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CHARACTERISTICS OF ROCKS BASED ON PETROGRAPHIC AND GEOCHEMICAL ANALYSIS: A STUDY IN THE 'LAND OF A THOUSAND MEGALITHS', INDONESIA

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Abstract: The megalithic traditions of Central Sulawesi represent one of Indonesia's most important prehistoric cultural landscapes, widely recognized as "The Land of a Thousand Megaliths." Despite their significance, scientific investigations into the lithological sources of the megaliths remain limited, with most previous research focusing primarily on archaeological and cultural aspects. This study aims to characterize the petrographic and geochemical properties of rocks associated with megalithic artifacts in the Bada and Behoa Valleys of Poso Regency, Central Sulawesi. A total of seven representative rock samples were collected based on lithological diversity and field resemblance to megalithic artifacts. Petrographic analysis was conducted using thin section microscopy to determine mineralogical composition, textures, and structural features, while geochemical analysis was performed through X-ray fluorescence (XRF) to quantify major oxides and support tectonomagmatic interpretations. The petrographic results revealed that five samples belong to plutonic igneous rocks—classified as quartz monzonite and monzonite—while two samples were identified as metamorphic rocks, namely amphibolite and biotite–chlorite schist. Geochemical data indicate that the plutonic rocks are predominantly ferroan, with affinities to both calc-alkaline and tholeiitic magma series, whereas the metamorphic rocks are associated with island arc tholeiite protoliths. Weathering assessments show that most samples remain fresh, except for one moderately weathered monzonite. The results demonstrate that megalithic builders utilized locally available rocks that possessed suitable durability and mechanical strength for carving and construction. The findings further suggest a strong geological–cultural connection, as the communities strategically selected rock materials that ensured long-term preservation of the monuments. This study provides new insights into the raw material sources of megalithic artifacts in Central Sulawesi and contributes to broader discussions on lithic technology, resource procurement, and heritage conservation. By integrating petrographic and geochemical approaches, the research establishes a scientific foundation for future geoarchaeological studies and supports conservation strategies for safeguarding Indonesia's megalithic heritage.

Keywords: central sulawesi, geochemical analysis, megalith, petrographic, rock characteristics

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INTRODUCTION

Megalithic cultural heritage stands as a monumental expression of how prehistoric humans interacted with their natural surroundings. Different locations around the world have megalithic sites that have become the focus of scientific research which unites archaeology with anthropology and geoscience approaches at places like Stonehenge in the United Kingdom, Carnac in France and Göbekli Tepe in Turkey. The research investigates both the religious and social aspects of the monuments and their stone origins as well as construction methods and site network dynamics (Freire-Lista, 2021; Sanjuán et al., 2023). The advancement of material-based analytical research during the last decade has emerged from petrographic and geochemical methods including X-ray fluorescence (XRF). The analytical techniques prove useful for tracking stone material origins and studying manufacturing methods while understanding human-geological resource interactions (Štrba, 2015; Ali et al., 2017; Tibbits et al., 2023). The techniques generate empirical data about rock mineralogical and chemical compositions that enhances archaeological interpretations which previously relied on observations of form and context (Wang et al., 2022). Geoscientific approaches gain increased significance in megalithic research because evidence-based cultural heritage preservation has become a worldwide priority. The conservation of cultural sites built from

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natural stone requires both understanding their geological features and assessing their exposure to weathering processes (Viles, 2013; Visone et al., 2025). Stone material durability against erosion together with climate change and human activity determines the physical survival of heritage sites in many cases. The combination of petrographic and geochemical information serves both academic research needs and enables the creation of efficient conservation strategies (Pereira, 2023).

The use of archaeology-geology integrated approaches at different sites across the world remains infrequent in Indonesia according to Kirleis et al. (2012) and Ansori et al. (2024). The application of integrated archaeological and geological methods in Indonesian megalithic research is relatively rare because the discipline has traditionally focused on cultural and chronological studies (Bonatz et al., 2008; Kealy et al., 2018). This situation is concerning because Indonesia hosts numerous megalithic sites which stretch from Sumatra and Nias to Sumba and Sulawesi (Steimer, 2018).

Studies of megalithic structures now focus on material stone properties in addition to their symbolic value and historical context. The El Pozuelo dolmens in Spain and the Wietrzychowice site in Poland show that megalith builders commonly obtained their rocks from local sources (Linares-Catela et al., 2023; Pawlikowski et al., 2020). Modern analytical methods that include petrographic mineralogical and geochemical studies have analyzed megalithic stones such as Stonehenge sarsens to determine their composition and properties (Nash et al., 2021). Research studies reveal information about the origin of raw materials used in construction alongside techniques for building megaliths and their relationship with the surrounding landscape (Wheatley et al., 2010). The study of stone texture in addition to tool production mechanics has been conducted by researchers (Tilley, 2004; Wadley & Kempson, 2011). Through multidisciplinary research scientists obtain a deeper understanding of prehistoric landscapes and megalithic phenomena (Columbu et al., 2023).

