, reduced atmospheric disturbance, and underground water circulation. Internal stratigraphic relationships within the tunnel system demonstrate clear distinctions between compact conglomerate substrate and unconsolidated sedimentary fill deposits (Fig. 4). Excavation activities additionally documented visible contact zones between lithified conglomerate formations and loose tunnel infill material (Fig. 5; Table 1).

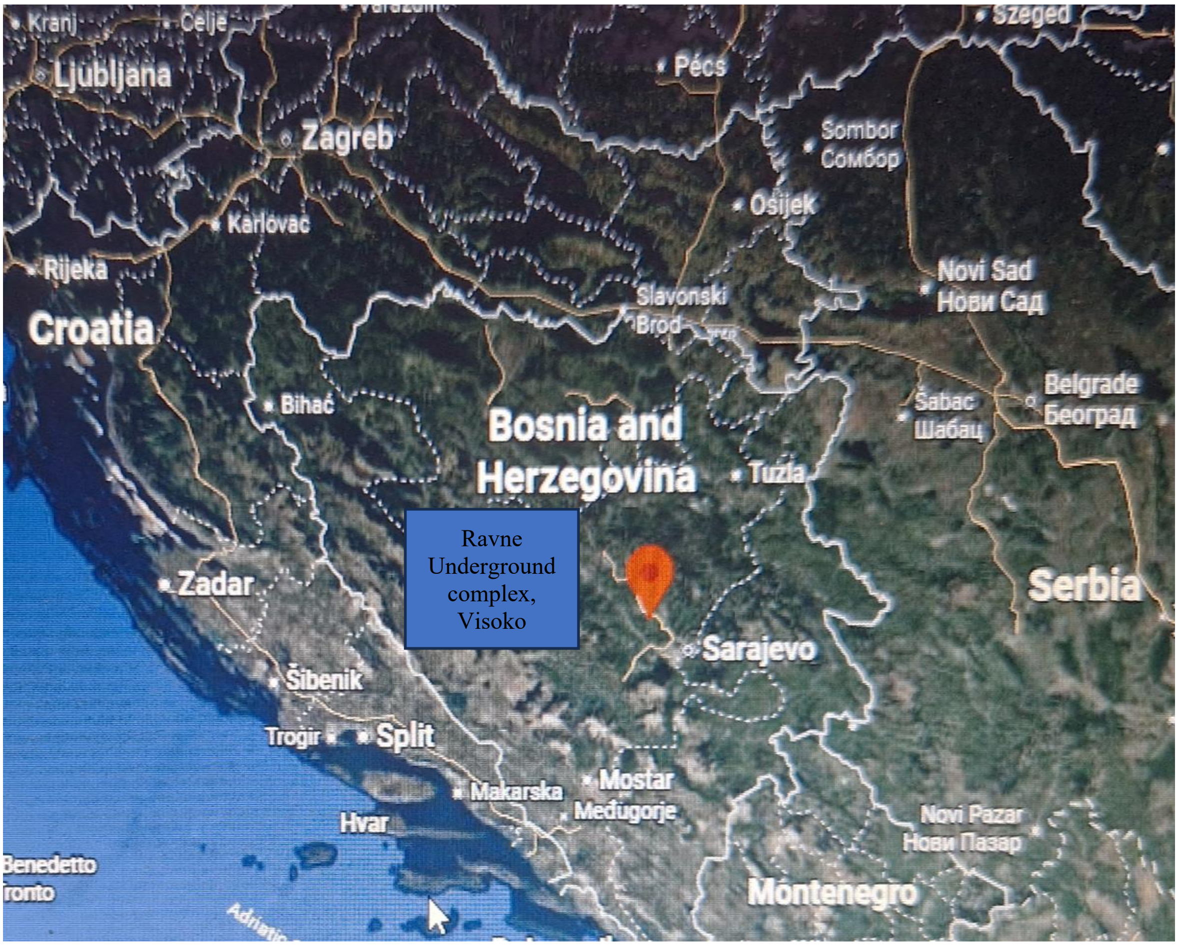

Fig. 1 Geographic location of the Ravne Underground Complex near Visoko, Bosnia-Herzegovina.
Regional map showing the position of Visoko within Bosnia and Herzegovina and the broader Balkan Peninsula. The location of the Ravne Underground Complex is indicated. Base map: Google Earth.

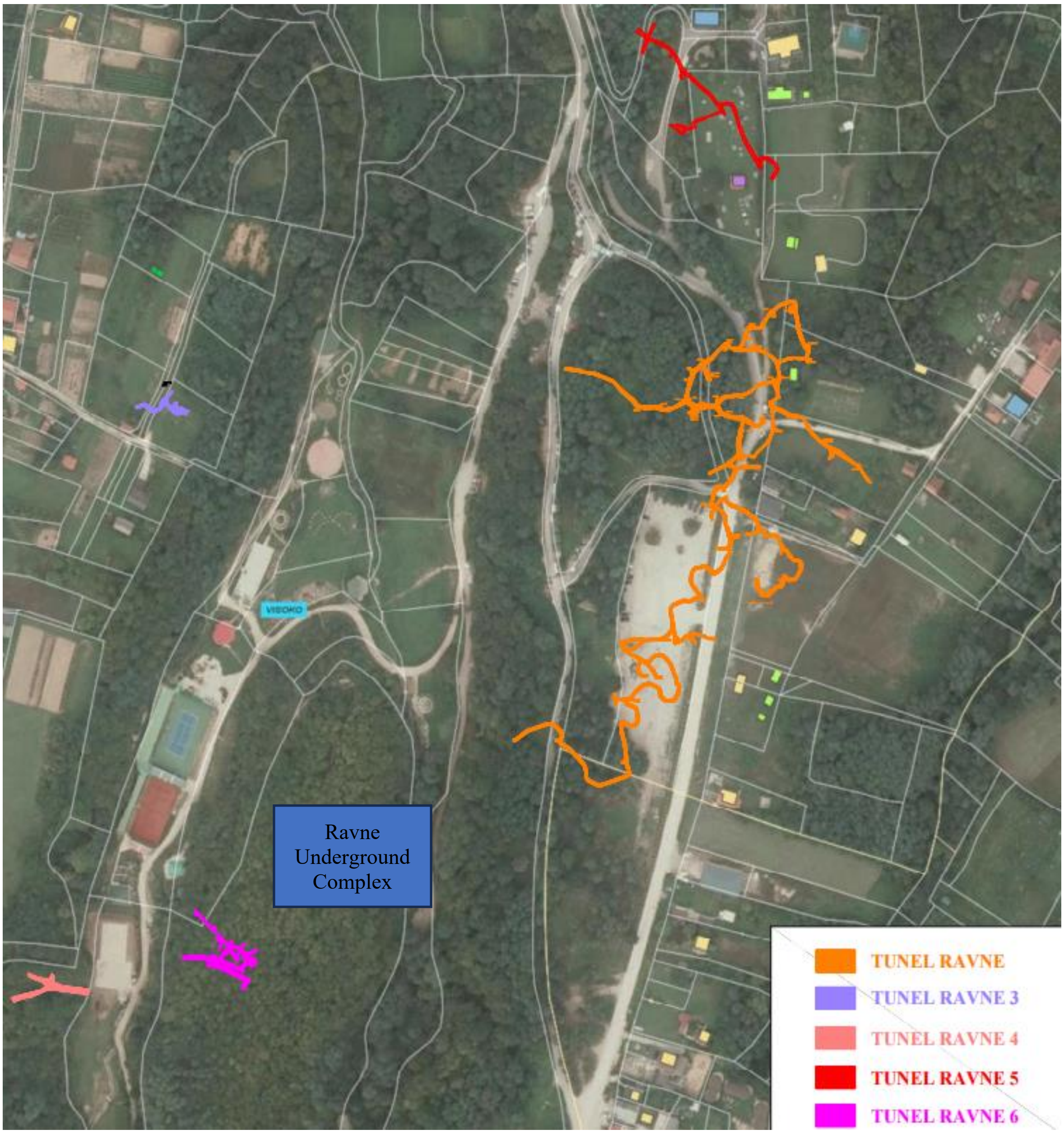

Fig. 2 Spatial distribution of documented tunnel sections within the Ravne Underground Complex.
Plan view showing the relative positions of Ravne tunnels 1-6 and associated underground passages near Visoko, Bosnia-Herzegovina. Geodetic survey and mapping: Geoprom d.o.o., Visoko.

West-east geological cross-section of the Ravne Valley illustrates the relationship between the Ravne Conglomerate Formation and the underlying marl-sandstone sequence. The conglomerate layer forms a relatively stable horizontal unit containing the documented tunnel passages. The geological structure contributes to environmental isolation, stable subterranean microclimatic conditions, and underground water circulation within the Ravne Underground Complex [5].

