

Article

Rock Density Model of Ethiopia and Its Implications for Gravimetric Geodesy and Geophysics

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Abstract

Robust and accurate lithological parameters are essential in engineering, geology, geophysics, geodesy, and resource exploration. Among these parameters, rock density plays a fundamental role in gravimetric geodesy and geophysics. However, the systematic collection, analysis, and categorization of rock density data remain insufficient in many countries around the world, including Ethiopia. Ethiopia is characterized by extreme topographic variations (exceeding 4500 m) and complex geology, dominated by Cenozoic volcanic formations associated with the East African Rift System. Consequently, the commonly adopted upper continental crustal density of 2670 kg/m³ is inadequate for precise geodetic applications (e.g., the definition and realization of the geodetic vertical datum) as well as for gravimetric modeling and interpretation (e.g., the compilation of Bouguer, isostatic, and mantle gravity maps) in the country. To address these limitations, we prepared the first comprehensive digital rock density model of Ethiopia, with a particular focus on its applications in gravimetric geodesy and geophysics. The rock density model has been prepared by integrating the Ethiopian geological database, comprising 88 lithological units, with established global rock-density databases to assign representative density values and their uncertainties to each geological unit. The height-weighted average densities, accounting for the mass contribution of elevated terrain, were computed from a 90-m-resolution digital elevation model. The rock density map shows significant density variations across Ethiopia, ranging from 1528 to 2892 kg/m³. The average height-weighted density of Ethiopia is 2430 ± 352 kg/m³, which is 9% lower than the standard density of 2670 kg/m³. We expect that the use of the rock density model instead of assuming only a constant density value for the whole country will improve the accuracy of gravimetric geoid modeling and orthometric height determination, both essential for the modernization of the geodetic vertical datum. This demonstrates the necessity of region-specific density models for countries in tectonically active and/or geologically complex settings. The study also provides a transferable methodological framework for developing similar products in other data-sparse regions.



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1. Introduction

Albeit measurements and analyses of lithological parameters describing physical characteristics and composition of rocks, including factors like texture (grain size, sorting), mineralogy, and physical properties (density, porosity, permeability, strength, seismic velocity), are crucial in geology, engineering, geodesy, geophysics, and resource exploration, the current classification of these parameters is often incomplete in many countries around the world. Among these lithological parameters, the rock density is a fundamental physical property required in many Earth science applications, including the gravimetric determination of the geoid and orthometric heights in physical geodesy and the gravimetric interpretation of Earth's inner structure in geophysics and natural resource exploration [1,2]. Knowledge of the density of different lithological units is particularly needed for gravimetric forward modeling of lithospheric structure, with examples given for continental sedimentary basins, marine sediment deposits, volcanic formations, mantle intrusions, and various density interfaces and structures within the oceanic and continental lithosphere. Conversely, gravimetric forward modeling techniques are used to validate density models derived from gravimetric data inversion. In gravimetric geophysics, topographic relief and density models are used to calculate and interpret Bouguer, isostatic, and mantle gravity maps [3–5]. The rock density information is also important for a volume-to-mass conversion and for subsurface modeling in resource estimates and geological mapping [6]. Moreover, gravity and magnetic interpretation techniques in geophysical exploration are based on delineating density contrasts between various rock types [7]. Despite its significance, rock density remains one of the most poorly constrained lithological parameters due to the scarcity of direct measurements and the challenges of spatial extrapolation. In light of these wide-ranging applications, establishing accurate rock density models at national and regional scales has become increasingly important. This is particularly true for countries undertaking geodetic modernization programs, where systematic errors in density assumptions propagate through gravity field computations to vertical datum realization, dictating the accuracy and reliability of geoid models and orthometric heights at leveling benchmarks [8,9]. This also has direct implications for the quality of geo-hazard assessment of coastal erosion and flooding due to sea level rise and other factors associated with climate change, such as landslide risk assessment.

The standard density of 2670 kg/m^3 for the upper continental crust has widely been used in geophysical and geodetic applications for over a century [10]. Hinze [11] provided a comprehensive historical review of density estimates and their sources. He noted that while this density value is reasonable for crystalline shield rock regions, its universal application is not realistic for diverse geological environments. This drawback mainly affects regions with rift-related deposits, volcanic sequences, and unconsolidated sediments whose densities are significantly lower than the crystalline basement rock's density [12].

Tenzer et al. [10] pioneered comprehensive national-scale modeling with their digital rock density map of New Zealand. They integrated geological mapping units with over 9000 density observations to derive a national average density of 2440 kg/m^3 , which is significantly lower than the standard (i.e., commonly adopted) value. Similar approaches were used to prepare rock density models of Brazil [13], Japan [14], Iceland [15], and Hong Kong [16]. More recently, Sheng et al. [17] prepared the UNB_TopoDensT density model, providing the first comprehensive assessment of lateral topographic density variations

worldwide. Findings from these studies demonstrated that the standard rock density of 2670 kg/m^3 largely overestimates density in many volcanic and young sedimentary regions, with implications for geodetic applications requiring centimeter-level accuracy [18].

Despite recent advances in rock density modeling, the continent of Africa is not yet sufficiently covered by this data. A main reason is Africa's diverse geological composition, which comprises extensive volcanic regions and rift systems with distinct density features [19,20] and difficult accessibility in large parts of the continent. Therefore, establishing a region-based rock density model is important for improving geodetic datum modernization and gravimetric interpretations across Africa.

A significant tectonic feature in Ethiopia is the Afar triple junction, where the Arabian, Nubian, and Somali plates meet and diverge (see Figure 1) [21,22]. These tectonic plates [23] connect the northern sector of the East African Rift System, the Gulf of Aden spreading center, and the Red Sea Rift. Within this wide plate boundary, the Main Ethiopian Rift crosses the country. This establishes a boundary between the Somali and Nubian plates and forms the East African Rift Valley segment. In the Afar region, the Cenozoic province formed by rift magmatism and flood basalts underlies the rift system. As a result, Ethiopia experienced many volcanic eruptions, mainly across the Ethiopian and Afar Rifts [24]. Volcanic rocks dominate Ethiopian geology. The Ethiopian Flood Basalt Province, which is one of the world's largest continental flood basalt provinces, covering nearly $600,000 \text{ km}^2$, exemplifies the volcanic dominance of Ethiopian geology [25]. This volcanic landform, with elevations greater than 4500 m , is crossed by the expanding East African Rift System, which creates a geologically adverse setting with a variety of rock types ranging from dense basalts to lighter volcanoclastic rocks [26].

Ethiopia is currently modernizing its national geodetic infrastructure. The accuracy of the geodetic vertical datum, practically realized through the geoid model and orthometric heights of leveling benchmarks, depends on gravity and leveling observations, the topographic relief model, and topographic density information. Using the standard density value of 2670 kg/m^3 introduces large inaccuracies, particularly in mountainous regions [27–30], where these errors could reach several decimeters and locally up to a few meters. Foroughi and Tenzer [31] demonstrated that relatively large errors could occur even in regions with moderately elevated topography or in lowlands, particularly in proximity to large mountains. These two factors—elevated topography and complex geology—require improved density information across the whole country. Furthermore, Ethiopia's development of a digital rock density model would also establish a benchmark for similar efforts across the continent.