The Bada and Behoa and Napu Valleys in Poso Regency Central Sulawesi represent the primary megalithic area of Indonesia. The region stands out because of its abundant megalithic artifacts which include stone figures and d olmen structures and engraved rock art distributed throughout an unperturbed natural environment (Kirleis et al., 2012). The area within Lore Lindu National Park contains cultural landmarks together with natural scenery and diverse species (Rahim et al., 2023). Since the beginning of the 20th century this site has attracted archaeological interest because of its special megalithic forms together with its complex prehistoric cultural associations. The evaluation of rocks through petrographic and XRF geochemical analysis has become extensive in various fields to establish provenance and composition as well as determine suitability for megalithic material applications. Scientists who studied the Bualemo area of Gorontalo used petrographic and XRF analysis to discover that the rocks belonged to andesite and basaltic andesite groups with tholeiitic island arc basalts that originated from subduction tectonic settings (Marfian et al., 2023; Permana et al., 2023). The fossilized wood from the Tohupo River showed that silica recrystallization formed a dominant quartz mineral structure. The XRF and petrographic methods proved that amorphous silica in the form of chalcedony exists in the rock which explains its resistance to weathering (Permana, 2019). The same techniques used in Otanmäki, Finland and Gua Musang, Malaysia have identified the physical–mechanical properties of gabbro and granite rocks as well as mineral compositions of granite and tuff rocks which could serve as construction and ornamental materials. The evaluation of rock weathering resistance depends on High SiO_2 content along with plagioclase and K-feldspar presence and rare earth elements (REEs) trace element ratios (Aladejare, 2021; Ismail et al., 2023; Oudy et al., 2023; Sebbab et al., 2024; Shafiee et al., 2024). An integrated analysis of petrographic and XRF data serves to both understand rock characteristics and assess their suitability as megalithic materials in geological and archaeological and engineering applications.

The development of petrographic and XRF analytical techniques provides researchers with strong potential to study material aspects of Central Sulawesi's megalithic sites. The petrographic microscope allows researchers to identify rock minerals and study rock textures yet XRF analysis generates quantitative data about major and minor chemical elements. The integrated analytical approach enables researchers to fully characterize rock samples and link their findings to natural geological settings. Scientific preservation strategies can b e designed using the obtained data.

The identification of weathering vulnerabilities or element leaching in rocks enables conservationists to select appropriate protective measures. The data obtained from geochemical analysis enables the creation of exact replicas and digital site reconstructions and science-based educational content for cultural tourism programs.

The integration of petrographic and geochemical data helps minimize the widespread speculative tendencies which commonly affect megalithic studies. The lack of strong material evidence forces researchers to build their interpretations about construction methods and distribution patterns and intersite relationships using unsupported assumptions or cultural analogies. Laboratory-based methods create an unbiased system for testing hypotheses which generates quantifiable results that can be duplicated. Through geochemical analysis scientists can detect distribution patterns which appear in rocks of identical composition to reveal either unified material origins of megalithic groups or new evidence of material transport patterns. The research findings will enhance existing knowledge about prehistoric economic and technological and social networks throughout Central Sulawesi. This research fulfils the essential requirement of material-based studies about megalithic rocks because Indonesia lacks sufficient scientific data about megalithic rocks in the "Land of a Thousand Megaliths." This research uses petrographic and geochemical XRF methods to study rock characteristics while proving material origins and analyzing their geological associations. The research contributes to an extensive project which aims to create an integrated system for cultural heritage preservation throughout the Land of a Thousand Megaliths. Scientific data collection through rock analysis will serve to develop a conservation model that uses empirical evidence.

The research serves as a starting point for developing geoarchaeological methods which will help protect and reposition megalithic sites. The growing environmental threats and rapid social changes demand deep scientific knowledge about megalithic heritage to protect both physical sites and cultural values and community identities.

MATERIALS AND METHODS

Research Location and Materials

The megalithic study sites are located in three valleys within the administrative region of Poso Regency (Figure 1). These three locations are the Bada Valley, the Behoa Valley, and the Napu Valley. Most of the sites especially those in the Behoa Valley are located within Lore Lindu National Park—a conservation area and a biosphere reserve. The park is made of hills and mountains, forests, and rivers that drain the area. There are various types of megalithic sites studied in the area which include Kalamba (stone vats), megalithic statues (menhirs), stone mortars, batu dakon (perforated stones), and dolmens.

It was a representative sampling in the “Land of a Thousand Megaliths” with focus on rocks used as raw material for megalithic artifacts. Samples were collected based on two criteria: physical integrity (nonweathered condition) and lithological variation. The rock samples for characterization analysis were collected from areas that were suspected to be sources of artifact production. These were based on physical resemblance to the existing artifacts and the presence of many stone fragments in certain areas. This was done in both Bada and Behoa Valleys. Three samples were collected from the Bada Valley for analysis and labeled BD-01, BD-02, BD-03, whereas four samples from the Behoa Valley were designated BH-01, BH-02, BH-03, and BH-04. However, rock sampling was not possible in the Napu Valley due to the fact that the megaliths are scattered across the area and there are no places that the heritage custodians or the local communities consider as artifact production sites such as those in Bada and Behoa Valleys. The samples were not taken directly from the artifacts as the petrographic and XRF analyses require destructive sampling which is not allowed for cultural heritage objects. The research team consulted and sought recommendations from the local heritage custodians to access the areas and to select potential rock samples that could be related to artifact production. The rock samples that were selected were not located within the boundaries that had been demarcated by the Cultural Heritage Preservation Office.