Schematic cross-section illustrates the relationship between consolidated conglomerate substrate, unconsolidated tunnel fill, and cavity space within the Ravne Underground Complex. Distinct sedimentological interfaces between lithified conglomerate and loose infill deposits are visible. Such stratigraphic compartmentalization may influence underground airflow, humidity retention, water movement, and localized environmental stability within the tunnel system.

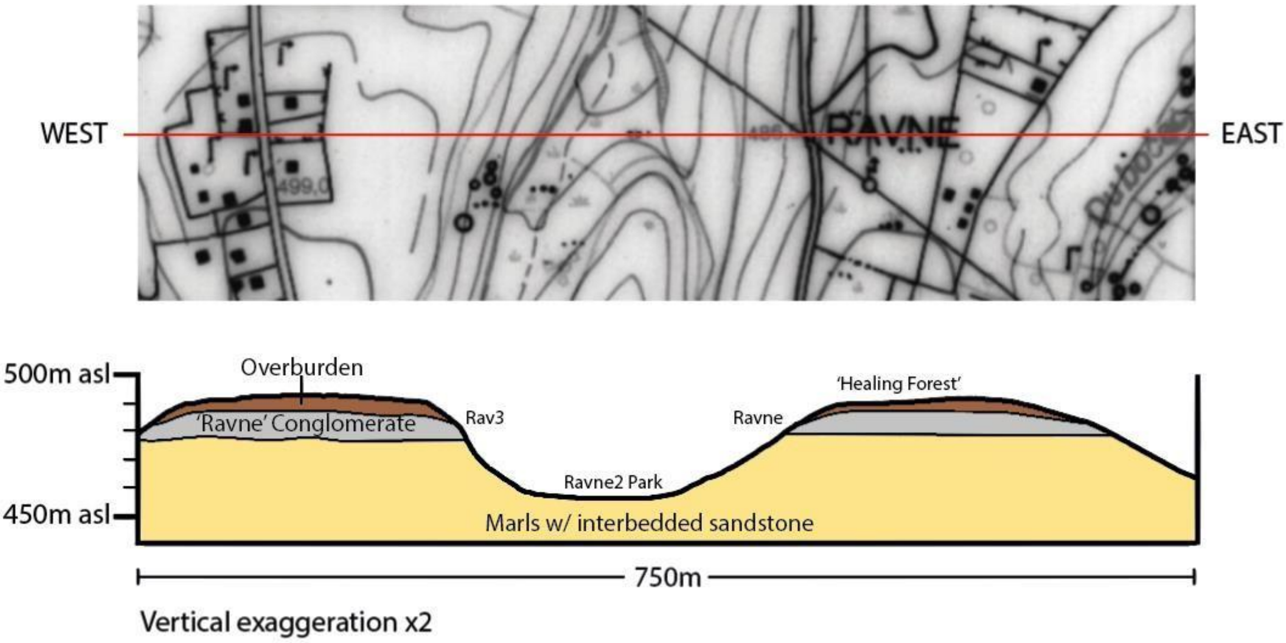

Fig. 3 Geological cross-section of the Ravne Valley showing the stratigraphic position of the Ravne Underground Complex.

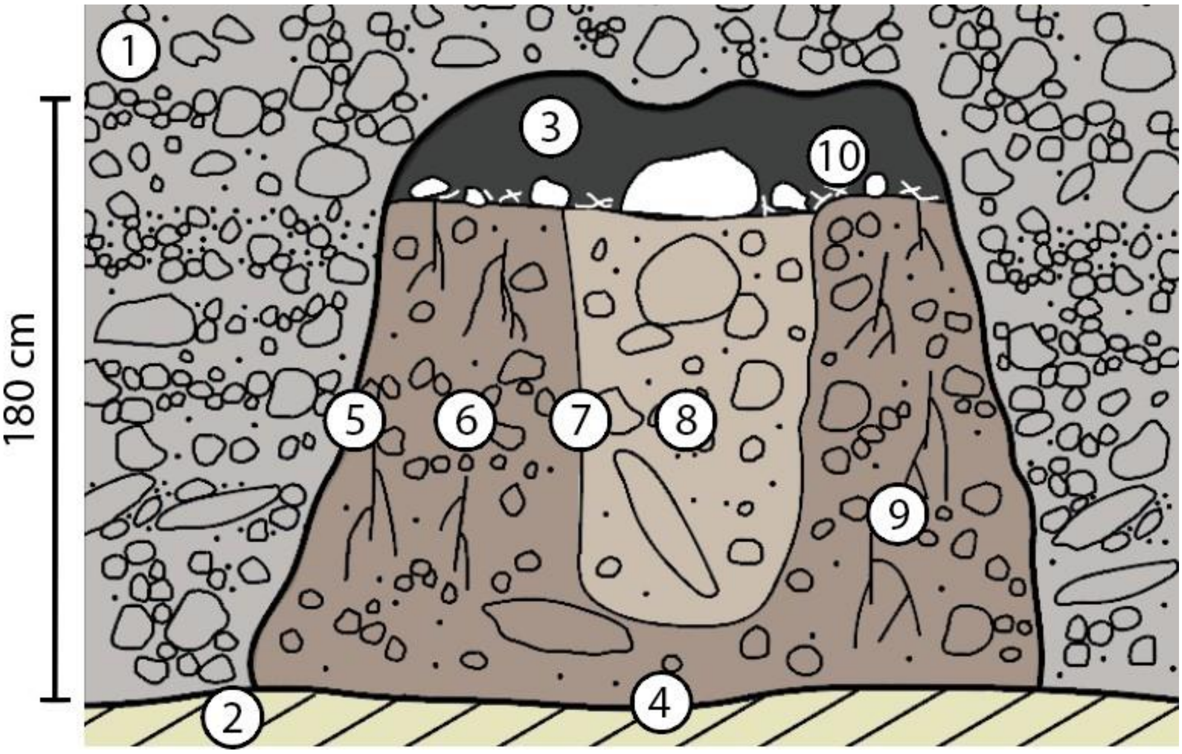

Fig. 4 Simplified stratigraphic schematic of tunnel fill and conglomerate relationships within the Ravne Underground Complex.

