Geodesy and Geodynamics 15 (2024) 75–81

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepage: http://www.keaipublishing.com/geog

# A detailed rock density model of the Hong Kong territories

Albertini Nsiah Ababio*, Robert Tenzer

*Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hong Kong, China*

ARTICLE INFO

*Article history:*
Received 1 March 2023
Accepted 10 May 2023
Available online 1 September 2023

*Keywords:*
Density model
Rock types
Gravimetric modeling
Hong Kong

ABSTRACT

We used the geological map and published rock density measurements to compile the digital rock density model for the Hong Kong territories. We then estimated the average density for the whole territory. According to our result, the rock density values in Hong Kong vary from 2101 to 2681 $kg \cdot m^{-3}$. These density values are typically smaller than the average density of 2670 $kg \cdot m^{-3}$, often adopted to represent the average density of the upper continental crust in physical geodesy and gravimetric geophysics applications. This finding reflects that the geological configuration in Hong Kong is mainly formed by light volcanic formations and lava flows with overlying sedimentary deposits at many locations, while the percentage of heavier metamorphic rocks is very low (less than 1%). This product will improve the accuracy of a detailed geoid model and orthometric heights.



## 1. Introduction

Since knowledge of the actual topographic density distribution is still, largely restricted by the lack of subsurface rock density samples, different assumptions about the topographic density have been proposed, most notably by assuming a constant (average) topographic density. In physical geodesy, the application of the average topographic density in the theory of orthometric heights [1,2] is well known. Furthermore, Molodensky [3,4] formulated the theory of normal heights based on disregarding the topographic density. Nevertheless, the gravitational contribution of topographic density distribution on orthometric heights, geoid, and gravity anomalies has been investigated in recent years more thoughtfully in physical geodesy and gravimetric geophysics applications. To estimate the topographic effect on gravity, geoid, and orthometric heights, digital rock density models are required together with digital terrain models.

The continental upper crustal density of 2670 $kg \cdot m^{-3}$ [5] is often adopted to represent the mean topographic density. This value was probably reported by Hayford [6] for the first time and has been used until now without a critical revision. A recent global study by Sheng et al. [7] indicates that this value could be overestimated. This is also supported by other studies. Tenzer et al. [8], for example, reported an average density of 2440 $kg \cdot m^{-3}$ for New Zealand, and de Medeiros et al. [9] provided an average density of 2459 $kg \cdot m^{-3}$ for Brazil.

Huang et al. [10] demonstrated that adopting a constant topographic density in mountainous areas is a rough estimate, leading to errors at the decimeter level in geoid modeling and orthometric height determination [11–15]. Similar findings were given by Kühtreiber [16], Pagiatakis and Armenakis [17], Kiamehr [18], and Abbak [19]. To address this issue in the context of ongoing modernization of the vertical geodetic datum in Hong Kong, we used available geological evidence and rock density samples to compile the digital rock density for the Hong Kong territories by applying methods and numerical procedures developed before by Tenzer et al. [8] and Sheng et al. [7]. Tenzer et al. [8] constructed a 1 × 1 arc-min digital rock density model of New Zealand by combining digital geological maps from different databases with in situ samples of rock density measurements and supplementary geological sources. Sheng et al. [7] applied a similar method to construct the UNB_TopoDensT global topographic density model available on a 1 × 1 arc-deg, 5 × 5 arc-min, and 30 × 30 arc-sec grids. They used the geological information from the global

* Corresponding author.
*E-mail address:* albertini.nsiahababio@connect.polyu.hk (A. Nsiah Ababio).

Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.geog.2023.05.006

lithospheric model GLiM [20] compiled by merging different local data sources from across the globe.

For a relatively small area like the Hong Kong territories, the $5 \times 5$ arc-min global grid is too coarse to realistically depict the topographic density variations, especially due to a relatively complex geological setting for such a small area. We, therefore, developed a very detailed rock density model for Hong Kong that will be used to compute and apply the anomalous topographic density corrections to newly determined orthometric heights of leveling benchmarks [21] and the newly developed detailed geoid model [22]. According to our preliminary estimates, the anomalous topographic density could modify the geoid and orthometric heights up to $\pm 1$ cm due to (as already mentioned) the relatively complex geology as well as elevated topography (that magnifies the topographic effect on geoid and orthometric heights). Next, a summary of numerical procedures used in preparing the new digital rock density model is given.