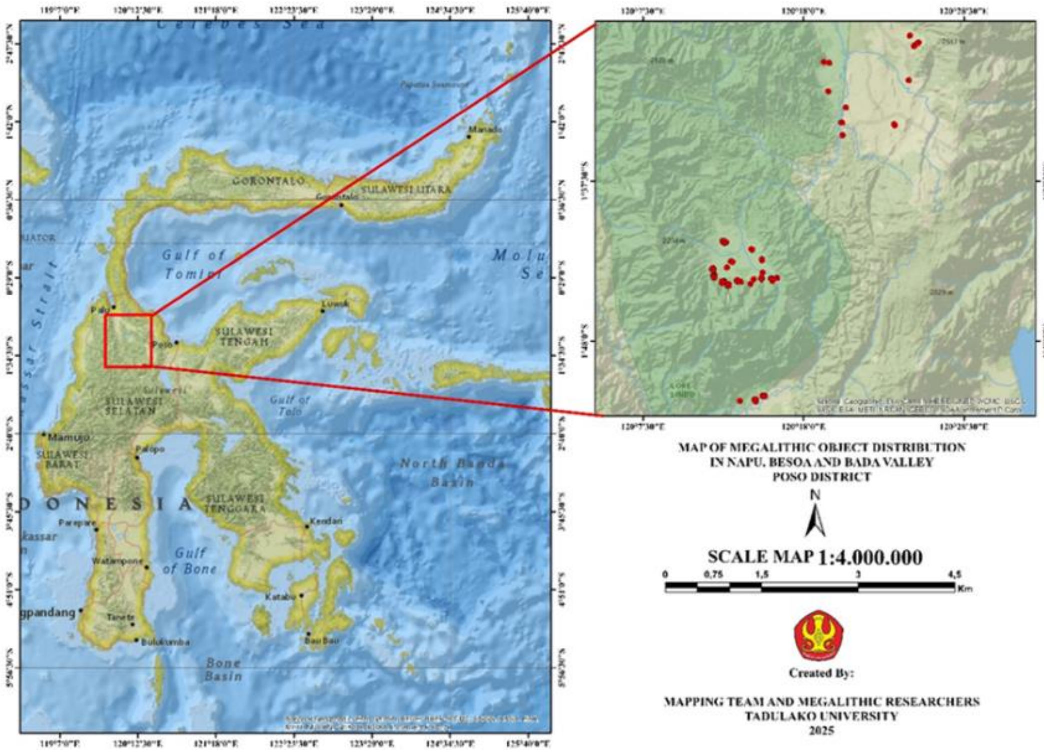


Figure 1. Map of the megalithic site distribution in the research area

Research Method

The research methodology includes two major components: a field survey and laboratory analysis. The fieldwork involved observation of rocks at several places in the study area as well as collection of rock samples for further laboratory analysis. A total of seven rock samples were analyzed in terms of petrographic characteristics and geochemical composition through XRF. The rock samples were analyzed petrographically using a polarizing microscope to identify the rock types, mineral composition and texture of both the rock and its constituent minerals.

Each sample was thin sectioned and then analyzed at the Petrography Laboratory of the Geological Engineering Program, Department of Earth Sciences and Technology, Universitas Negeri Gorontalo. The goal of petrographic analysis was to identify the minerals based on their optical properties and textural characteristics and to estimate the major minerals in weight percentages using the point counting technique (Azzam et al., 2024; Permana et al., 2024; 2025). XRF geochemical analysis was performed to quantify the major oxide elements such as SiO_2, Al_2O_3, FeOt, MgO, CaO, Na_2O, K_2O, TiO_2, MnO, and P_2O_5. Ten major oxides were quantified in weight percent (normalized to 100%) and were used to support interpretations of rock genesis based on its chemical composition. This analysis is aimed at categorizing rock types by total alkali silica content and magma series (Lozano & Bernal, 2005; Bloise et al., 2020). Additionally, the major element data was subject to additional geochemical modelling using the GCDkit software, which is based on the R programming language. GCDkit provides a systematic framework for interpreting whole-rock geochemical data through statistical functions, normalization routines, and a wide range of discrimination diagrams. In this research, the software was applied for data validation and screening, geochemical visualization, rock classification, and multivariate analysis (Janoušek et al., 2006).

RESULTS

Field Survey: The Bada Valley extends across two subdistricts South Lore and West Lore with elevations between 750 and 850 meters above sea level (Table 1). The megalithic sites in South Lore are distributed across Gintu, Bulili, Bakekau, Bomba, Pada-Pada, Bewa, Badangkaea, and Runde villages. The villages of Langkeka, Lelio, Kolori, Kageroa, Tomehipi, and Tuare in West Lore contain megalithic archaeological sites. The Tawailia River runs through the valley as a major watercourse which belongs to the Lariang River system together with its tributaries including Mulalawa, Halu Taba, Halu Tomoeda, Halu Mangilu, Halu Ntanaono, Halu Tamahingki, Halu Baloli, Halu Betaua, Halu Haroawu, Halu Kalinunu, Halu Kasirau, Halu Karape, Halu Nonghawa, Halu Tiko, Halu Busunga, and Halu Lebo rivers. The megalithic sites in this region exist within Quaternary lake deposits (Ql) geological formations which consist mainly of clay, sand and gravel.