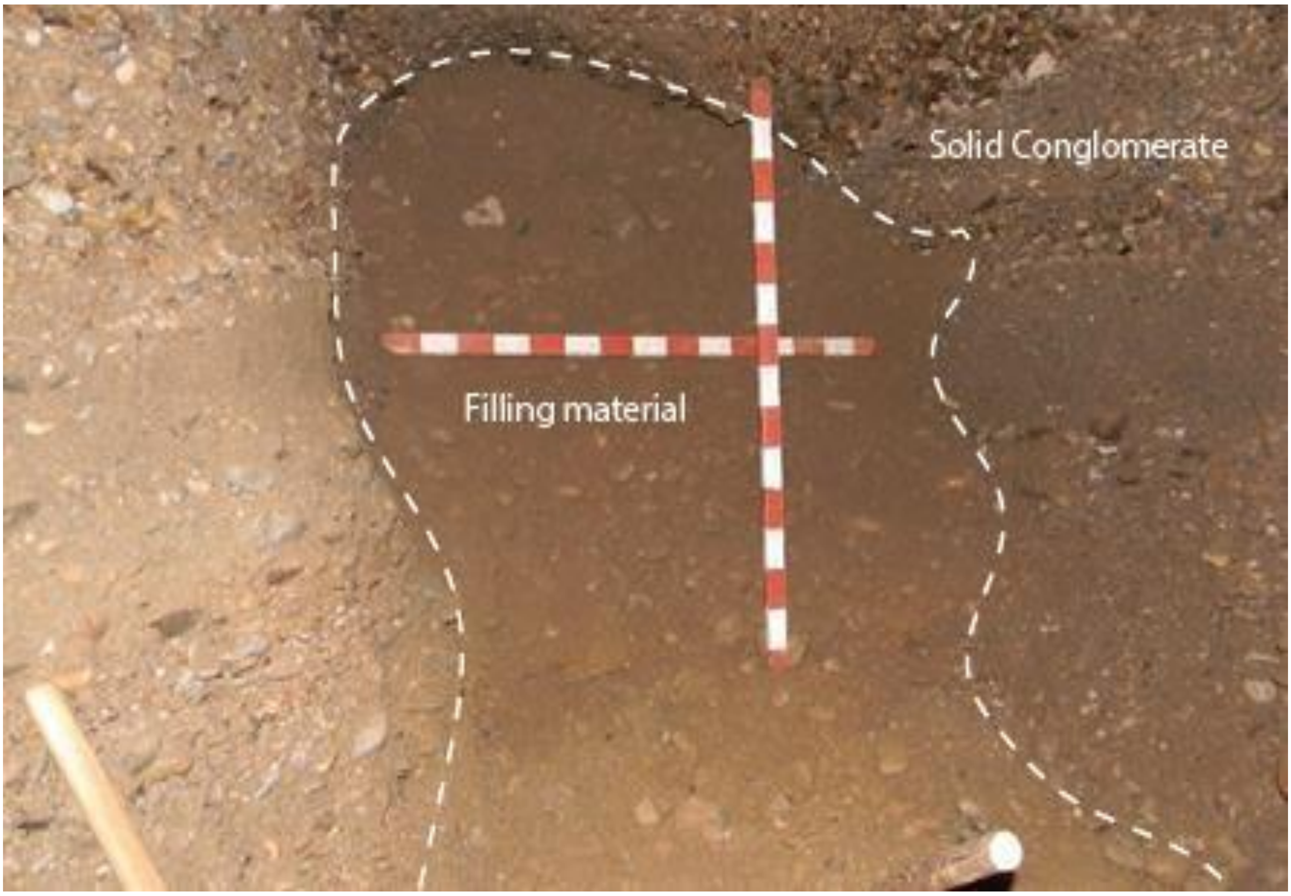

Fig. 5 Contact zone between compact conglomerate substrate and unconsolidated tunnel infill material in the Ravne tunnel system. The image shows a clear boundary between the lithified conglomerate and the loose sedimentary fill, as observed during excavation at Ravne 6.

Table 1 Stratigraphic units identified within the Ravne 6 tunnel section during the 2025 field investigations.

Unit	Description	Thickness	Contact type	Interpretation
SJ 001	Loose sand and pebble fill; poorly sorted; no cementation	Up to full tunnel height (1.2-2.4 m)	Sharp against the conglomerate	Loose unconsolidated tunnel fill
SJ 002	Compacted hard clay floor; homogeneous texture	>1 m (minimum observed)	Sharp over conglomerate; distinct from SJ 001	Natural compact clay accumulation forms a stable floor surface
SJ 003	Lithified conglomerate (rounded clasts in sandy matrix)	Several meters (structural)	Structural boundary	Natural geological substrate

The table summarizes the principal sedimentological and geological units documented during excavation and environmental observations at Ravne 6, including unconsolidated fill, compact clay deposits, and lithified conglomerate substrate.

Petrographic analyses identified quartz, quartzite, calcite, sandstone fragments, chert, shale, schist, and basalt within the conglomerate matrix (Fig. 6). Quartz-bearing geological formations are of particular interest because several environmental studies have suggested that mineral composition, electrostatic interactions, and water-mineral interfaces may influence localized ionization processes in natural environments. Underground environmental measurements within the Ravne tunnel system were conducted using portable air ion counters and associated monitoring instruments deployed at multiple locations over extended observation periods (Fig. 7).

Macroscopic and microscopic petrographic analysis of conglomerate material collected from the Ravne tunnel system. Thin-section examination identified quartz, quartzite, calcite, sandstone fragments, chart, shale, schist, and basalt within the conglomerate matrix.

The mineralogical heterogeneity and quartz-rich composition may contribute to electrostatic and piezoelectric interactions within the subterranean environment. Petrographic analysis was performed in accordance with ASTM standards.

Portable instrumentation used during long-term environmental measurements within the Ravne tunnel system, including AlphaLab air ion counters and auxiliary monitoring devices. Measurements of negative air ion concentrations, temperature, humidity, and environmental conditions were conducted at multiple underground locations between 2010 and 2025.

One of the most significant environmental characteristics of the Ravne Underground Complex is the presence of permanent underground water channels within several sectors of the tunnel network (Fig. 8). Flowing water in confined subterranean environments may contribute to ion formation through aerosolization, hydrogeological circulation, droplet fragmentation, and charge separation processes. Similar mechanisms have been described in studies involving waterfalls and highly humid natural environments, where elevated concentrations of negative air ions have been measured [1, 2].

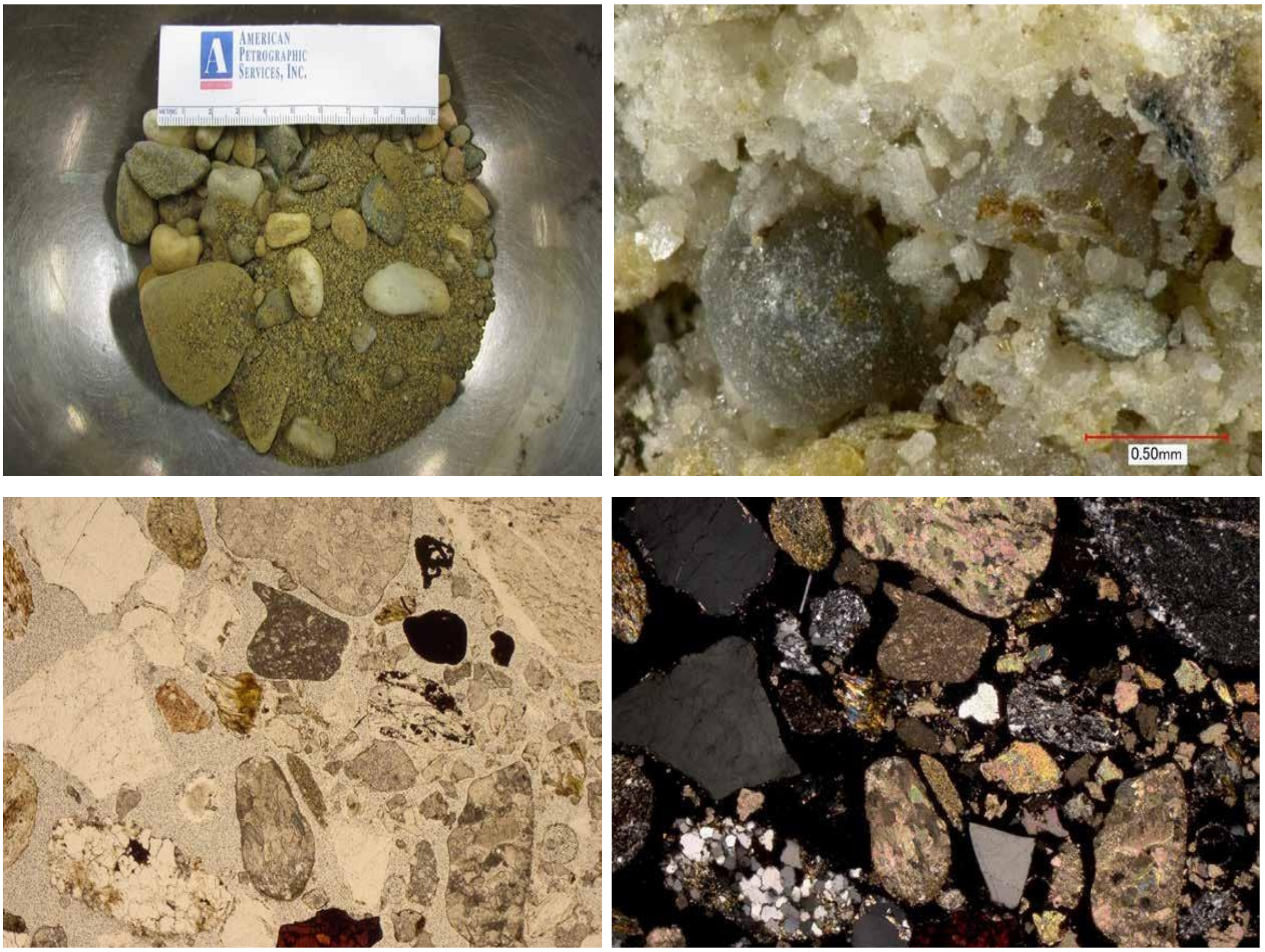

Fig. 6 Petrographic characteristics of conglomerate samples collected from the Ravne Underground Complex.

Fig. 7 Environmental monitoring instruments used for field measurements within the Ravne Underground Complex.