## 2. Hong Kong rock density model

Hong Kong shares a border with the coast of the southern part of China, covering an approximate land area of 1104 km$^2$. Essentially, the nature of the terrain ranges from coastal lowlands to rugged mountain chains, reaching the highest elevation of 957 m (Tai Mo Shan). The first geological memoire of Hong Kong [23] was published prior to the establishment of the Hong Kong geological survey (HKGS) in 1982 by using earlier surveys conducted in the 1940's by Canadian geologists. In January 1967, the British Geological Survey began the second geological survey in Hong Kong. The survey finished in March 1969, and results were published as a memoir with two geological maps compiled at a scale of 1:50000 in 1971. The establishment of the HKGS resulted in the production of standard geological maps compiled at different scales (1:100000, 1:20000, and 1:5000), which provide useful information associated with the land. The geological information of Hong Kong can be accessed online interactively as a web-based map with attached geological definitions and detailed descriptions [24].

Deformations in the structural evolution of rocks in Hong Kong are recorded during the Jurassic and Cretaceous epochs. Both geological epochs are characterized by prominent volcanic eruptions associated with the intrusion of enormous amounts of magma with granitic composition into the Earth's crust. Consequently, the geological setting of Hong Kong is characterized mainly by igneous rocks, which are undoubtedly dominated by volcanic and intrusive types. Approximately 50% of the physical surface of Hong Kong is covered by volcanic rocks and dominates its mountainous depictions [25], composed of bulk sequences of tuff associated with minor lava flow such as andesite, rhyolite, dacite, and trachydacite lavas. Additionally, roughly 35% of the surface area is occupied by major and minor sub-volcanic intrusive rocks. Granite and granodiorite are the major sub-volcanic rocks that occupy about 17.60% and 2.23% of the land surface, respectively. On the other hand, the minor sub-volcanic intrusive rocks take the form of rhyolite, quartz monzonite, and leucogranite. Sedimentary rocks in Hong Kong are located mostly in the western [26] and northern [27] parts. Their formation dates back to the late Paleozoic.

The rocks in Hong Kong have been mapped at scales of 1:20000 and 1:5000 by using Devonian, Carboniferous, and Permian as their Chronostratigraphic classification as well as adopting formations and groups as their litho-stratigraphic classification [cf. [28,29]]. Through thermal and dynamic processes, some of these rocks have undergone metamorphosis. The northwestern part of the New Territories is covered by superficial deposits broadly categorized into colluvium, alluvium, and marine deposits [30]. Subsequently, after a thorough review, it was deduced that the superficial deposits were primarily made up of alluvium (together with beach deposits) and colluvium deposits from mass wasting [31]. The interactive online geological memoire of Hong Kong describes the lithological composition of these deposits as a mixture of well, semi, and poorly sorted sand, clay, silt, and gravels. It is worth noting that portions of the coastal areas of Hong Kong (approximately 7%) have been reclaimed from the sea for various purposes, causing them to lack a distinct geological definition due to the nature of materials used in the filling. The beginning of the reclamation activities of the region can be dated as far as the mid-1800s and is still ongoing today.

The digital geological maps of Hong Kong further classify the rocks into their respective litho-stratigraphic categories by using the main rock types present in their formations. The geological map of Hong Kong consists of about 53 different formations, which have further been reclassified using the main rocks into 22 individual lithological units (Fig. 1) for this study. Based on the formations in the 1:100000 digital geological map published by the HKGS in 2006, we obtained a classified version of the lithological units by adopting the major and dominant rock types to assign specific density values to them. It is worth noting that the 1:100000 web-based map adopts geological updates and interpretations provided by the 1:20000 geological maps of Hong Kong with their accompanying memoirs [26,27,32–35].

To prepare the lateral rock density model of Hong Kong, we applied a three-step approach which begins with assigning specific density values with associated uncertainties to the lithological units, resulting in a GIS vector map. The digital density model was obtained through the discretization of data and implementation of aggregation procedures on the density vector map. Rock density measurements were the main source of information utilized in allocating the respective densities of the major types of rocks. Tenzer et al. [8] provided a detailed rock density database containing various rock density values alongside their respective uncertainty spreads. The database identifies 123 main rock types compiled from in situ rock density measurements in New Zealand. This database has been the basic source for assigning rock density values in this study (see Table 1). Since rock density measurements are relatively sparse, where information is missing, the densities were attributed according to different sources, including geological maps, research theses, and articles.