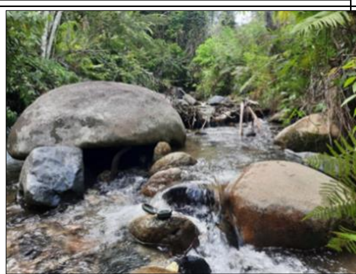
The Behoa Valley which locals also call Besoa Valley exists as a highland basin that reaches elevations between 1,200 and 1,300 meters above sea level (Table 2). The administrative area of Lore Tengah Subdistrict exists within Poso Regency. The entire area falls within Lore Lindu National Park (TNLL) boundaries where megalithic sites exist in Doda, Bariri, Hanggira, Lempe, Baleura, Torire, Rompo and Katu villages. Topographic maps show that this region serves as a meeting point for various river branches (uwei) which flow from different directions before uniting to form the main river Uwei Torire.

Napu Valley is administratively located within three subdistricts: North Lore, centered in Wuasa; East Lore, centered in Maholo; and Lore Peore, centered in Watutau. Topographically, this region is a highland plateau with elevations ranging from 1,100 to 1,200 m above sea level. The research team did not obtain any rock samples from this area.

Table 1. Locations of Megalithic Sites in the Bada Valley

Sample Code and Location	Photograph	Remark
BD-01 and North of the Manitu-Mpoime megalith site		The rock samples were obtained from the western area of the Halu Iso megalithic statue. This location is locally known as Tokalaea, a name attributed to its past morphological resemblance to a pregnant figure.
BD-02 and Suso megalith Site		A sample provided by the Megalith Custodian was collected from the area surrounding the *Kalamba* megalithic site.
BD-03 and Topopo-nono megalith site		A sample provided by the Megalith Custodian was collected from the area surrounding Tomompanana or Topoponono, located within the paddy field zone.

Table 2. Locations of Megalithic Sites in the Behoa Valley

Sample Code and Location	Photograph	Remark
BH-01 and Wineki megalith site		The rock sample was collected from a presumed workshop area, characterized by the presence of large stone fragments thought to be unfinished or unworked materials intended for mega-lithic production.
BH-02 and Wineki megalith site		The rock sample was obtained from the western section of the presumed workshop zone, situated within a hilly landscape.
BH-03 and the river area south of the Wineki megalith site		The rock sample was collected from a river boulder identified by the Megalith Custodian as likely originating from the same lithological material used in megalith construction.
BH-04 and The river area south of the Wineki megalith site		The sample was taken from a river boulder, which, according to the Megalith Custodian, is part of the same type of stone used in the production of megalithic objects.

Petrographic Analysis

The analysis involved studying rock microscopic features to better understand structural and mineralogical characteristics which served as essential information for following geochemical research. The study analyzed five plutonic igneous rock samples and two metamorphic rock samples through petrographic observations.

A. Plutonic Igneous Rock Group

Sample BD-01

The microscopic evaluation shows fresh rock contains phaneritic–porphyritic texture and holocrystalline crystallinity with inequigranular crystal relationships and euhedral–subhedral crystal forms measuring between 0.08 and 1.2 mm. The rock presents a massive structure. The mineral composition includes plagioclase (33%), K-feldspar (19%), quartz (9%), hornblende (7%), biotite (5%), titanite (6%), opaque minerals (3%), sericite (8%), and microlite (10%). Thin section examination reveals albite twinning in plagioclase with an An-35 composition that confirms andesine type (Figure 2A-B). Travis (1955) classifies this rock as monzonite.

Sample BD-02

The microscopic study exposed fresh rock material with phaneritic–porphyritic texture and holocrystalline crystallinity alongside inequigranular crystal relationships and euhedral–subhedral crystal forms measuring between 0.08–1.6 mm. The rock has a massive structure. The rock contains plagioclase (35%) and K-feldspar (20%) and quartz (11%) along with hornblende (3%) and biotite (6%) and titanite (3%) and opaque minerals (2%) and sericite (10%) and microlite (10%). Plagioclase reveals albite twinning with an An-40 composition that indicates the rock has andesinity (Figure 2C-D). The rock classification follows the definition of quartz monzonite (Travis, 1955).

Sample BD-03

The microscopic study of fresh rock material displayed phaneritic–porphyritic texture together with holocrystalline crystallinity and inequigranular crystal relationships and euhedral–subhedral crystal forms. The massive structure contains crystals measuring between 0.08 and 1.6 mm. The rock composition consists of plagioclase (37%), K-feldspar (19%), quartz (11%), hornblende (9%), biotite (6%), titanite (1%), opaque minerals (2%), sericite (8%), and microlite (7%). Plagioclase displays albite twinning with an An-42 composition which indicates andesinity (Figure 2E-F). The rock receives its identification as quartz monzonite from Travis (1955).