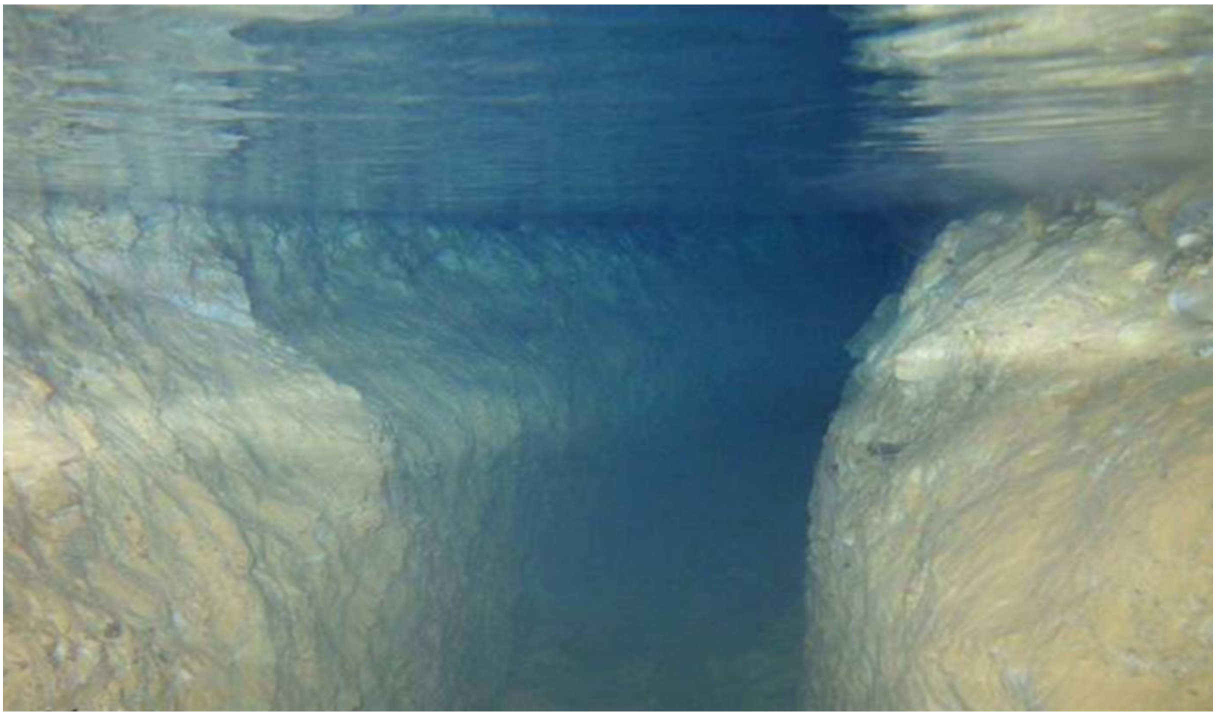

Fig. 8 An underground water channel documented within the Ravne tunnel system.

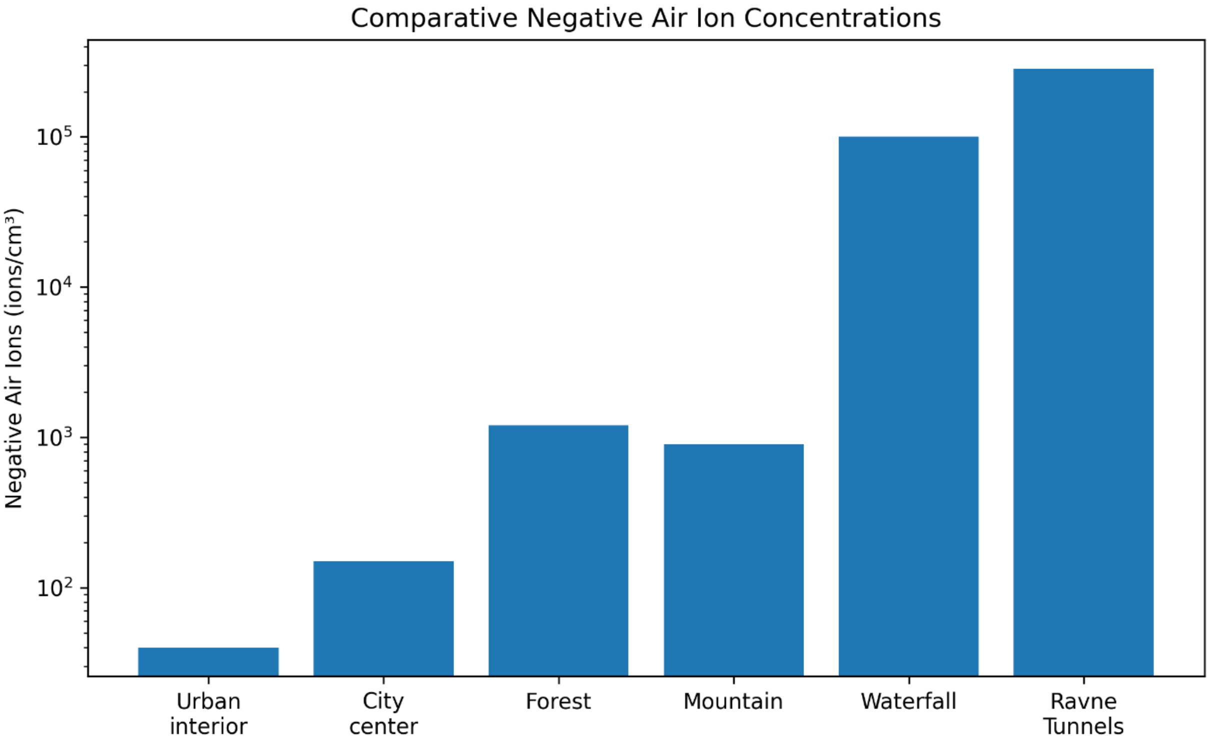

Fig. 9 Comparative negative air ion concentrations measured by the author and compiled from environmental observations in selected urban, natural, and subterranean environments.

Permanent underground water channels occur within several sections of the Ravne tunnel network. Continuous water movement through conglomerate formations may contribute to the generation of negative air ions via aerosolization, hydrogeological circulation, and charge separation processes within the subterranean environment.

Repeated measurements conducted within the Ravne Underground Complex documented NAI concentrations frequently exceeding 20,000 ions/cm³, while isolated underground sections occasionally exhibited substantially higher values than those typically reported for urban environments, forests, caves, or mountainous regions (Fig. 9; Tables 2-3). Microclimatic monitoring also demonstrated relatively stable temperature and humidity conditions throughout the year within the underground environment (Fig. 10). Such environmental stability may contribute to the persistence and accumulation of elevated concentrations of negative ions in confined subterranean spaces. Comparative analysis of selected subterranean environments further indicates that the Ravne tunnel system exhibits substantially higher NAI concentrations than many documented underground settings (Fig. 11; Tables 2-3).

Comparative concentrations of NAIs (negative air ions) reported in selected urban, natural, and subterranean environments. The Ravne Underground Complex exhibits substantially elevated NAI concentrations compared with typical urban interiors, city environments, forests, and mountainous regions, approaching values observed near large waterfalls and other highly ionized natural settings. Values are shown on a logarithmic scale to facilitate comparison across environments with markedly different ion concentrations.

Representative measurements of temperature and relative humidity recorded within the Ravne Underground Complex during long-term environmental monitoring in 2023 (twice a week, mean values). The subterranean environment exhibits limited seasonal variation, maintaining relatively stable temperature and humidity conditions throughout the year. Such microclimatic