To address requirements associated with modernization of vertical geodetic datum as well as improved gravimetric interpretation for various geophysical applications and resources exploration, we underscored four primary objectives of this study: (1) compilation of the first comprehensive digital rock density model for Ethiopia by integrating geological map with established rock density databases; (2) quantify the height-weighted average density and its uncertainty for geodetic applications; (3) characterize spatial density variations across major geological units; (4) examine implications of using region-specific density values versus the standard continental density for gravity field modeling and vertical datum modernization.

2. Materials and Methods

2.1. Geographic and Physiographic Setting of the Study Area

Ethiopia is located in the Horn of Africa between approximately 3° N and 15° N latitude and 33° E and 48° E longitude, covering roughly 1.1 million km^2 (Figure 1). The country exhibits remarkable physiographic diversity, ranging from the Danakil Depression

at 125 m below sea level, formed through continental rifting processes, to the Simien Mountains with topographic elevations exceeding 4500 m [32].

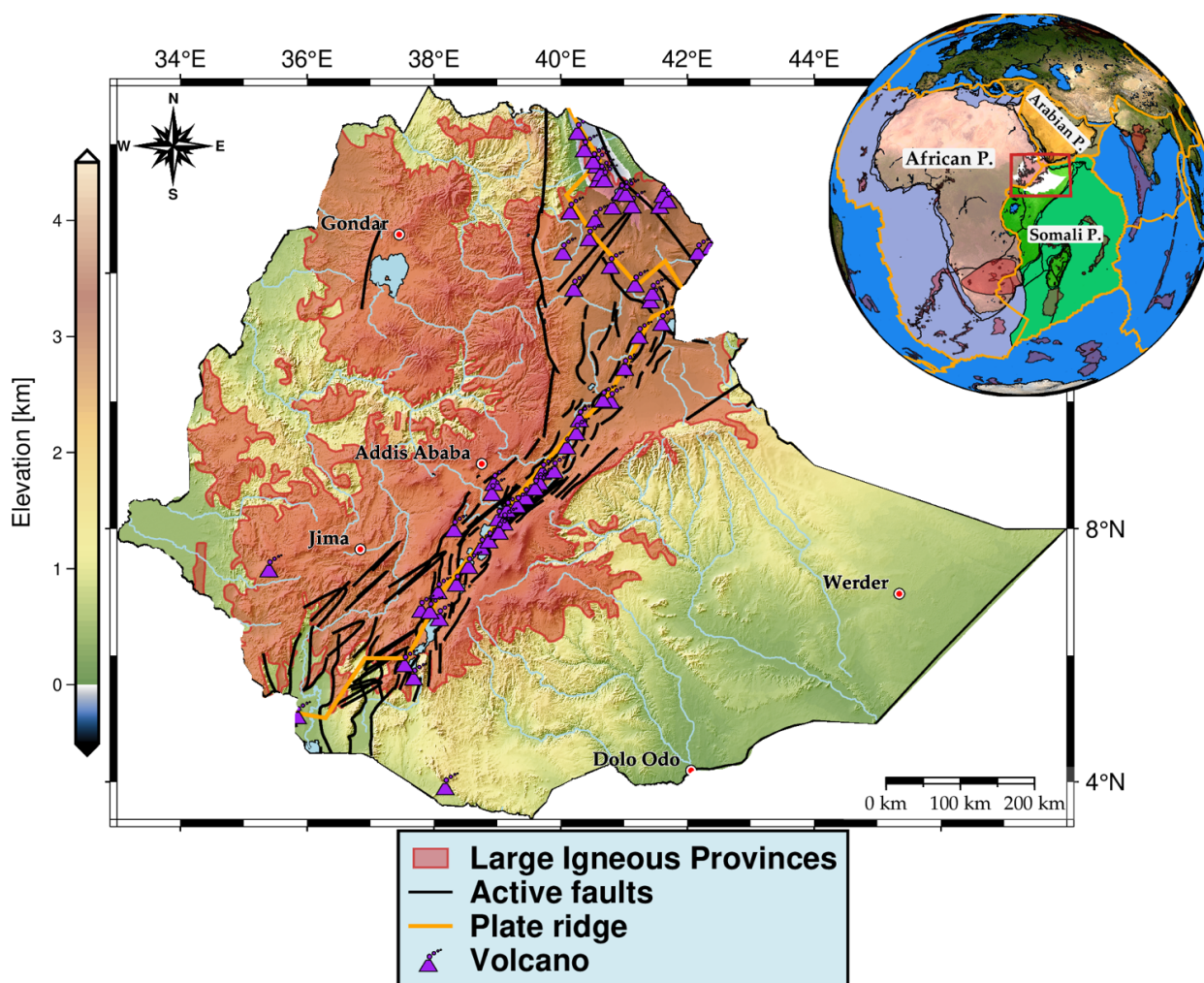


Figure 1. Topographic map of Ethiopia derived from the 90 m SRTM DEM. The inset highlights Ethiopia's position at the Afar triple junction of the African, Somali, and Arabian plates.

This elevation change, approximately 4600, represents one of the most dramatic topographic relief variations in Africa. Deep river valleys carve through high terrain, as observed in the Blue Nile gorge, which has incised up to 1500 m into the volcanic plateau [33]. This relationship between underlying geology and topography is very important for understanding rock density distribution, meaning that extreme topographic differences necessitate accurate density modeling for geodetic applications, as topographic corrections scale directly with both the assumed density and elevation.

2.2. Geological Evolution

Cenozoic volcanism associated with continental rifting and the Afar mantle plume has substantially influenced Ethiopian geological evolution [34]. This evolution can be classified into three phases. In the first phase, the Precambrian crystalline basement was formed (>550 Ma ago) in western and northern Ethiopia. It mainly involves high-grade metamorphic rocks, including migmatites, gneisses, and schists [35]. These ancient basement rocks have rock densities ranging from 2600 to 2800 kg/m³. The second phase is the acquisition of attributes through the creation of Paleozoic–Mesozoic sedimentary sequences (550–65 Ma). It is found in significant numbers in the Ogaden region of eastern

Ethiopia. The overlying Mesozoic section is largely composed of sandstones, shales, and marine limestones of the Adigrat and Antalo formations [36]. The third and ongoing phase is associated with the formation of the Cenozoic Volcanic Province, known as the Ethiopian Flood Basalt Province (Figure 1). This is the most extensive geological type in Ethiopia. Its formation began approximately 30 Ma ago with the impingement of the Afar mantle plume [37].

2.3. Tectonic Configuration

The Ethiopian tectonic configuration (Figure 1) is characterized by the triple junction of the Arabian, Nubian, and Somali plates. It is topographically manifested by the Afar Depression, an active extensional basin where continental rifting transitions to oceanic spreading [38]. The area comprises numerous volcanic centers, hydrothermal activity, and complex fault patterns, making it one of the best modern analogs for plateau uplift and continental breakup processes. The western and eastern plateaus are the uplifted flanks of the rift system, with uplift initiating around 30 Ma and continuing to the present. This uplift, driven by dynamic mantle processes, has shaped Ethiopia's complex terrain and influenced regional climate patterns. The Main Ethiopian Rift is a developing continental rift that exhibits typical rift morphology, with border faults, step-faulted margins, and central volcanic ranges [39]. These ongoing tectonic processes have significant consequences for rock density distributions. Active rifting produces young, low-density volcanic and sedimentary materials in the lithospheric column [40], while uplifted plateaus are characterized by felsic volcanic sequences with densities lower than those of mafic rift-floor basalts.