By acknowledging that depth, porosity, and mineral structure can cause variations in density measurements for the same rock type, we considered several available sources. Nonetheless, we narrowed our selection to a single source for each rock type for uniformity and consistency. For a lithological unit, some of the classifications presented in the geological map (Fig. 1) show a combination of different rock types in different areas. Practically, the formations of these rocks vary in size, quantity, and thickness. The classification, therefore, requires a unique density representation to facilitate the modeling. Areas designated to be reclaimed lands were assigned the value of the adopted average upper crustal density of 2670 kg$\cdot$m$^{-3}$. For a lithological unit with the combination of different main rock types, the representative rock density for each geological unit was obtained by averaging the density values of the respective main rocks. This was executed by assuming that these rock combinations possess similar layer thicknesses and samples. Similarly, their uncertainties were estimated using a simple average of their standard deviations. For rock types with missing uncertainty information, such as andesite lava and dolomite, their standard deviations have been computed prior to the assumption that the range of their densities adopts a normal distribution with a confidence level of 95% as presented by Vaníček and Krakiwsky [39], so that

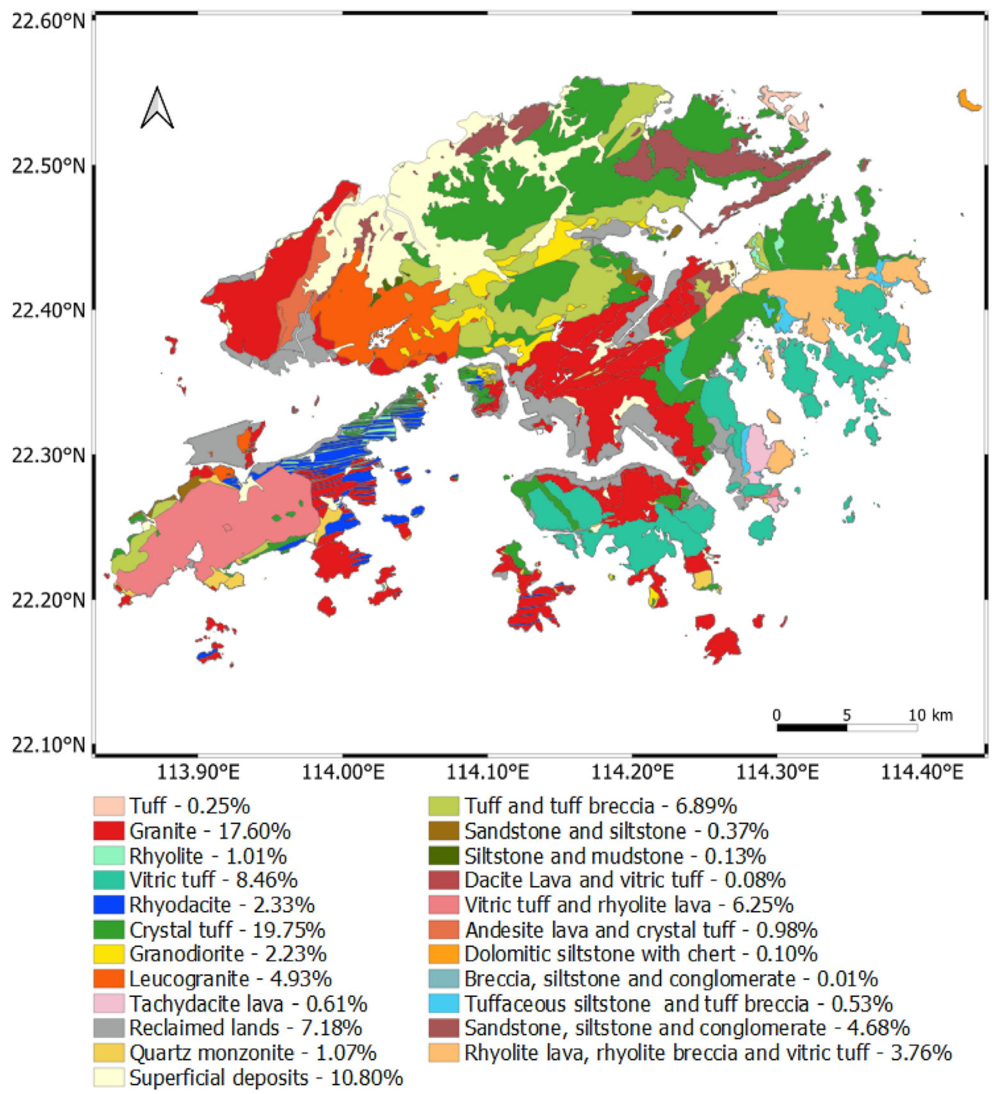


**Fig. 1.** Geological map of Hong Kong showing the main (surface) rock types. The legend provides the percentage of land coverage of each main rock type.

$$\sigma = \frac{\Delta\rho}{2\sqrt{\xi x^2_{(1,0.95)}}} \tag{1}$$

where $\Delta\rho$ is the difference between the maximum and minimum density values for each rock type, and $\xi x^2_{(1,0.95)}$ is the representative value for the chi-square with a 95% confidence level.