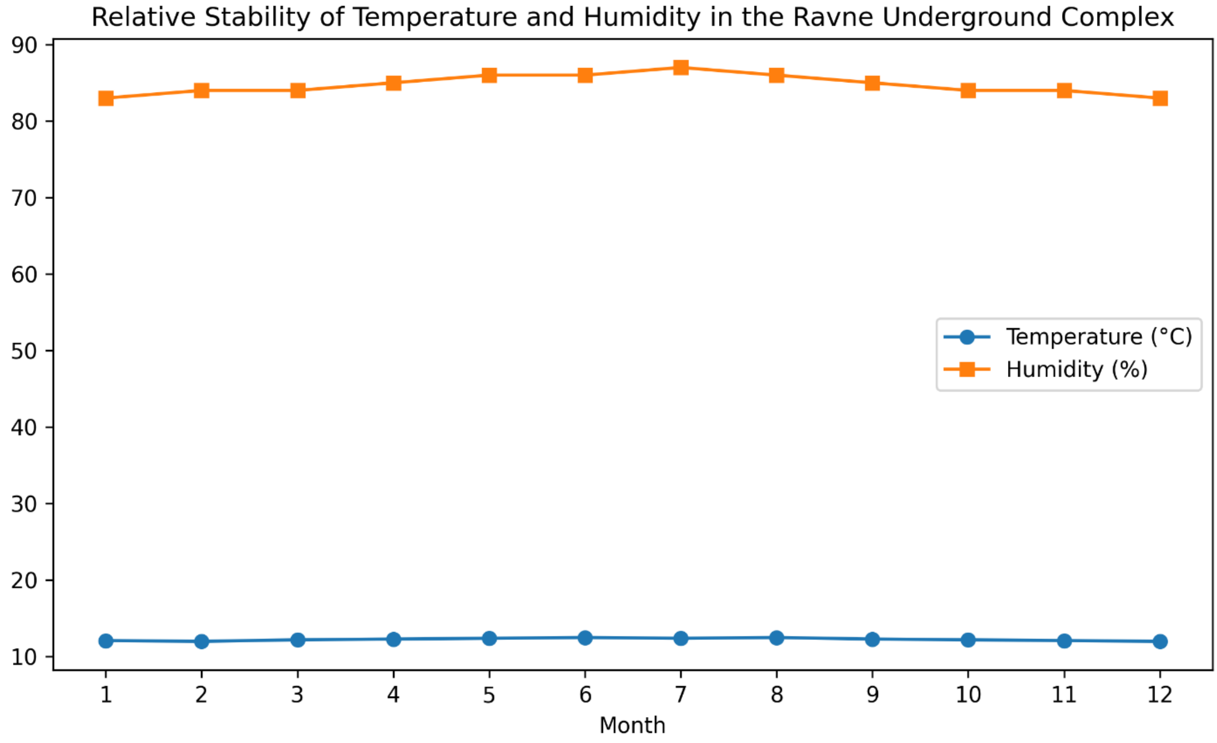

Fig. 10 **Relative stability of temperature and humidity within the Ravne Underground Complex in 2023.**

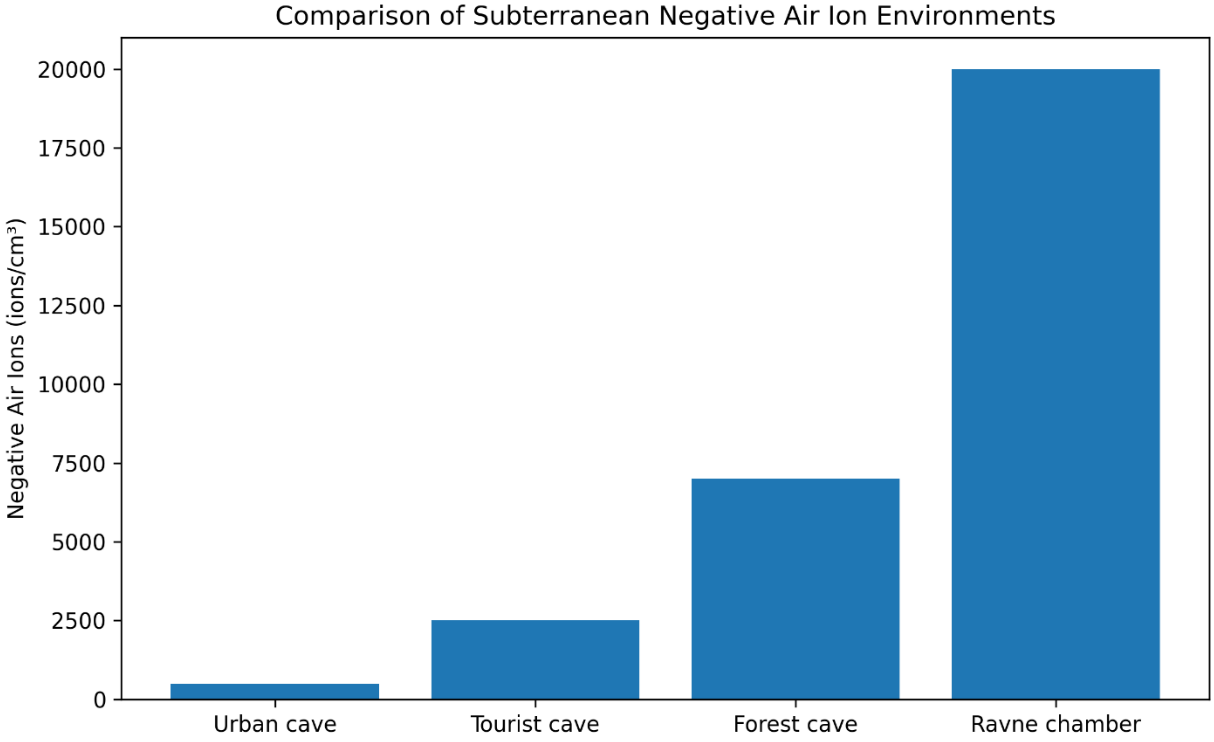

Fig. 11 **Comparison of negative air ion concentrations in selected subterranean environments in 2023.**

Table 2 Global comparative measurements of NAI (negative air ion) concentrations at archaeological, natural, and subterranean sites recorded by the author (2018-2025).

Country/region	Site	Environment type	Recorded NAI range (ions/cm³)	Notes
Bosnia-Herzegovina	Ravne Tunnel Complex	Underground tunnel system	10,000-330,000	Stable year-round ionization
Zimbabwe	Great Zimbabwe	Megalithic complex	Up to 100,000	Measured before a thunderstorm
Italy (Sardinia)	La Prisgiona Nuraghe	Megalithic stone structure	Up to 6,000	Elevated natural ionization
Slovenia	Rešeto, Cerkniško Lake	Natural karst environment	Up to 5,000	High humidity conditions
Italy	Damanhur Ritual Circle	Sacred ceremonial site	Up to 2,600	Stable atmospheric conditions
Croatia	Sveta Foška Church	Historical stone structure	Up to 2,100	Rain-associated ion increase
Serbia	Najdanov Krug	Archaeological/geophysical site	1,000-1,500	Local geomagnetic anomaly
North Macedonia	Kanda Geoglyph	Archaeological landscape	1,000–1,500	Elevated geomagnetic readings
Bosnia-Herzegovina	Igman Mountain	Mountain environment	Up to 1,200	Clean alpine atmosphere
Bosnia-Herzegovina	Jahorina Mountain	Mountain environment	Up to 1,200	Outdoor high-altitude conditions
United States	Yellowstone National Park	Geothermal natural environment	Up to 1,000	Geothermal activity present
Germany	Avebury Sanctuary	Megalithic site	500-1,000	Stable moderate ionization
Germany	Zuschen Fritzlar	Archaeological site	500-1,000	Moderate ionization
United States	Red Rock Canyon	Desert canyon environment	400-900	Dry high-elevation conditions
United States	Sage Wall	Stone formation	400-900	Moderate environmental ionization
United Kingdom	Silbury Hill	Tumulus site	Around 400	Stable but low ionization
South Africa	Adam’s Calendar	Megalithic site	200-3,000	Weather-dependent variability
Ethiopia	Axum	Archaeological complex	200-3,000	Variable atmospheric conditions

Source: Modified and summarized from Osmanagich [6].

Table 3 Comparative overview of negative air ion concentrations reported in published scientific studies.

Study	Environment type	Reported NAI range (ions/cm³)	Stability characteristics	Main observations
Bratt & Trinh (2021)	Natural limestone caves	2,000-6,000	Seasonal variation	Stable cave microclimate with moderate ionization
Herscu (2018)	Mountain and urban environments	500-12,000	Variable	Significant seasonal fluctuations
Chudnovsky et al. (2004)	Subterranean cavities	500-5,000	Relatively stable	Strong natural shielding effects
Kolarž et al. (2012)	Waterfalls and humid environments	10,000-50,000	Weather-dependent	Strong Lenard-effect ionization
Harrison (2006)	Atmospheric condensation environments	Variable	Dynamic	Ionization linked to condensation processes
Laakso et al. (2007)	Atmospheric nucleation events	Variable	Event-controlled	Air ions associated with aerosol formation
Jiang et al. (2018)	Indoor and outdoor environmental studies	Typically < 5,000	Environment-dependent	Relationship between air quality and ionization
Xiao et al. (2023)	Environmental ionization review	Variable	Comparative review	Biological and environmental implications of NAIs

Source: Osmanagich [6].