2.4. Lithological Framework and Density Implications

The Ethiopian complex geology can be classified into major rock groups, each with characteristic density ranges that represent their composition and origin. The first group consists of volcanic rocks, mainly trachyte, basalts, and rhyolites, with associated pyroclastics, forming extensive plateau sequences and rift-related volcanic centers. Densities of these rocks range from dense olivine basalts (2800 kg/m^3) to lighter rhyolitic tuffs (2100 kg/m^3). The second major rock group consists of sedimentary rocks, formed primarily by Mesozoic limestones and sandstones in rift valleys and the Ogaden Basin, as well as by Quaternary sediments. Sedimentary rocks are characterized by medium-to-variable density mainly within $2400\text{--}2600 \text{ kg/m}^3$, although high variations could occur based on their cementation and composition. The third group comprises intrusive rocks, including gabbroic bodies, syenites, and granites, associated with rift magmatism. These rocks are characterized by densities ranging from 2700 to 2900 kg/m^3 . Finally, in the western and northern parts of Ethiopia, large parts of the Precambrian basement are composed of metamorphic rocks with densities $2600\text{--}2800 \text{ kg/m}^3$, depending on metamorphic grade and composition. This geological variety, combined with complex topography and the prevalence of volcanic rocks, which are generally lower in density, suggests that the mean rock density in Ethiopia is below the standard density value (2670 kg/m^3). As already explained, this has major implications for geodetic and geophysical applications [41,42].

2.5. Input Data

Compilations of rock density models require various data types and sources, including geological maps with lithological unit specifications, a digital terrain model, and rock densities obtained either from direct measurements within the study area or from other sources (published geological/geophysical exploration reports). Additional geological, petrological, and geophysical information, along with published rock-density maps from other countries, could be used for comparative studies and validation.

2.5.1. Geological Data

The primary geological data used in this study were obtained from the Geological Institute of Ethiopia (GIE), formerly known as the Geological Survey of Ethiopia, in digital format. The dataset comprises 88 distinct lithological units covering the entire country (Figure 2). Each lithological unit shapefile includes comprehensive fields such as rock codes, rock type classification, geographic coordinates, and area. The geological map was prepared from geological data obtained from GIE at a scale of 1:2,000,000. It provides sufficient resolution for modeling of regional density while acknowledging that local-scale heterogeneities may not be fully captured.

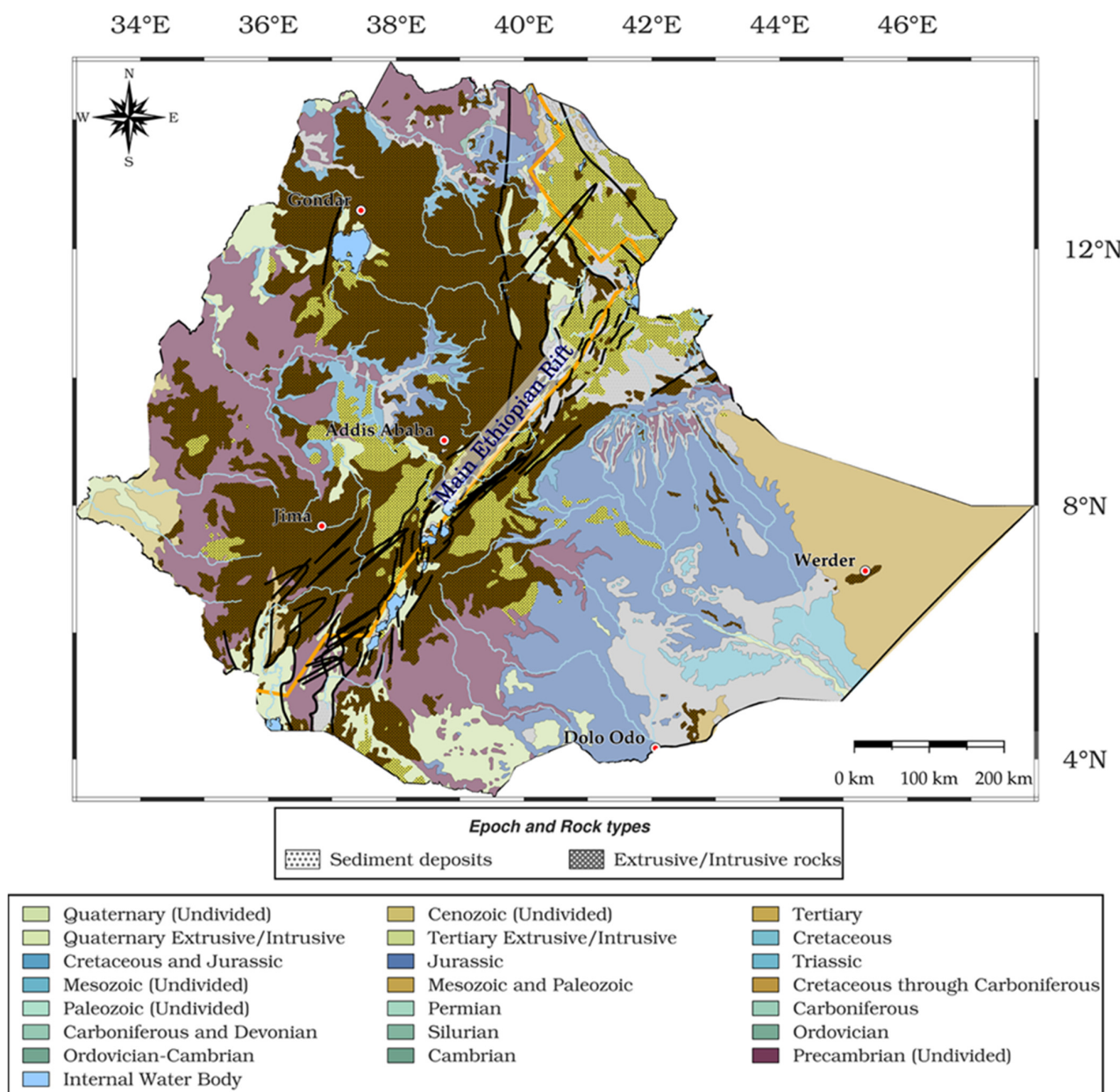


Figure 2. Geological map of Ethiopia. Black solid lines indicate structural faults.

2.5.2. Topographic Data

90 m resolution Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM) was used in this study. The DEM covers the entire Ethiopia. The topographic elevations within the country range from −125 to 4531 m (Figure 1). The DEM data were processed using standard procedures such as void filling, projection conversion

(to Universal Transverse Mercator Zone 37N), and quality assessment. The vertical accuracy of the global SRTM is ± 16 m [43], which is adequate for regional density modeling.