To deduce the final representative density value over the study area, an average topographic density value was computed by using the assigned lithological density values alongside their topographic heights according to the expression given by Sheng et al. [7]. It reads,

$$\overline{\rho} = \frac{\sum_{i=1}^{n} \rho_i(\phi,\lambda) \cdot H_i(\phi,\lambda)}{\sum_{i=1}^{n} H_i(\phi,\lambda)} \tag{2}$$

where $\rho_i(\phi,\lambda)$ is the density value at an individual grid point (obtained from the topographic density model) of which position is defined by latitude $\phi$ and longitude $\lambda$. The topographic heights $H_i$ have been extracted from the digital terrain model (DTM) of Hong Kong provided on a 5 m grid.

## 3. Results and discussion

The Hong Kong digital rock density model (see Fig. 2) was compiled in a GIS environment using a 2 arc-sec spaced regular grid covering the full extent of area. As stated earlier, due to unavailable density models, the continental upper crustal density of 2670 kg·m$^{-3}$ [5] is mostly adopted in geodetic and geophysical applications. Nevertheless, studying the geological setting of Hong Kong shows different lithological units with varied densities ranging from 2101 to 2681 kg·m$^{-3}$ with associated uncertainties also ranging from 70 to 292 kg·m$^{-3}$. Using these values, the estimated average density of the upper crust in Hong Kong computed according to Eq. (2) was deduced to be 2303 kg·m$^{-3}$ with a standard deviation of 223 kg·m$^{-3}$. As specified before, roughly 50% of the Hong Kong territories is covered by volcanic rocks, mainly composed of bulk sequences of tuff associated with lava. Tuff is a highly porous rock of a relatively low density (cf. Table 1), resulting in the overall lower average density value of the whole Hong Kong territories. Considering the nature of the land distribution in Hong