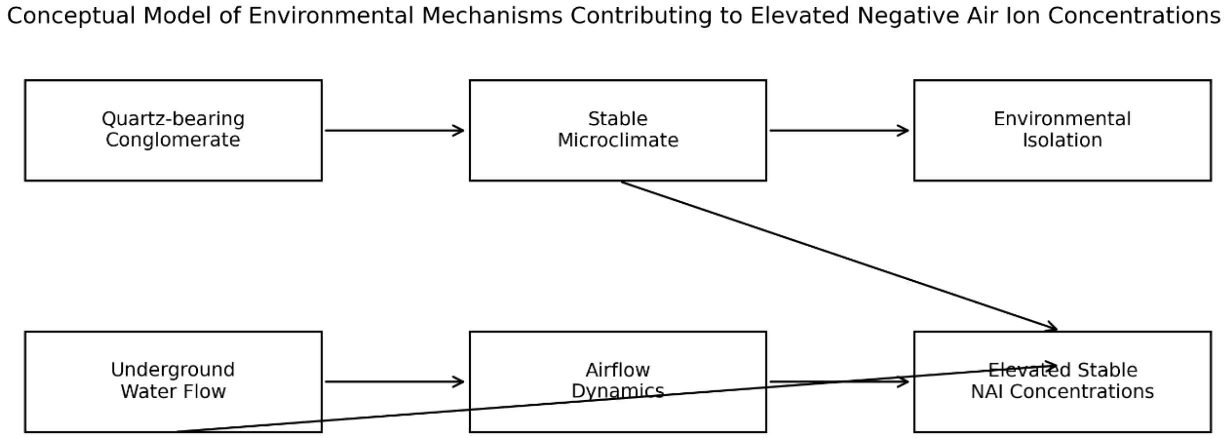

Fig. 12 Conceptual model of environmental mechanisms contributing to elevated negative air ion concentrations within the Ravne Underground Complex.

stability may contribute to the persistence and accumulation of elevated concentrations of negative air ions within the tunnel system.

Comparative concentrations of NAIs (negative air ions) measured or reported in selected subterranean environments, including urban caves, tourist caves, natural forest caves, and the Ravne Underground Complex in 2023 (measurements done in January and June of 2023). The Ravne tunnel system exhibits elevated NAI concentrations compared with most documented underground environments, suggesting stable geological, hydrological, and atmospheric conditions conducive to long-term ion persistence.

Previous investigations of the Ravne Underground Complex addressed environmental measurements of negative air ions, underground microclimatic conditions, hydrological observations, regenerative environmental characteristics, geological analyses, and archaeological stratigraphy [5-10]. These studies documented the complex geological structure of the tunnel system, conglomerate formations, sedimentary fill sequences, and underground water circulation within different sectors of the Ravne network.

Despite the growing body of environmental observations, the origin and persistence of elevated concentrations of negative air ions within the Ravne tunnel system have not previously been examined within an integrated geological, hydrological, mineralogical, and microclimatic framework. The present article evaluates the interaction of several environmental factors that may contribute to the formation and long-term stability of a subterranean ionization environment. Particular attention is given to the possible role of underground water movement, quartz-bearing conglomerates, airflow dynamics, stable humidity and temperature conditions, and environmental isolation within the Ravne Underground Complex.

The relationships proposed in this study are summarized in a conceptual environmental model that integrates geological, hydrological, atmospheric, and microclimatic mechanisms that may contribute to elevated concentrations of negative air ions within the Ravne Underground Complex (Fig. 12). The site may therefore represent a useful natural laboratory for future interdisciplinary research involving hydrogeology, cave atmospheres, atmospheric electricity, environmental ionization processes, and stable subterranean environmental systems.

Conceptual model illustrating the interaction of geological, hydrological, atmospheric, and microclimatic factors proposed to contribute to the generation and long-term persistence of elevated concentrations of NAIs (negative air ions) within the Ravne Underground Complex. Quartz-bearing conglomerates, underground water circulation, stable subterranean microclimatic conditions, airflow dynamics, and environmental isolation may collectively support the formation of a stable subterranean ionization environment.

2. Materials and Methods

2.1 Legal and Institutional Framework

Scientific investigations within the Ravne Underground Complex were conducted under the supervision of the Archaeological Park: Bosnian Pyramid of the Sun Foundation, headquartered in Visoko, Bosnia-Herzegovina. The Foundation serves as the principal research institution coordinating archaeological, geological, environmental, geodetic, and multidisciplinary investigations within the Bosnian Valley of the Pyramids project area.

Field activities, environmental measurements, geological observations, and sampling procedures presented in this article were carried out as part of the Foundation's ongoing scientific and conservation efforts, in cooperation with domestic and international researchers.

Archaeological excavation and underground research activities within the Ravne tunnel network are conducted under annual permits issued by the Ministry of Culture and Sports of the Zenica-Doboj Canton and in cooperation with the local Heritage Museum Visoko. All site activities are additionally subject to review procedures established by the Federal Institute for the Protection of Monuments of Bosnia-Herzegovina.

Environmental monitoring within the Ravne Underground Complex has been conducted continuously throughout the stages of tunnel excavation, cleaning, conservation, and the development of public access. The principal investigator and corresponding author participated directly in long-term field investigations, environmental measurements, site documentation, and interdisciplinary coordination related to the Ravne tunnel system.

The geological, hydrological, microclimatic, and environmental datasets used in this article were obtained during authorized field investigations conducted between 2010 and 2025 within the protected research area managed by the Archaeological Park: Bosnian Pyramid of the Sun Foundation.

2.2 Study Area

The Ravne Underground Complex is located near the town of Visoko in central Bosnia-Herzegovina, approximately 30 km northwest of Sarajevo (Fig. 1). The tunnel system extends beneath the Ravne Valley and the adjacent slopes of the Bosnian Valley of the Pyramids region. The investigated underground network includes interconnected passages, chambers, side tunnels, dry-stone wall structures, water-bearing sections, and excavated corridors distributed across multiple sectors of the Ravne complex (Fig. 2).

Geologically, the tunnel system is developed primarily within horizontally layered conglomerate formations overlying Miocene marl and sandstone deposits (Fig. 3). The conglomerate consists of rounded clasts embedded within a sandy-calcareous matrix exhibiting variable lithological composition. Petrographic analyses identified quartz, quartzite, calcite, sandstone fragments, chert, shale, schist, and basaltic components within collected samples (Fig. 6).

The underground environment is characterized by relatively stable temperatures, elevated humidity, reduced atmospheric disturbance, and permanent water circulation within selected sections of the tunnel system (Figs. 8 and 10). The combination of confined subterranean conditions and active hydrogeological processes provided the basis for environmental monitoring and investigation of negative air ion concentrations.

2.3 Environmental Measurements

Environmental measurements within the Ravne Underground Complex were conducted during repeated field campaigns between 2010 and 2026. Measurements were performed at multiple locations distributed throughout the underground network, including tunnel intersections, chambers, water-bearing sections, excavated corridors, and environmentally isolated sectors.

Negative air ion concentrations were measured using portable AlphaLab air ion counters, including the

AlphaLab AIC3ST and AIC3PRO models (AlphaLab Inc., Salt Lake City, Utah, USA) (Fig. 7). The instruments were used during different stages of environmental monitoring between 2010 and 2026. All instruments were calibrated approximately every six months according to manufacturer recommendations.

The air ion counters operated within a measurement range of 0 to 2,000,000 negative air ions per cubic centimeter (ions/cm³). Spot measurements consisted of two consecutive recordings per location, with each measurement representing an average sampling interval of approximately five minutes.

Measurements were repeated under varying seasonal conditions and at different distances from tunnel entrances in order to evaluate spatial and temporal variability within the subterranean environment.

Temperature and relative humidity were monitored using portable digital environmental sensors. Additional field observations included airflow characteristics, groundwater presence, condensation zones, sediment moisture, and overall microclimatic stability across different tunnel sectors.

Measurements were conducted at heights approximating normal human breathing zones within accessible tunnel sections. In areas with underground water circulation, observations additionally considered the proximity of measurement points to active water channels, wet conglomerate surfaces, and zones of increased humidity.

2.4 Geological and Stratigraphic Investigations

Geological observations and stratigraphic documentation were conducted during excavation and cleaning activities within several sectors of the Ravne tunnel system. Particular attention was given to the relationships between compact conglomerate substrate, unconsolidated tunnel fill deposits, and underground cavity morphology (Figs. 4 and 5).

Field observations documented visible stratigraphic boundaries between lithified conglomerate formations and loose sedimentary fill material. Sedimentological characteristics, including grain size, compaction, clast composition, moisture retention, and structural stability, were visually examined and recorded during excavation activities.

The regional geological structure of the Ravne Valley and associated conglomerate formations was evaluated using previously published geological analyses and field observations from the Ravne tunnel system (Fig. 3).

2.5 Petrographic Analysis

Representative conglomerate samples collected from the Ravne Underground Complex were subjected to petrographic examination by APS Inc. (American Petrographic Services) in Saint Paul, Minnesota, USA. Laboratory analysis was performed beginning January 9, 2012, and on subsequent dates in accordance with APS Standard Operating Procedure 00LAB004, “Petrographic Examination Aggregates for Concrete”, and in general accordance with ASTM C295 [11].