2.5.3. Rock Density Database

Since systematic density measurements in Ethiopia are limited, we assigned rock densities to all 88 lithological units based on the comprehensive database compiled by [10]. Their database provides density measurements for 123 main rock types from over 9000 samples, with accompanying statistical information including standard deviations, means, and measurement counts. Additional density values were obtained from [6]. Furthermore, incorporated information from published studies with density measurements from similar geological settings in rift regions. Tadesse et al. [44] indicated that the average Precambrian basement density is 2600 kg/m^3 , and that the overlying volcano-sedimentary rocks have densities of approximately 2400 kg/m^3 in the Southern Main Ethiopian Rift. Huang et al. [45] showed densities of 2550 kg/m^3 for pyroclastics and basalt/trachyte lavas ranging from 1200 to 2500 kg/m^3 along the Northern Kenya Volcanic Rift. Their study also reports intrusive/high-temperature alteration bodies with densities 2000 – 2700 kg/m^3 . Taylor [46] reported a silicic volcano within the Main Ethiopian Rift and applied a rhyolite melt density of 2300 kg/m^3 . The density-value assignment approach from global databases to mapped lithological units follows a well-established practice in regional-level density modeling [10,16]. This approach may introduce assignment uncertainty, but it is the most practical methodology for regions lacking systematic in situ density measurements.

2.6. Method

The methodology developed by [10] was used to compile the rock density model of Ethiopia. All datasets used were consistently represented in the UTM Zone 37N coordinate system. Topological errors in the geological shapefile were corrected. The International Union of Geological Sciences (IUGS) rock categorization scheme was adopted in geological unit classification. The classification primarily considers texture, lithology, geological age, alteration state, and mineral composition. The rock density was set to the average values reported by [10] and other comparable geological sources. GIS platforms, typically QGIS 3.28, are standardly used for spatial data management, analysis, and displaying maps. In this study, the Python 3.13 programming language was used to perform statistical analyses, automate geoprocessing workflows, assign density values, and calculate height-weighted average density. SciPy and NumPy Python libraries were used for uncertainty quantification. Python libraries ESDA and libpysal were used for Spatial autocorrelation analysis (Moran's I and Geary's C). The density values for individual rock types in Ethiopia are summarized in Appendix A.

2.6.1. Height-Weighted Average Density

The height-weighted average density was computed according to the following equation [16]:

$$\bar{\rho} = \frac{\sum_{i=1}^n \rho_i(\phi, \lambda) \cdot H_i(\phi, \lambda)}{\sum_{i=1}^n H_i(\phi, \lambda)} (H > 0). \quad (1)$$

where $\bar{\rho}$ denotes the height-weighted average density [kg/m^3], ρ_i is the density at grid point i [kg/m^3], H_i is the topographic height at grid point i [m], n is the total number of grid points, and ϕ, λ denote geographic latitude and longitude. We note that for negative elevations, density values were not assigned in Equation (1). The algorithm was implemented in Python. It should be noted that this formulation weights density by topographic height rather than by an area alone, thereby giving greater weight to elevated regions where topographic corrections have a larger effect on gravity computations. This

approach is physically motivated for geodetic applications where the mass contribution of topographic relief is of primary concern [47].

2.6.2. Analysis of Uncertainty and Error Propagation

To quantify the combined uncertainty in the final height-weighted average density, we adopted a standard-error-propagation framework [48] that accounts for measurement, spatial, and assignment uncertainties. The measurement uncertainty (σ_{meas}) is taken as the standard deviation associated with the density value in the source databases, in this case from [10]. The spatial uncertainty (σ_{spat}) was estimated from the inherent heterogeneity of rock densities within each mapped lithological unit across Ethiopia's variable landscape. The assignment uncertainty (σ_{assign}) was quantified through expert evaluation of the confidence in correlating Ethiopian geological units with analogous rock types globally. The total combined uncertainty (σ_{total}) was then calculated based on these three uncertainty sources according to the following equation:

$$\sigma_{total} = \sqrt{\sigma_{meas}^2 + \sigma_{spat}^2 + \sigma_{assign}^2}. \quad (2)$$

The Monte Carlo simulation with thousands of iterations was performed to validate the analytical propagation and assess the overall effect on the average density, with randomly varying inputs within the defined uncertainties. Each uncertainty component was sampled from a normal distribution with the respective standard deviation, and the height-weighted average was recalculated for each iteration. The resulting distribution of average densities was used to verify the analytical uncertainty estimate and to assess the sensitivity of the result to individual uncertainty components.

3. Results

This section presents the rock density map and the numerical results, with average density estimates and density uncertainty statistics.

3.1. Rock Density Map of Ethiopia

Ethiopia's digital rock density map is presented in Figure 3, showing spatially continuous density variations across the country. The national pattern of density values ranges from 1528 to 2892 kg/m³, with a mean of 2450 kg/m³ and a median of around 2352 kg/m³. The rock density variations reflect the distribution of Neoproterozoic basement, overlying Cenozoic flood basalts, the actively extending Main Ethiopian Rift, and the thermally elevated lithosphere of the Afar region. In northern Ethiopia, around Gondar and the high plateaus, densities are generally higher, often between 2500 and 2668 kg/m³, reflecting the presence of thick Pan-African basement terranes of the Arabian–Nubian Shield overlain by the Oligocene flood basalts of the Ethiopian Traps. These values are consistent with a relatively coherent lithosphere of the northern Ethiopian Plateau, which is built on juvenile Neoproterozoic crust rather than on Archean cratonic roots. The basement terranes and extensive basaltic sequences form a mechanically strong highland block, and these higher densities contrast with the progressively lower values observed towards the rift. Moving from the plateau towards the Main Ethiopian Rift, the density distribution decreases along a well-defined corridor that aligns with active faults and Quaternary volcanic centers. Densities within this axial rift zone frequently fall between 2200 and 2300 kg/m³, and in localized sectors can approach 2000 kg/m³. These reductions correspond to the combined effects of crustal thinning, elevated heat flow, shallow partial melt zones, and the widespread accumulation of young basaltic lava flows, pyroclastics, and porous rift sediments.

The low-density signature reflects the geodynamic setting of an actively extending continental lithosphere that is progressively evolving towards a nascent oceanic spreading.

In Afar, densities are among the lowest in the country, commonly below 2000 kg/m^3 . This pattern reflects a very thin crust, shallow magma reservoirs, and persistently high temperatures at the triple junction of the Red Sea, the Gulf of Aden, and the Main Ethiopian Rift. The spatial correlation between low-density zones, active spreading segments, fissural volcanism, and silicic volcanic centers aligns with geophysical evidence for shallow partial melt and transitional crust evolving toward incipient oceanic lithosphere. Towards southern Ethiopia, the density increases again, generally rising above $2400\text{--}2500 \text{ kg/m}^3$, as the terrain transitions from the rift axis onto the southern plateau. This region is underlain by Neoproterozoic basement similar to that of the north, and the higher densities relative to the rift reflect thicker and cooler lithosphere. Although some modification has occurred due to the southward propagation of the rift, this area lacks the intense magmatic and extensional activity of the rift interior and retains densities typical of stable highland crust. Further eastwards, the Somali Plateau and areas such as Werder and Dolo Odo show predominantly high densities exceeding 2500 kg/m^3 . These values correspond to extensive Neoproterozoic basement exposures and the mechanically strong interior of the Somali Plate. The sharp contrast between these high-density eastern domains and the low-density rift valley emphasizes the structural and compositional boundary separating the intact Somali Plate from the extended Ethiopian Rift lithosphere.