Sample BH-01

Fresh rock under microscopic observation showed a phaneritic–porphyritic texture and holocrystalline crystallinity along with inequigranular crystal relationships and euhedral–subhedral crystal forms. The massive rock structure contains crystals with sizes spanning between 0.02 and 1.72 mm. The mineral composition of the sample consists of plagioclase (37%), K-feldspar (19%), quartz (11%), hornblende (8%), biotite (6%), titanite (3%), sericite (8%), and microlite (8%). The plagioclase exhibits albite twinning with an An-40 composition indicating andesinity (Figure 2G-H). The rock falls under the category of quartz monzonite according to Travis (1955).

Sample BH-03

The microscope shows the rock to be fresh with a phaneritic–porphyritic texture, holocrystalline crystallinity and inequigranular crystal relationships. The crystals display euhedral to subhedral shapes while their dimensions span between 0.08 and 1.2 mm. The structure is massive. Plagioclase (37%) and K-feldspar (19%) and quartz (11%) and hornblende (10%) and biotite (10%) and sericite (9%) and microlite (4%) make up the mineral composition. Plagioclase displays albite twinning with an An-36 composition which points to andesine (Figure 2I-J). The rock classification follows the definition of quartz monzonite (Travis, 1955).

B. Metamorphic Rock Group

Sample BH-02

The microscopic inspection of the fresh rock sample shows nematoblastic texture alongside subhedral to anhedral crystal forms and crystal dimensions between 0.02 and 1 mm and a foliated structure. The mineral composition includes plagioclase (25%), K-feldspar (10%), quartz (20%), and hornblende (45%). The thin section shows plagioclase with albite twinning that indicates the An-57 composition and thus labradorite type (Figure 2K-L). The rock falls under the category of amphibolite according to O'Dunn & Sill (1986).

Sample BH-04

The microscope shows the rock as fresh with lepidoblastic texture, subhedral to anhedral crystal forms, general crystal sizes of 0.02 to 1 mm and a schistose foliation structure. The rock contains plagioclase (10%) and K-feldspar (7%) and quartz (15%) and biotite (38%) and chlorite (27%) and opaque minerals (3%). The thin section shows plagioclase displaying albite twinning with an An-54 composition which indicates labradorite (Figure 2M-N). Biotite-Chlorite Schist represents the rock classification according to O'Dunn & Sill (1986).