Petrographic examination included both hand-sample analysis and thin-section microscopy. Observations were conducted using an Olympus SZ60 stereo-zoom microscope with magnification up to 65×, a Nikon E600 polarizing light microscope with magnification up to 600×, and a Keyence VHX-1000 digital microscope with magnification up to 200×.

Macroscopic and microscopic analyses identified unconsolidated silt- to pebble-sized grains consisting primarily of rounded to sub-angular particles. Lithologies observed within the samples included carbonate, silicified carbonate, chert, siltstone, sandstone, shale, slate, schist, quartzite, and basalt. Individual mineral grains identified during analysis included quartz, hematite, and calcite. Calcite spar cementation between sand-sized and pebble-sized grains was additionally documented.

APS concluded that the observed mineralogical composition, grain variability, and calcite spar cementation are consistent with a naturally formed conglomerate deposit.

Particular attention in the present study was given to quartz-bearing components due to their potential relevance to electrostatic interactions and environmental ionization processes under humid subterranean conditions.

2.6 Comparative Environmental Analysis

Measured negative air ion concentrations from the Ravne Underground Complex were compared with values reported in selected urban, natural, and subterranean environments based on previously published environmental studies and field measurements (Figs. 9 and 11). Comparative environments included urban interiors, city environments, forests, mountainous regions, waterfalls, caves, and subterranean systems characterized by elevated humidity and active water circulation.

The comparison was intended to place the Ravne measurements within a broader environmental context and to evaluate the relative magnitude of documented subterranean ion concentrations.

2.7 Conceptual Environmental Model

A conceptual environmental model was developed to evaluate potential interactions among geological composition, groundwater circulation, airflow dynamics, stable microclimatic conditions, and environmental isolation within the Ravne Underground Complex (Fig. 12).

The model integrates geological, hydrological, atmospheric, and mineralogical observations collected during long-term field investigations and environmental monitoring. Emphasis was placed on the possible contribution of flowing water, quartz-bearing conglomerates, humidity stability, and confined subterranean conditions to the generation and persistence of elevated concentrations of negative air ions within the tunnel system.

3. Results

3.1 Geological and Stratigraphic Observations

Field investigations within the Ravne Underground Complex documented a relatively stable subterranean environment developed primarily within horizontally layered conglomerate formations overlying marl and sandstone deposits (Fig. 3). The conglomerate consists of rounded clasts embedded in a sandy-calcareous matrix, exhibiting variable lithological composition and varying degrees of cementation.

Internal tunnel stratigraphy revealed clear sedimentological distinctions between compact conglomerate substrate and unconsolidated tunnel fill deposits (Fig. 4). Excavation activities within Ravne 6 also documented visible contact zones separating lithified conglomerate formations from loose sedimentary material that occupies portions of the tunnel passages (Fig. 5; Table 1).

The conglomerate formations exhibited relatively high structural stability across several sections of the tunnel system despite elevated humidity and the long-term presence of groundwater circulation. Localized clay-rich floor deposits and compact sedimentary horizons were also observed in multiple sectors of the underground network.

3.2 Petrographic Characteristics of the Conglomerate

Petrographic examination of conglomerate samples identified substantial mineralogical heterogeneity within the tunnel matrix (Fig. 6). The thin-section analyses documented the presence of quartz, quartzite, calcite, sandstone fragments, chert, shale, schist, and basaltic material embedded within the conglomerate structure.

Quartz-bearing components were common throughout the examined samples. Rounded clasts of varying grain size and lithological composition were observed within a cemented matrix exhibiting heterogeneous mineral distribution. Microscopic examination additionally revealed variable grain contacts, cementation patterns, and mineral interfaces.

The identified mineralogical composition suggests multiple lithological sources contributed to conglomerate formation and indicates potentially favorable conditions for electrostatic interactions in humid subterranean environments.

3.3 Underground Water Circulation

Permanent underground water channels were documented within several sectors of the Ravne tunnel network (Fig. 8). Water movement was observed both along tunnel floors and through localized seepage zones associated with conglomerate formations and sedimentary interfaces.

The presence of flowing water was commonly associated with elevated humidity, localized condensation, and reduced accumulation of airborne particulates within enclosed sections of the tunnel system. Water-bearing sectors frequently exhibited stable airflow conditions and relatively limited temperature variability compared with surface environments.

The observed hydrological activity indicates active underground circulation within portions of the Ravne conglomerate formation and suggests ongoing interaction between groundwater movement and the subterranean atmospheric environment.

3.4 Environmental Measurements and Negative Air Ion Concentrations

Environmental monitoring conducted between 2010 and 2025 documented consistently elevated concentrations of negative air ions throughout multiple sections of the Ravne Underground Complex. Measurements were performed using portable air ion counters and associated environmental monitoring instruments deployed at different underground locations (Fig. 7).

Recorded NAI concentrations frequently exceeded 20,000 ions/cm^3 in deeper sectors of the tunnel network, while isolated chambers occasionally exhibited substantially higher values. Measured concentrations exceeded values commonly reported for urban interiors, city environments, forests, and many mountainous regions (Fig. 9).

Spatial variability in NAI concentrations was also observed within the underground network. Environmentally isolated sections, characterized by stable humidity, reduced airflow disturbance, and proximity to underground water circulation, generally exhibited higher measured values than sectors near tunnel entrances.

Comparative analysis of selected subterranean environments further demonstrated that the Ravne tunnel system exhibits elevated NAI concentrations compared with many documented cave and other underground environments (Fig. 11).

3.5 Microclimatic Stability

Environmental monitoring indicated relatively stable subterranean microclimatic conditions throughout the Ravne Underground Complex (Fig. 10). Temperatures remained relatively constant across seasons, while relative humidity generally remained elevated in enclosed underground sections.

The subterranean environment exhibited substantially lower atmospheric variability than the surrounding surface conditions. Seasonal fluctuations commonly observed in outdoor environments were significantly reduced within deeper sectors of the tunnel network.

Limited airflow disturbance, stable humidity, and relatively constant temperatures were particularly characteristic of environmentally isolated sections exhibiting elevated NAI concentrations. Condensation zones associated with underground water circulation were also documented in several sectors of the tunnel system.

3.6 Integrated Environmental Relationships

The collected geological, hydrological, mineralogical, and atmospheric observations indicate the presence of several interacting environmental factors within the Ravne Underground Complex. Quartz-bearing conglomerate formations, underground water circulation, stable humidity, reduced atmospheric disturbance, and confined subterranean conditions collectively appear to contribute to the persistence of elevated concentrations of negative air ions.

The observed environmental relationships are summarized in the conceptual model presented in Fig. 12, which integrates geological structure, hydrological activity, airflow dynamics, microclimatic stability, and environmental isolation within the Ravne tunnel system.

4. Discussion

The environmental conditions documented within the Ravne Underground Complex indicate an unusually stable subterranean atmosphere, characterized by elevated concentrations of negative air ions, constant microclimatic conditions, underground water circulation, and quartz-bearing conglomerate formations. Although no single mechanism can presently explain the full magnitude and persistence of measured NAI concentrations, the collected geological, hydrological, mineralogical, and atmospheric observations suggest that several interacting environmental processes are likely involved.

One of the most significant factors appears to be the continuous presence of underground flowing water within confined tunnel sectors (Fig. 8). Previous atmospheric and environmental studies demonstrated that moving water can generate substantial quantities of negative air ions through droplet fragmentation and charge separation processes commonly described as the Lenard effect [1]. In natural environments such as waterfalls, river canyons, coastal zones, and highly humid cave systems, elevated ion concentrations are commonly associated with aerosolization of water and persistent humidity.

The Ravne Underground Complex differs from many ordinary cave systems in that portions of the tunnel network combine active underground water movement with relatively stable airflow and limited atmospheric disturbance. Such environmental stability may contribute not only to ion generation but also to the prolonged persistence of ions within enclosed underground sectors. In outdoor environments, ion concentrations often fluctuate rapidly due to atmospheric mixing, wind activity, temperature gradients, pollution, and solar radiation. In contrast, the Ravne tunnel environment exhibits substantially reduced atmospheric variability (Fig. 10).

The mineralogical composition of the Ravne conglomerate may also contribute to localized ionization processes. Petrographic analyses identified abundant quartz-bearing material within the tunnel matrix (Fig. 6). Quartz-rich geological formations are known to exhibit electrostatic and piezoelectric properties under specific physical conditions, particularly in environments involving moisture, pressure variation, friction, or microfracturing. Although the present investigation did not directly measure piezoelectric activity, the combination of quartz-bearing conglomerates, groundwater movement, and confined humidity-rich conditions may represent a favorable environment for localized electrostatic interactions.