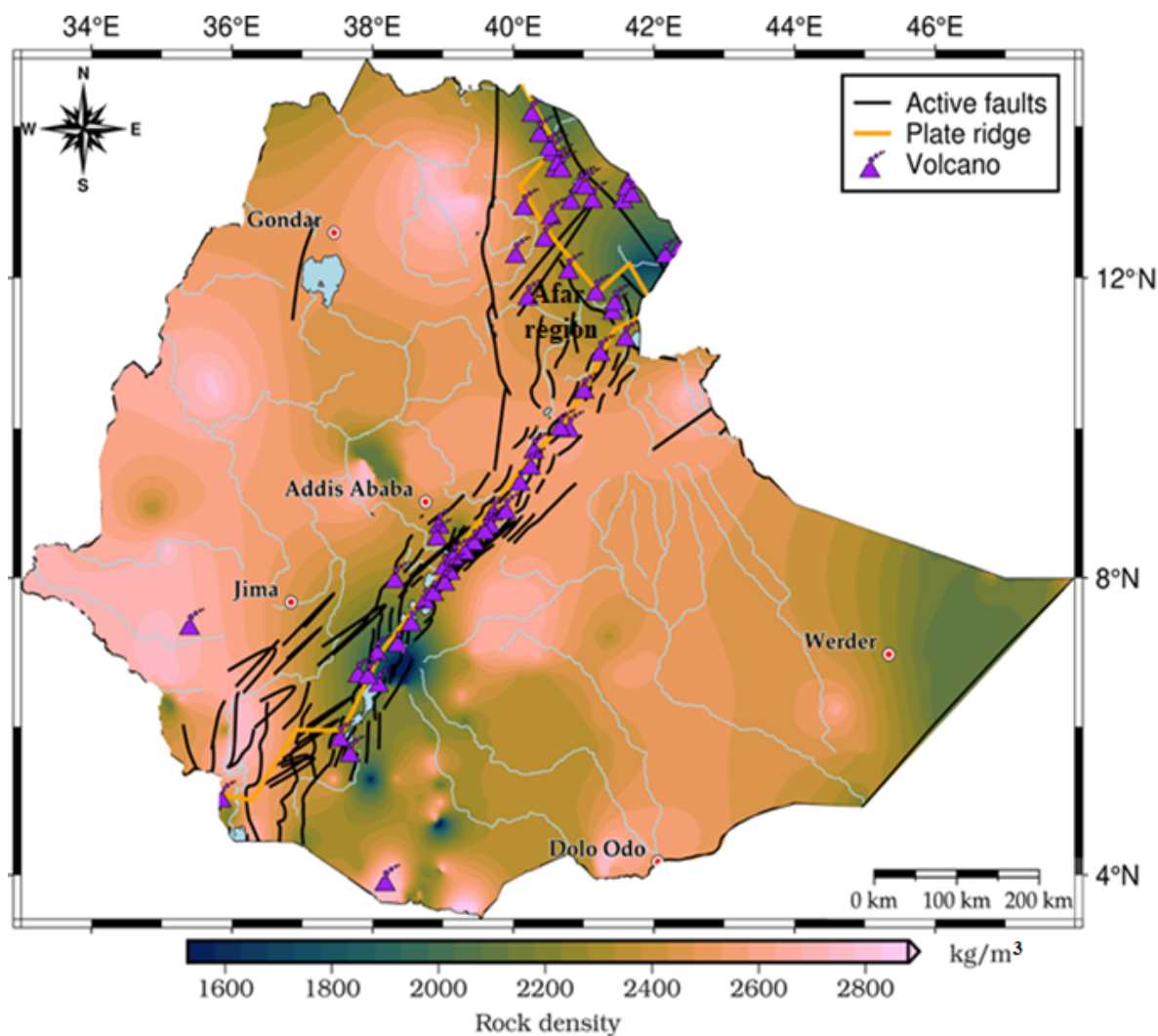


Figure 3. Digital rock density map of Ethiopia.

Overall, the continuous density field in Figure 3 truthfully represents the fundamental geological and geodynamic framework of Ethiopia. High-density values over the northern and southern plateaus correspond to consolidated Neoproterozoic basement overlain by basaltic traps, intermediate densities mark transitional margins around the rift, and the lowest densities coincide with the hot, thin, magma-rich lithosphere of the Main Ethiopian Rift and Afar. The map thus provides a coherent physical representation of how lithology, temperature, crustal thickness, and active tectonics shape the density structure of Ethiopia.

3.2. Statistical Characterization

3.2.1. Descriptive Statistics

The statistical analysis of Ethiopia's rock density distribution is summarized in Table 1. Statistics are calculated for the 88 mapped lithological units. The mode represents the most frequently assigned density value, reflecting the dominance of trachytic and intermediate volcanic compositions in the geological database.

Table 1. Statistical summary of rock density distribution in Ethiopia.

Rock Density Statistics	Values and Description
Number of geological units	88
Minimum density	1528 kg/m ³ (Diatomite, Afar Depression)
Maximum density	2892 kg/m ³ (Gabbro, Western Plateau)
Range	1356 kg/m ³
Simple arithmetic mean	2450 kg/m ³
Median	2352 kg/m ³
Mode	2640 kg/m ³ (most common value)
Standard deviation	255 kg/m ³
Coefficient of variation	10.4%
Skewness	−0.32 (slight left skew)
Kurtosis	2.15 (platykurtic distribution)

3.2.2. Average Density

The impact of topographic variations on rock density modeling can be characterized by the height-weighted density value and its associated uncertainty parameters, as shown in Table 2.

Table 2. Height-weighted density characteristics.

Density Specifications	Values
Weighted average density	2430 kg/m ³
Weighted standard deviation	194 kg/m ³
Relative error (1σ)	7.7%

The height-weighted mean density of 2430 kg/m³ is 9% lower than the value of 2670 kg/m³ typically attributed to the upper continental crust. The difference between the height-weighted mean of 2430 kg/m³ and a simple arithmetic mean of 2450 kg/m³ reflects the topographic weighting effect, meaning that areas with higher elevations receive greater weight in the calculation. This difference indicates that higher-elevation regions in Ethiopia, primarily composed of volcanic plateau sequences, have systematically lower densities than lower-elevation rift zones.

3.2.3. Spatial Correlation Analysis of Rock Density

The rock density distribution across Ethiopia was evaluated using Geary's C [49] and Moran's I [50] spatial statistics. Geary's C complements this by quantifying local spatial similarity: values below 1 indicate clustering of similar values, and values above 1 suggest dispersion. Moran's I measures the global spatial autocorrelation, ranging from -1 (perfect dispersion) to $+1$ (perfect clustering), with 0 indicating a random pattern. The statistical significance of both indices was evaluated using p -values: $p < 0.05$ indicates a statistically significant spatial pattern, while $p > 0.05$ indicates the observed pattern could be due to random chance. Our study provided Moran's I = 0.040 ($p = 0.143$) and Geary's C = 0.917 ($p = 0.205$). Because both p -values are greater than the 0.05 significance threshold, these results indicate that Ethiopian rock densities show no statistically significant spatial autocorrelation. Nonetheless, the absence of statistically significant autocorrelation at the unit-centroid level does not necessarily imply that the density field is spatially random, as it is affected by the limited number of observations and the fact that the spatial structure of the model resides in the geological unit geometry rather than in pointwise density values.