**Table 1**
The adopted density values for the main rock types in Hong Kong.

| Main rocks | Density ($kg\cdot m^{-3}$) | Min ($kg\cdot m^{-3}$) | Max ($kg\cdot m^{-3}$) | No. of samples | STD ($kg\cdot m^{-3}$) | Source and comment |
|---|---|---|---|---|---|---|
| Tuff | 2113 | 1410 | 2940 | 723 | 289 | Tenzer et al. [8] |
| Vitric tuff | 2113 | | | | | Vitric tuff adopts the same density as tuff |
| Crystal tuff | 2113 | | | | | Crystal tuff adopts the same density as tuff |
| Granite | 2640 | 2330 | 2940 | 288 | 77 | Tenzer et al. [8] |
| Granodiorite | 2681 | 2530 | 2940 | 53 | 70 | Tenzer et al. [8] |
| Leucogranite | 2300 | | | | | Annen and Scaillet [36] |
| Rhyolite | 2207 | 1360 | 2740 | 704 | 225 | Tenzer et al. [8] |
| Trachyte | 2591 | 2170 | 2950 | 31 | 182 | Tenzer et al. [8] |
| Dacite | 2402 | 1940 | 2700 | 79 | 175 | Tenzer et al. [8] |
| Lava | 2680 | 2540 | 2820 | 6 | 93 | Tenzer et al. [8] |
| Rhyodacite | 2350 | | | | | Hildreth et al. [37] |
| Sandstone | 2463 | 1510 | 3000 | 968 | 266 | Tenzer et al. [8] |
| Siltstone | 2347 | 1360 | 2880 | 471 | 283 | Tenzer et al. [8] |
| Mudstone | 2204 | 1320 | 2870 | 734 | 301 | Tenzer et al. [8] |
| Andesite Lava | 2630 | 2590 | 2660 | | 18 | Hildreth et al. [37] |
| Chert | 2564 | 2240 | 2740 | 11 | 162 | Tenzer et al. [8] |
| Quartz monzonite | 2640 | | | | | Carmichael [38] |
| Clay | 2067 | 1920 | 2450 | 9 | 171 | Tenzer et al. [8] |
| Silt | 1979 | 1720 | 2160 | 14 | 140 | Tenzer et al. [8] |
| Dolomite | 2840 | 2720 | 2840 | | 31 | Carmichael [38] |
| Sand | 2048 | 1690 | 3220 | 27 | 351 | Tenzer et al. [8] |
| Gravel | 2309 | 1870 | 2580 | 9 | 266 | Tenzer et al. [8] |
| Breccia | 2291 | 1540 | 3000 | 118 | 295 | Tenzer et al. [8] |
| Conglomerate | 2570 | 2110 | 3000 | 118 | 159 | Tenzer et al. [8] |

Kong (Fig. 1), we can clearly distinguish the mainland and the two main Islands. Considering the different geological configurations of these areas, we computed their average density values separately to assess their effect on the final average topographical density of the study area. The mainland (consisting of Kowloon and New Territories) has a similar geological setting to the Hong Kong Island, causing them to have close average density values as compared with Lantau Island. Moreover, these two areas have lower density values of 2275 and 2284 $kg\cdot m^{-3}$, respectively, compared with the estimated average density of the upper crust for the whole Hong Kong territories. Again, the lower density values are mainly attributed to the percentage coverage of the highly porous rocks in these regions. The Hong Kong Island has a similar coverage of granite and vitric tuff, with the remaining portions covered by crystal tuff, reclaimed lands, and quartz monzonite. However, the mainland has a wide coverage of various tuff, granite, superficial deposits, leucogranite, and rhyolitic lava and breccia. Lantau Island contains different lithological units but is prominently covered with vitric tuff and rhyolite lava. Furthermore, the area exhibits obvious occurrences of granite, rhyodacite, reclaimed lands, quartz monzonite, tuff and tuff breccia and partially also smaller proportions of superficial deposits, leucogranite, and rhyolite dyke