Another potentially important factor is the relatively low level of environmental contamination in the deeper sections of the tunnel system. Measurements conducted within the Ravne Underground Complex documented very low levels of electromagnetic disturbance and airborne particulate activity relative to urban environments. Previous environmental studies suggested that elevated pollution and aerosol loading may reduce the stability and persistence of atmospheric ions through rapid recombination processes. The isolated underground conditions at Ravne may therefore allow elevated ion concentrations to persist for longer periods than in surface environments.

The observed environmental relationships appear consistent with measurements reported from selected cave systems and subterranean environments where elevated negative air ion concentrations have also been documented [1]. However, comparative analysis indicates that measured values from several sectors of the Ravne tunnel system exceed concentrations commonly reported from many natural cave environments (Fig. 11). The combination of active hydrology, quartz-bearing conglomerates, stable humidity, and restricted atmospheric exchange may therefore create an unusually favorable environment for subterranean ionization.

An additional consideration involves the long-term stability of the Ravne microclimate itself. Temperatures and humidity levels within the tunnel system remained relatively constant throughout seasonal monitoring periods (Fig. 10). Such stability likely contributes to the preservation of underground atmospheric equilibrium and the reduction of rapid environmental fluctuations that could otherwise disrupt ion persistence.

The conceptual environmental model presented in Fig. 12 summarizes the principal relationships proposed in this study. According to this model, elevated concentrations of negative air ions within the Ravne Underground Complex likely result from the interaction of several mutually reinforcing environmental factors rather than from a single isolated mechanism. Flowing underground water, mineral composition of conglomerates, stable humidity, restricted airflow variability, and environmental isolation collectively appear to support the generation and persistence of subterranean ionization processes.

Several limitations should also be acknowledged. The present study was primarily observational and environmental in character. Direct experimental investigation of electrostatic generation mechanisms, aerosol physics, groundwater chemistry, radon interactions, or piezoelectric effects was beyond the scope of the current investigation. Additional long-term monitoring using standardized atmospheric instrumentation, continuous ion-recording systems, hydrochemical analyses, and controlled comparative cave measurements would further improve understanding of the environmental processes operating within the Ravne tunnel system.

Nevertheless, the environmental characteristics documented in the Ravne Underground Complex demonstrate that the site constitutes an unusual subterranean microenvironment, warranting continued multidisciplinary investigation. The combination of geological stability, active underground hydrology, stable atmospheric conditions, and elevated concentrations of negative air ions provides a valuable setting for future research in cave climatology, hydrogeology, environmental physics, and subterranean atmospheric processes.

5. Conclusion

Environmental investigations conducted within the Ravne Underground Complex documented an unusual subterranean microenvironment characterized by elevated concentrations of negative air ions, stable humidity and temperature conditions, underground water circulation, and quartz-bearing conglomerate formations.

Geological observations demonstrated that the tunnel system is developed within relatively stable conglomerate formations overlying marl and sandstone deposits. Stratigraphic investigations documented clear distinctions between compact conglomerate substrate and unconsolidated sedimentary fill deposits, while petrographic analyses identified substantial mineralogical heterogeneity, including abundant quartz-bearing material.

Long-term environmental monitoring repeatedly documented elevated concentrations of negative air ions within multiple sectors of the tunnel network. Measured values exceeded concentrations commonly reported for many urban environments and numerous natural outdoor settings. The highest values were generally associated with environmentally isolated underground sections characterized by stable humidity, reduced atmospheric disturbance, and active underground water circulation.

The collected geological, hydrological, mineralogical, and atmospheric observations suggest that the elevated negative air ion concentrations within the Ravne Underground Complex are likely produced through the interaction of several environmental factors rather than by a single isolated mechanism. Flowing underground water, quartz-bearing conglomerates, stable subterranean microclimatic conditions, restricted airflow variability, and environmental isolation collectively appear to contribute to the persistence of a stable underground ionization environment.

Although the present investigation was primarily observational and environmental in character, the results indicate that the Ravne Underground Complex represents a valuable natural setting for future multidisciplinary research involving hydrogeology, cave climatology, atmospheric ionization, environmental physics, and subterranean environmental systems.

Additional long-term investigations involving continuous atmospheric monitoring, hydrochemical analysis, aerosol physics, radon measurements, and comparative cave studies may further clarify the environmental mechanisms responsible for the generation and persistence of elevated concentrations of negative air ions within the Ravne tunnel system.

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7. Conflict of Interest

The author serves as founder and director of the Archaeological Park: Bosnian Pyramid of the Sun Foundation. This affiliation is disclosed for transparency. The author declares no financial or commercial conflicts of interest related to the present study.

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9. Data Availability Statement

The geological observations, environmental measurements, petrographic analyses, and microclimatic datasets supporting the findings of this study are available from the corresponding author upon reasonable request.

Selected environmental measurements and geological documentation were obtained during long-term field investigations conducted within the Ravne Underground Complex between 2010 and 2025 under the supervision of the Archaeological Park: Bosnian Pyramid of the Sun Foundation.

10. AI (Artificial Intelligence) Use Disclosure

Artificial intelligence-assisted language tools were used exclusively for limited editorial support during preparation of the manuscript, including language refinement, organizational assistance, and formatting suggestions. All scientific interpretations, environmental analyses, geological observations, field measurements, conclusions, and final manuscript content were developed, reviewed, and approved by the author.

The author assumes full responsibility for the scientific accuracy, originality, and integrity of the article.

References

[1] Kolarž, P., Filipović, D., Marković, V., Mijić, Z., and Marinković, B. 2012. "Air Ionization Balance in Waterfalls and Relation to the Lenard Effect." *Atmospheric Chemistry and Physics* 12: 3687-98. doi:10.5194/acp-12-3687-2012.

[2] Wu, C. C., Lee, G. W. M., Yang, S., Yu, K.-P., and Lou, C. L. 2006. "Influence of Air Humidity and the Distance from the Source on Negative Air Ion Concentration in Indoor Air." *Science of the Total Environment* 370 (1): 245-53. doi:10.1016/j.scitotenv.2006.07.020.

[3] Jiang, S. Y., Ma, A., and Ramachandran, S. 2018. "Negative Air Ions and Their Effects on Human Health and Air Quality Improvement." *International Journal of Molecular Sciences* 19 (10): 2966. doi:10.3390/ijms19102966.

[4] Xiao, S., Wei, T., Petersen, J. D., Zhou, J., and Lu, X. 2023. "Biological Effects of Negative Air Ions on Human Health and Integrated Multiomics to Identify Biomarkers: A Literature Review." *Environmental Science and Pollution Research* 30 (27): 69824-36. doi:10.1007/s11356-023-27133-8.

[5] Osmanagich, S. 2025. "Archaeological Stratigraphy and Environmental Analysis of the Ravne 3 Tunnel Complex." *Acta Scientific Environmental Science* 2 (1): 68-96. doi:10.5281/zenodo.17505655.

[6] Osmanagich, S. 2025. "Environmental Ionization in Enclosed Geospheres: Comparative Study of Global and Local Measurements (2018-2025)." *Journal of Advanced Artificial Intelligence, Engineering & Technology* 1 (3): 24. doi:10.56147/aaiet.1.3.24.

[7] Osmanagich, S. 2025. "Public Health and Epidemiological Implications of Ionized Air: Negative Air Ions and Their Role in Microbial Reduction—Evidence from the Ravne Tunnel Complex in Bosnia-Herzegovina." *Archives of Epidemiology & Public Health Research* 4 (2): 1-6. doi:10.33140/AEPHR.04.02.06.

[8] Osmanagich, S. 2025. "Ravne Tunnel Complex (Visoko, Bosnia-Herzegovina) as a Scientifically Documented Regenerative Environment: Multi-year Monitoring of Ionization, Radiation, and Other Energy Metrics (2018-2025)." *Acta Scientific Environmental Sciences Journal* 9 (6): 122-33. doi:10.31080/ASMS.2025.09.2099.

[9] Osmanagich, S. 2026. "Systematic Archaeological Investigation of the Ravne Underground Complex in Bosnia and Herzegovina." *Archaeological Discovery* 14 (2): 125-51. doi:10.4236/ad.2026.142007.

[10] Osmanagich, S. 2026. "An Anthropological Interpretation of the Subterranean Ravne Tunnel System (Central Bosnia)." *Advances in Anthropology* 16 (1): 23-50. doi:10.4236/aa.2026.161002.

[11] American Petrographic Services, Inc. 2012. *Petrographic Examination Report for Bosnian Pyramid Underground Tunnel Sample (APS Job No. 10-07386).* Saint Paul, Minnesota, USA.