3.2.4. Quantification of Uncertainty of the Ethiopian Rock Density Model

The height-weighted average rock density of Ethiopia is 2430 kg/m^3 . As shown in Equation (2), there are three components of uncertainty. In our study, measurement uncertainty $\sigma_{\text{meas}} = 298 \text{ kg/m}^3$, spatial uncertainty $\sigma_{\text{spatial}} = 143 \text{ kg/m}^3$, and assignment uncertainty $\sigma_{\text{assign}} = 122 \text{ kg/m}^3$. Total $\sigma = 352 \text{ kg/m}^3$, which is computed from $\sqrt{(298^2 + 143^2 + 122^2)}$. Therefore, the final output (average rock density with total uncertainty) is $2430 \pm 352 \text{ kg/m}^3$ (with a relative uncertainty of 14.5%). This result is validated by applying the Monte Carlo simulation (10,000 iterations), generating a mean of $2430 \pm 352 \text{ kg/m}^3$ with a 95% confidence interval of 1740–3120 kg/m^3 .

4. Discussion

4.1. Interpretation of Ethiopia's Rock Density Features

The calculated height-weighted average density of 2430 kg/m^3 is 9% lower than the commonly adopted continental upper crustal density of 2670 kg/m^3 . The rock density of 2430 kg/m^3 suggests that the Ethiopian crust is fundamentally younger, with crystalline shields, volcanic rocks, and less metamorphically altered than cratons. This basic lithological variation reflects the observed density deficit, as young volcanic sequences characteristically exhibit lower bulk densities than their crystalline counterparts due to vesicularity, higher porosity, and the predominance of felsic to intermediate compositions [12,51].

These density variations introduce systematic errors in the orthometric and geoid models. For highland topography (averagely exceeding 1500 m elevation), the difference of 240 kg/m^3 between the standard density (2670 kg/m^3) and the Ethiopian average weighted rock density (2430 kg/m^3) would result in a difference of approximately 15 mGal in the Bouguer gravity reduction and a terrain correction error that could impact geoid computation based on local topography roughness [47,52]. These biases would distribute into the determination of orthometric heights, potentially the reason for systematic errors in the vertical datum of a country. Similar density-derived geodetic errors have been reported in other volcanic regions. Hirt et al. [53] indicated that terrain density differences could contribute biases of up to 30 cm in quasi-geoid models when standard density assumptions are implemented.

4.2. Comparison with Other Volcanic Regions

To assess the reliability of the estimated rock densities in Ethiopia, we compared our findings with those of other studies conducted in various regions. The average density values for different countries and worldwide are given in Table 3.

Table 3. Comparative rock density analysis of volcanic terranes worldwide. Values for comparison regions are derived from published national rock density studies. The global volcanic mean is calculated as the unweighted average of the listed volcanic terranes.

Regions	Average Density [kg/m ³]	Difference from 2670 kg/m ³	Geological Setting	Source
Ethiopia	2430	−9.0%	Flood basalt province	This study
Hong Kong	2303	−13.7%	Volcanic complex	[16]
Brazil (Parana)	2459	−7.9%	Flood basalt	[13]
New Zealand	2440	−8.6%	Volcanic arc	[10]
Japan	2500	−6.4%	Volcanic Rock	[14]
Iceland	2520	−5.6%	Volcanic hotspot/mid-ocean ridge	[15]
UNB_TopoDens model	2247	−15.8%	Global average topographic-weighted rock density	[17]
Mean of comparative regions	2414.14	−9.5%	Various settings	This study

The computed average rock density for Ethiopia (2430 kg/m³) aligns closely with the average density (2414.14 kg/m³) reported in various global studies, with a difference of 15.85 kg/m³, corresponding to 0.65%. This inconsistency across geographically disparate regions spanning different tectonic settings, from the Ethiopian continental flood basalts to the New Zealand volcanic arc and the Icelandic volcanic hotspot/plume that is interacting with a mid-oceanic spreading ridge (i.e., the Mid-Atlantic Ridge dominated by flood basalts), shows that the rock density for volcanic-dominated terrains is different from that of crystalline shield regions.

4.3. Implications for Geodetic Applications

The rock density difference of 9% between the standard value (2670 kg/m³) and the Ethiopian average (2430 kg/m³) directly affects Ethiopia’s initiative to modernize the national geodetic vertical datum. This impact can be classified into several interconnected segments. First, the Bouguer gravity anomalies calculated employing the standard density will be systematically biased, influencing subsurface modeling efforts and geological interpretation. The magnitude of this error is substantial. Applying the standard density of 2670 kg/m³ instead of the Ethiopian average density would overestimate the Bouguer plate correction by approximately 10 mGal for every km of topographic elevation, potentially masking genuine geological signals in gravity maps [54]. Second, the geoid-to-quasigeoid separation [55], which depends on topographic density assumptions, will be underestimated when using the standard density, potentially resulting in decimeter-level bias in orthometric heights in the highlands [30,56]. Third, the geoid model determination, which defines the vertical datum, will be influenced if terrain corrections are calculated with inappropriate density values. Given that Ethiopia is updating existing and establishing new geodetic infrastructure as part of its national development program, adopting the region-specific density of 2430 kg/m³ rather than the global standard would ensure that the resulting vertical datum achieves the accuracy levels needed for engineering, modern surveying, and scientific applications [57]. Fourth, in addition to immediate geodetic appli-

cations, the density model computed in this study has broader implications for geophysical research in the region. Variations in rock density (shown in Figure 3) provide constraints for gravity inversion studies, lithospheric structure models, and isostatic analyses of the Ethiopian highlands and rift system. The documented density contrasts between the high-density rift floor and lower-density plateau sequences contribute to understanding the mass distribution and dynamic support mechanisms of the Ethiopian topography [58,59].

4.4. Broader Implications and Limitations

The methodology developed in this study provides a transferable framework for constructing rock-density models in data-sparse regions. The integration of geological mapping with available density databases represents a practical compromise between the ideal of comprehensive in situ measurements and the reality of limited data availability in developing countries. However, several limitations should be acknowledged.

The primary limitation is the reliance on density values derived from analogous rock types and density values taken in different countries rather than direct measurements of Ethiopian samples. Although the agreement with available regional studies [44,45] and global volcanic-rock averages [17] provides confidence in the first-order reliability of the adopted values, systematic differences between Ethiopian rocks and their counterparts from existing databases could introduce biases that are difficult to quantify. These effects may be particularly important in geological regions with complex volcanic, sedimentary, metamorphic, or tectonic histories. The impact of these potential biases depends on both the magnitude of the density difference and the areal extent of the affected geological unit. Local density deviations associated with small geological bodies may have limited influence on the national-scale height-weighted average, but they may be important for local gravity interpretation or local-scale applications. In contrast, systematic deviations in widespread units, such as the Ethiopian Plateau flood basalts, Cenozoic volcanic rocks of the Main Ethiopian Rift and Afar Depression, Precambrian basement rocks, or major sedimentary basins, could have a more significant effect on regional density estimates and geophysical modeling results. Therefore, the model should be regarded as a first-order national density model rather than a substitute for detailed local density surveys.