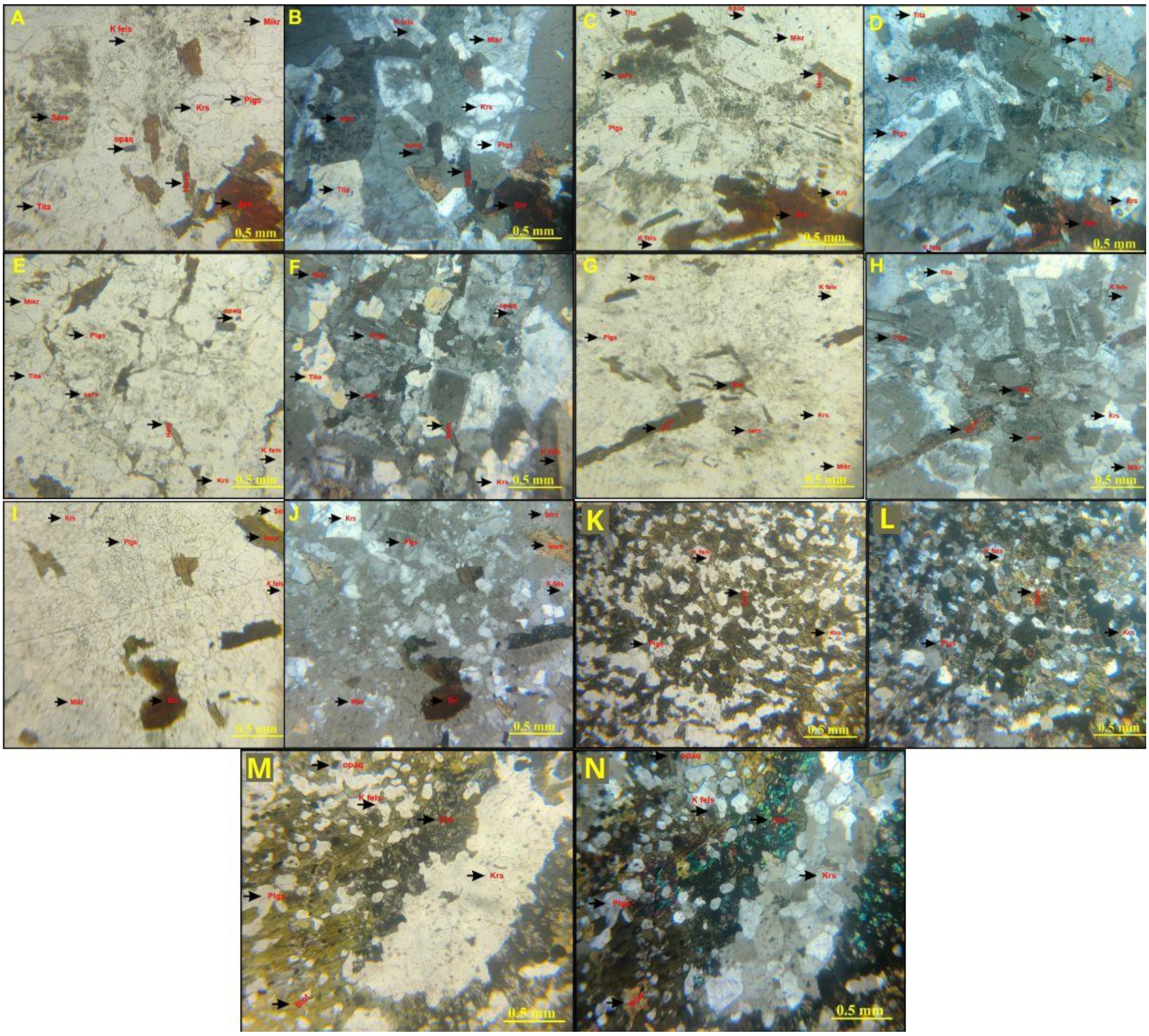


Figure 2. Photomicrographs of five plutonic igneous rock samples and two metamorphic rock samples
Left: plane-polarized light (PPL); right: cross-polarized light (XPL)

Geochemical Analysis

All seven rock samples examined through petrographic analysis were subject to geochemical analysis to determine their major element composition (Table 3). Major oxide data was normalized and then plotted onto various geochemical diagrams in order to interpret the geochemical characteristics of the samples.

Several plot methods were employed for characterization including the FMW weathering index diagram (Ohta & Arai, 2007), TAS plutonic diagram (Middlemost, 1994), TAS volcanic diagram (Le Bas et al., 1986), ferroan–magnesian classification diagram (Frost et al., 2001), AFM diagram for magma series classification (Irvine & Baragar, 1971), and geotectonic setting diagram (Mullen, 1983).

Table 3. Results of the XRF Geochemical Analysis of Rock Samples, Presented in Normalized Weight Percent (wt.%)

Sample Code	SiO_2	TiO_2	Al_2O_3	FeOt	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
BD-01	54.30	0.96	19.15	5.09	0.97	0.72	4.97	1.19	5.07	0.97
BD-02	66.84	0.56	14.33	2.85	0.5	0.54	3.98	1.53	6.43	0.39
BD-03	66.87	0.40	13.24	3.60	0.31	0.65	3.15	1.7	7.54	0.24
BH-01	66.46	0.40	14.48	3.06	0.25	0.53	4.40	1.63	6.28	0.25
BH-02	43.23	3.22	13.07	17.78	0.57	3.6	11.3	1.03	0.31	0.58
BH-03	64.33	0.13	14.82	3.94	0.8	0.15	3.97	1.06	7.19	0.26
BH-04	42.88	4.07	12.18	18.21	0.66	3.21	10.94	1.42	0.54	0.86

A. Weathering Trend

Rock condition verification was conducted to assess the degree of freshness and to ensure that the samples had not undergone intensive weathering processes that could compromise the accuracy of the geochemical analysis results. Based on the FMW diagram (Figure 3A), six (6) samples are classified as fresh rocks, except sample BD-01, which has moderate weathering characteristics (Table 4). The total major oxide content of sample BD-01 is less than 95%, suggesting a high loss on ignition (LOI) value. Although the sample appears fresh macroscopically, the geochemical data indicate more significant alteration than the other samples do. Loss on ignition (LOI) in geochemical analysis refers to the mass loss observed after a sample is subjected to high-temperature heating (typically at 1,000°C). This loss results from the volatilization of components such as moisture, and organic matter present in the rock.

Table 4. Sample Distribution and Weathering Classification Based on the FMW Diagram

Sample Code	Description
BD-01	The samples show moderate weathering, as most of the mobile elements (M) have been leached, resulting in a relative enrichment of Al and Fe.
BD-02, BD-03, BH-01, BH-03	The fresh rock samples cluster closely near the field adjacent to the F apex.
BH-02, BH-04	The fresh rocks exhibit a slight reduction in mobile elements, although not yet dominant, reflecting a mafic-derived original rock composition.

B. Classification of Plutonic Igneous Rocks

The TAS diagram (SiO_2 vs. $Na_2O + K_2O$) was used to classify the plutonic igneous rock types of five (5) samples (BD-01, BD-02, BD-03, BH-01 and BH-03) as proposed by Middlemost (1994). The five plutonic samples contain silica (SiO_2) content of 54.30 – 66.87 wt.%. The $Na_2O + K_2O$ (total alkali) content varies from 6.26 wt.% to 9.24 wt.% relative to the SiO_2 (silica) content (Figure 3B). From the TAS diagram, four (4) of the rock samples fall within the quartz monzonite field in the intermediate plutonic rocks category, while one sample is in the monzonite field also in the intermediate category. BD-01 is in the monzonite field and is an intermediate plutonic rock with a nearly balanced plagioclase and orthoclase and minor quartz content. Samples BD-02, BD-03, BH-01, and BH-03 fall in the quartz monzonite field, which are felsic plutonic rocks that are silica and alkali enriched, with more quartz than monzonite, along with plagioclase and orthoclase.