Consequently, new in situ density measurements are essential for the whole country, while spatially optimizing their field collection according to geological setting. In addition, the 1:2,000,000 scale of the geological map is suitable for national and regional modeling but cannot fully resolve local rock density variations associated with small-scale lithological heterogeneity, minor intrusions, localized alteration zones, weathering effects, or narrow structural features. Consequently, the model captures broad density patterns associated with major geological units but does not represent site-scale density variability.

A relatively high uncertainty in the height-weighted average density, $\pm 352 \text{ kg/m}^3$, equivalent to approximately 14.5%, reflects the variability of published density values and the uncertainty introduced by assigning representative densities to broad geological units. The Monte Carlo simulations provide a means of propagating these uncertainties through the model and evaluating their potential effect on the final estimates. However, they cannot fully eliminate potential systematic bias caused by the absence of direct in situ density measurements in the country. The uncertainty estimates should, therefore, be interpreted as propagated literature-based and classification-based uncertainties, rather than as a complete replacement for measurement-based validation.

As stated above, future refinement of the rock density model should prioritize ground-based density measurements in regions where density variability is expected to be high, where major geological units cover large areas, or where density contrasts are likely to strongly influence geophysical interpretations. Priority areas should include the following:

Main Ethiopian Rift and Afar Depression, where young volcanic rocks, intrusive bodies, sedimentary deposits, geothermal alteration, and magmatic processes may produce strong density contrasts; the Ethiopian Plateau flood–basalt provinces, where density may vary with lava composition, vesicularity, weathering, alteration, and stratigraphic level; Precambrian basement exposures in northern, western, southwestern, and southern Ethiopia, where metamorphic grade, lithological diversity, deformation, and intrusive bodies may generate significant density variability; and major sedimentary basins, such as the Ogaden, Blue Nile, Mekele, and Gambela basins, where compaction, porosity, cementation, and lithological composition strongly influence bulk density. Additional measurements should also target major tectonic boundaries and volcanic transition zones, particularly where the rift, plateau, basement, and sedimentary domains meet, because these areas are expected to contain strong density gradients relevant to gravity and regional geophysical modeling. Targeted in situ density measurements in these regions would help quantify the differences between Ethiopian lithology units and their global analogues, reduce the present uncertainty, and improve the reliability of the model for future applications.

Despite the limitations, the model represents a significant advancement over the previous absence of systematic rock-density information for Ethiopia. The framework established here can be progressively refined as new in situ measurements become available, consistent with the adaptive modeling approach advocated by [11] for regional geophysical studies.

5. Conclusions

We have developed and presented the first comprehensive digital rock density model of Ethiopia. The estimated height-weighted average density of $2430 \pm 352 \text{ kg/m}^3$ is 9% lower than the conventionally adopted value of 2670 kg/m^3 used in most gravimetric applications. This discrepancy is attributed to Ethiopia's unique geological configuration, dominated by extensive volcanic sequences, especially felsic and intermediate compositions across the high plateaus. The density model shows considerable spatial variations, with rock densities ranging from diatomite and other low-density sedimentary units (1528 kg/m^3) to dense mafic intrusive bodies (2884 kg/m^3).

The rock density model has meaningful and direct implications for Ethiopia's geodetic applications. Using the rock density model rather than a constant value for the whole country will significantly improve the accuracy of geoid modeling and orthometric height determination. Utilizing this region-specific density model is particularly crucial for Ethiopia, a region characterized by high topographic elevations and complex geology, where incorrect rock density estimates could lead to significant errors.

Beyond immediate geodetic applications, this research provides a proven approach for developing rock density models in data-limited regions, particularly in Africa. By aligning Ethiopia's rock density characteristics with those of other regions worldwide, such as New Zealand, this study situates the country within a global geophysical context and underscores the need to move beyond uniform continental averages. This digital rock model could be used as a fundamental data source to support potential research in geodesy, tectonic modeling, and resource evaluation across the Horn of Africa. In the context of Ethiopia's continuing geodetic modernization program, adopting the region-specific density model established here will enhance the reliability and accuracy of the national vertical datum.

Although the study presented here represents a significant contribution to improved geodetic and geophysical applications in the country, the accuracy of the developed rock density model is limited by the lack of direct measurements as well as small-scale geological mapping. Future efforts should focus on collecting in situ density measurements to refine

and validate the model, improve the spatial resolution of geological mapping, and further extend the methodology to neighboring countries in the East African Rift System, while integrating the density model with gravity observations to develop an improved regional geoid for East Africa.

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Appendix A

Ethiopian rock data: rock code, rock type, rock density, and their standard deviation (STD).

ID	Area Code	Rock Code	x_Coordinate	y_Coordinate	Rock Type	Density in kg/m ³	STD
1	540502838.2	Ara	617633.126079133	1212584.29863866	unknown/unclassified	2670	200
2	38879345.02	Ara	471964.252917459	448207.087022257	Rhyolite	2207	225
3	8605992003	ARa	423737.858136098	574710.076008463	Rhyolite (Acidic)	2207	225
4	10518771848	ARb	59030.2487289022	934341.475466063	Basalt (Trap series)	2768	162
5	2550982511	ARk	257865.366419363	579491.164990824	Trachyte	2591	182
6	66584061.65	Arl	494120.071548435	456255.33715982	Rhyolitic lava	2207	225
7	39165861171	ARl	339322.321898481	916296.860331571	Rhyolite lava flow	2207	225
8	3292107410	ARy	377121.508999153	587341.955709883	Rhyolitic Tuff	2113	289
9	5297983442	dt	119782.38379699	1034862.65151752	Diatomite	1528	141
10	36911976.74	Dt	143687.953110914	1004320.3464606	Diatomite (lake)	1528	141
11	762544498.7	gb	187925.368721248	962705.237134117	Gabbro	2884	147
12	11471783516	gd	84489.8808966487	1111665.16813078	Granodiorite	2681	70
13	460721520.6	gd/tn	64578.6209383893	745107.417337254	Granodiorite/Tonalite Mix	2740	85
14	883312687.2	gd/tn	46607.2591613722	843666.830353388	Granodiorite/Tonalite Mix	2740	85
15	9372665082	gt1	321112.032617125	679261.419161355	Granite Type 1	2640	77
16	5415131265	gt2	184483.285922379	1040062.09174577	Granite Type 2	2640	77
17	6807023804	gt3	378135.22667388	1101786.99092325	Granite Type 3	2640	77
18	2811525179	gt4	424004.495818334	851501.397926411	Granite Type 4	2640	77
19	676599000.8	gt5	520220.724140156	1267726.10987628	Granite Type 5	2640	77
20	23138184445	Ja	424769.758830442	1194542.24141906	Jurassic Sandstone	2463	266
21	1540701689	Jag	563598.25085998	1482886.66949456	Jurassic Agglomerate	2570	159