C. Protolith of the Metamorphic Rocks

The protolith (original rock) interpretation of two (2) metamorphic rock samples (BH-02 and BH-04) was carried out using the TAS diagram (SiO_2 vs. $Na_2O + K_2O$), as proposed by Le Bas et al. (1986). Both metamorphic samples have silica (SiO_2) contents of 42.88 – 43.23 wt.%. The alkali content ($Na_2O + K_2O$) ranges between 1.34 – 1.96 wt.% relative to the silica composition (Figure 3C). Based on the TAS diagram, the protoliths of these metamorphic samples are classified as picrobasalts due to low silica and very low total alkali content.

D. Ferroan–Magnesian Properties

The ferroan–magnesian affinities of five plutonic igneous rock samples (BD-01, BD-02, BD-03, BH-01, and BH-03) were interpreted using the FeOt/(FeOt + MgO) vs. SiO_2 diagram proposed by Frost et al. (2001). The relationship between the silica (SiO_2) content and total iron (FeOt) content was analyzed to assess the geochemical trend. All samples in the FeOt/(FeOt + MgO) vs. SiO_2 plot (Figure 3D) are in the ferroan field above the dividing line showing an iron enriched relative to magnesium composition. The SiO_2 content ranges from approximately 60 to 68 wt.%. The FeOt/(FeOt + MgO) ratio is about 0.88 for sample BD-01 which has the lowest SiO_2 content of 54.30 wt.%. The remaining samples (BD-02, BD-03, BH-01, and BH-03) have relatively high silica contents (64–67 wt.%) with FeOt/(FeOt + MgO) ratios ranging from 0.84 to 0.96. Sample BH-03 has the highest FeOt/(FeOt + MgO) ratio (0.96) which indicates that it has the strongest ferroan affinity among the analyzed samples.

E. Magma Series

Magma series classification using the ternary AFM diagram (Irvine & Baragar, 1971) indicates that three (3) rock samples fall within the tholeiitic series, whereas four (4) samples belong to the calc-alkaline series (Figure 3E). The three tholeiitic samples included BD-01, BH-02, and BH-04. Sample BD-01 lies in the center of the tholeiitic field which has a moderate FeO content. The FeO apex in the upper part of the tholeiitic field of BH-02 and BH-04 indicates high iron content. The four samples classified as the calc-alkaline series are BD-02, BD-03, BH-01, and BH-03. BD-02 plots in the calc-alkaline field with moderate alkali content and BD-03 is close by also in the calc-alkaline domain. BH-01 is in the lower part of the calc-alkaline field, and BH-03 is in the upper part of the calc-alkaline field indicating a greater alkali trend.

F. Magma Origin Based on Major Element Geochemistry

The trilinear diagram was used to determine the origin of the magma based on the weight percentage values of TiO_2, $10 \times MnO$, and $10 \times P_2O_5$. Mullen (1983) defines five tectonomagmatic settings using this diagram that include MORB (Mid-Ocean Ridge Basalt), IAT (Island Arc Tholeiite), Island Arc Calc-alkaline Basalt, Oceanic Island Tholeiitic Basalt, and Oceanic Island Alkaline Basalt. The tectonic discrimination diagram from Mullen (1983) shows that five (5) plutonic igneous rock samples (BD-01, BD-02, BD-03, BH-01, and BH-03) lie in the Island Arc Calc-alkaline Basalt field (Figure 3F). Magmas of the calcalkaline type are mainly generated in subduction zones and are typical of convergent margins. The tectonic discrimination diagram also indicates that two (2) metamorphic rock samples (BH-02 and BH-04) plot in the Island Arc Tholeiite (IAT) field (Figure 3F).

IAT represents a basaltic magma type that formed in island arc settings along subduction zones. The magma type is characterized by its tholeiitic composition, which is typically enriched in Fe and low in K_2O. Major elements such as TiO_2, MnO, and P_2O_5 show distinct values that differentiate IATs from both MORBs and OIBs.