ID	Area Code	Rock Code	x_Coordinate	y_Coordinate	Rock Type	Density in kg/m ³	STD
22	2118047990	Jb	416008.584427479	1088342.90842534	Jurassic Basalt	2768	162
23	12588268375	Jg	817836.893695549	839601.523411997	Jurassic Conglomerate	2570	159
24	12796782251	Jg1	842311.923035437	653950.835665707	Jurassic Conglomerate 1	2570	159
25	23999279707	Jg2	867932.863885026	738300.733159229	Jurassic Conglomerate 2	2570	159
26	43688722884	Jh	727198.14054179	752416.432263531	Jurassic Shale	2335	190
27	9167469226	Jt	534887.58588272	1345316.81192876	Jurassic Tuff	2113	289
28	46786800873	Ju	822645.612877983	828660.866214364	Jurassic Undifferentiated	2459	225
29	9113619908	Ka	595285.560022526	1053679.77862706	Cretaceous Sandstone	2463	266
30	3941189729	Kb	1092997.27935597	640641.719948289	Cretaceous Basalt	2768	162
31	1352810803	Kf	1143546.39145843	655364.988697363	Cretaceous Fine-grained	2347	283
32	11590833365	Kg1	787618.117458309	632246.885527126	Cretaceous Conglomerate 1	2570	159
33	45261146136	Kg2	947541.432150462	643544.247404921	Cretaceous Conglomerate 2	2570	159
34	18675069664	Km	1012669.38767849	635164.006804482	Cretaceous Mudstone	2204	301
35	14563693.25	lake	661192.131631418	1540949.50182061	lake sediments	1979	140
36	140053290	late	222019.442280386	688503.691334874	late sediments	2300	200
37	293055511.9	Late	387749.17960248	741277.546273458	Late sediments (capital)	2300	200
38	32426850574	Na	756573.340545942	1223089.11092315	Neogene Andesite	2565	170
39	378244822	Nad	481877.902559267	1575064.78554856	Neogene Andesite Dacite	2402	175
40	1580504468	Nb	215408.340415582	704218.151517344	Neogene Basalt	2768	162
41	8429347785	Nc	494368.324783635	901511.005490716	Neogene Conglomerate	2570	159
42	2659241441	Ncb	563893.38440614	814497.929747768	Neogene Conglomerate-Breccia	2291	295
43	2414142352	Ndb	730729.668074442	1270855.03483563	Neogene Dolerite	2749	146
44	936462473.1	Nmr	765410.37861113	1110636.38066609	Neogene Marl	2344	250
45	29398965679	Nn	449662.966981816	872041.548088874	Neogene Ignimbrite	2125	247
46	700394471.6	Nq	676978.505678859	1127831.43848018	Neogene Quartzite	2610	73
47	1368050633	NQ	302065.415615132	679440.328850409	Neogene-Quaternary Volcanics	2666	166
48	2867119154	NQtb	592309.906904119	1094999.48042258	Neogene-Quaternary Tuff-Breccia	2202	292
49	2166046877	Nrs	671240.305369584	1520626.4148287	Neogene Rhyolite Sandstone	2335	278
50	21151993952	Ntb	464739.262601254	1061564.75218932	Neogene Tuff-Breccia	2202	292
51	10104249041	Nts	332491.999121655	521826.886533231	Neogene Tuff-Sandstone	2288	278
52	399651273.6	Ntt	43287.5689095193	1033503.46211509	Neogene Tuff-Trachyte	2352	236
53	82210523792	P2a	471070.23208171	1240996.361007	Paleogene Andesite 2	2565	170
54	22002401965	P3a	420810.24586213	1345394.10442531	Paleogene Andesite 3	2565	170
55	9800589712	Pa	1266256.10548733	840922.57876198	Paleogene Andesite	2565	170
56	58989527256	Pj	1137788.57120537	846590.011401805	Paleogene Limestone	2484	211
57	40524889552	Pjb	234194.357126536	752663.362782696	Paleogene Limestone-Basalt	2626	187
58	20483652562	Pjr	244919.890209742	798732.934909986	Paleogene Limestone-Rhyolite	2345	218
59	69314660.65	pk	1477214.12308242	892892.681609751	Paleogene Karst	2484	211
60	18729249874	PNa	572060.800356131	1109063.49718178	Paleogene-Neogene Andesite	2565	170

ID	Area Code	Rock Code	x_Coordinate	y_Coordinate	Rock Type	Density in kg/m ³	STD
61	4763563317	PNab	599105.187117252	821324.85980943	Paleogene-Neogene Andesite-Basalt	2666	166
62	36645293088	PNmb	200706.553814838	929291.876822081	Paleogene-Neogene Mudstone-Basalt	2486	232
63	25860669783	PNtb	374428.163986081	1284419.39376626	Paleogene-Neogene Tuff-Basalt	2440	226
64	3388545430	PR1r	526721.918228121	701642.727812591	Precambrian Rhyolite	2207	225
65	4039607700	PR1w	500433.71773027	626074.802121174	Precambrian Schist	2732	115
66	5691331060	PR2a	519606.554969249	555781.223472585	Precambrian Amphibolite	2892	115
67	7409925012	PR2b	63512.6041080588	961253.795276548	Precambrian Basalt	2768	162
68	1029850887	PR2d	473802.886960195	1512035.83135605	Precambrian Diorite	2797	119
69	65067498.02	PR2k	482557.604190949	608254.53102374	Precambrian Quartzite	2610	73
70	12436564522	PR2l	483626.644109186	1545607.43467246	Precambrian Limestone	2716	117
71	2105808501	PR2s	422461.572794287	1563088.55777058	Precambrian Schist	2732	115
72	309580658.1	Pr2t	531422.966127041	1435071.16152871	Precambrian Tonalite	2800	200
73	3521894969	PR2t	525071.879922846	1515748.104947	Precambrian Tonalite (R capital)	2800	200
74	9877540477	PR2td	171659.842232718	1190484.23403107	Precambrian Tonalite-Diorite	2798	119
75	21672118977	pt	1349161.12776366	818236.713696129	Paleogene Tuff	2113	289
76	57721240.99	Pt	1270594.08707264	927377.933044562	Paleogene Tuff (Capital)	2113	289
77	4093465627	Pzt	442736.021061192	1442445.29554518	Paleogene Zeolite Tuff	2113	289
78	97536058693	Q	421283.130845194	804451.330786204	Quaternary Alluvium	2179	108
79	20844463133	Qb	685844.82317862	1230266.52730739	Quaternary Basalt	2768	162
80	25086173277	Qb1	316086.485775771	1023315.21504316	Quaternary Basalt Type 1	2768	162
81	23209885.01	Qbb	355889.949314615	601617.492897065	Quaternary Basalt Breccia	2195	358
82	2400839408	Qbt	674208.808302776	1463762.42514386	Quaternary Basalt-Tuff	2440	226
83	10234875170	Qd	474693.079230249	855024.369673473	Quaternary Diatomite	1528	141
84	7319881784	Qg	696771.960795877	817633.857473738	Quaternary Gravel	2309	266
85	43294334496	Qh	614140.667416693	1077606.7936572	Quaternary Highland Sediments	2200	200
86	9503652425	Qp	663673.457130259	1348529.522323	Quaternary Pumice	1719	310
87	7011980965	Qr	608570.328230602	1131090.17120597	Quaternary Rhyolite	2207	225
88	2412038402	tn	124140.505358088	1200034.34090809	Tonalite	2800	200

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