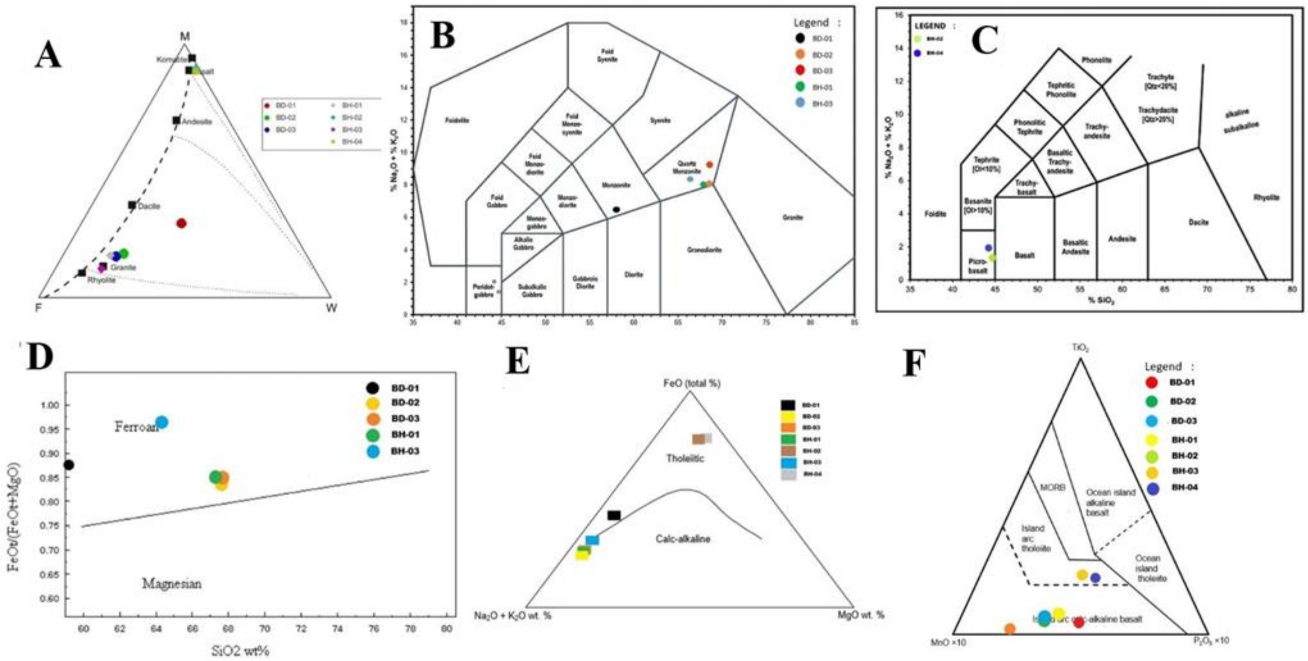


Figure 3. Geochemical data analysis using Geochemical Data Toolkit (GCDkit)

DISCUSSION

The Bada Valley contains two kinds of plutonic igneous rocks: quartz monzonite and monzonite according to field survey analysis that is supported by petrographic and XRF geochemical examinations. The Bada Valley plutonic rocks share an age with the Kumbo Granite Formation (Tpkg) which is dated to the Pliocene at approximately 3.35 million years ago (Sukamto, 1975; Simandjuntak et al., 1997). The Behoa Valley contains three main rock formations which include quartz monzonite plutonic rocks along with amphibolite metamorphic rocks and biotite–chlorite schist. The quartz monzonite of Behoa Valley shares the same age as Kumbo Granite Formation and its age corresponds to the Pliocene epoch at 3.35 Ma. The amphibolite metamorphic rocks share a correlation with the Latimojong Formation (Kls) which exists from the Late Cretaceous period (ca. 100–66 Ma) through the Eocene period (ca. 56–34 Ma) (Simandjuntak et al., 1997). The Pompangeo Complex (MTmp) covers the time span from Early Cretaceous (ca. 100 Ma) through late Miocene (ca. 10 Ma) based on Simandjuntak et al. (1997) and Parkinson (1998). Table 5 displays a compilation of rock characterization methods obtained from petrographic and major element geochemical investigations.

Table 5. Summary of Rock Characterization Based on Petrographic and Geochemical Analysis

Megalit Site Location	Sample Code	Rock type	Rock Name	Protolith (Specific to Meta-morphic Rocks)	Weathering Trend	Fe-Mg Characteristics (Specific to Plutonic Igneous Rocks)	Magma Series	Magma Origin	Rock Age
Bada Valley	**BD-01**	Plutonic igneous rock	Monzonite	-	Moderate weathering	Ferroan	Tholeiitic	Island calc-alkaline basalt	*Pliocene*
	BD-02		Quartz Monzonite	-	Fresh	Ferroan	Calc-alkaline		
	BD-03		Quartz Monzonite	-	Fresh	Ferroan	Calc-alkaline		
Behoa Valley	**BH-01**		Quartz Monzonite	-	Fresh	Ferroan	Calc-alkaline		
	BH-02	Metamor-phic rock	Amphibo-lite	Picrobasalt	Fresh	-	Tholeiitic	Island arc tholeiite	*Last Cretaceous-Eocene*
	BH-03	Plutonic igneous rock	Quartz Monzonite	-	Fresh	Ferroan	Calc-alkaline	Island calc-alkaline basalt	*Pliocene*
	BH-04	Metamor-phic rock	Biotite-Chlorite Schist	Picrobasalt	Fresh	-	Tholeiitic	Island arc tholeiite	*Early Cretaceous-Last Miocene*

CONCLUSION

The megalithic structures in "The Land of a Thousand Megaliths" are predominantly composed of quartz monzonite and monzonite (plutonic igneous rocks), with a minor presence of metamorphic rocks such as amphibolite and biotite–chlorite schist. The source materials for these megaliths were derived from locally available rocks distributed around the sites, which exhibited physical and chemical properties suitable for megalithic artifact production.

This study provides significant insights into the lithic technology, resource utilization, and material selection strategies employed by the megalith-building communities in the Poso region. Furthermore, the findings support ongoing efforts to conserve geological and cultural heritage within Lore Lindu National Park.

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