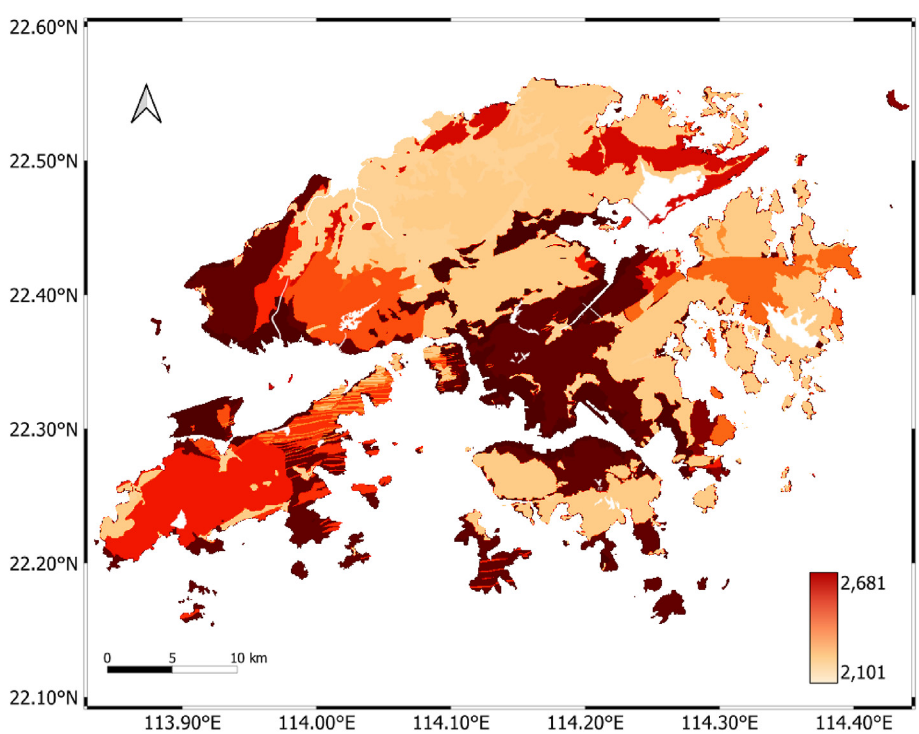


**Fig. 2.** Digital rock density model of Hong Kong compiled on a 2 arc-sec grid.

complexes. These lithological combinations averaged a topographical density value of 2396 kg·m$^{-3}$ for the Island, the highest average value among specified average densities of the particular area.

For evaluation and assessment purposes, we compared the estimated density model of Hong Kong with the global UNB_TopoDensT [7]. The 30 arc-sec resolution of the UNB_TopoDensT model was adopted for the comparison, whereas the model developed in this study was resampled to be compatible with the UNB_TopoDensT resolution. We used the nearest neighbor method to generalize our density model on a 30 arc-sec grid. The results of the comparison are presented in Figs. 3 and 4, where we showed grid differences and a histogram distribution of the magnitude of differences, respectively. The differences between these models (Fig. 3) are within 2681 and -690 kg·m$^{-3}$, with an average of 420 kg·m$^{-3}$. Maximum differences are detected along the coast where many reclamation activities have been undertaken, especially along the coast of the southern part of New Territories and Kowloon. Furthermore, smaller islands and the coastal areas of Lantau and Hong Kong Islands also have a similar situation. Extraction of the 30 arc-sec coverage of Hong Kong from the UNB_TopoDensT gives the range of density values from 0 to 2791 kg·m$^{-3}$ (Fig. 5). It is evident that the coastal areas and the portions where maximum differences occur were assigned by a

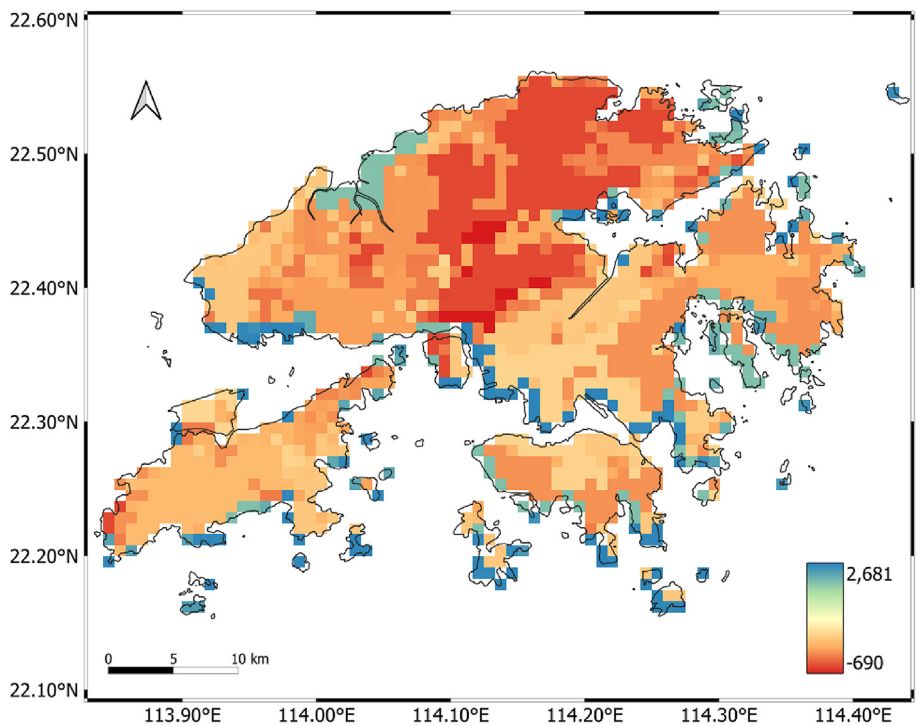


**Fig. 3.** Difference between the Hong Kong digital rock density and the UNB_TopoDensT compiled on a 30 arc-sec grid.

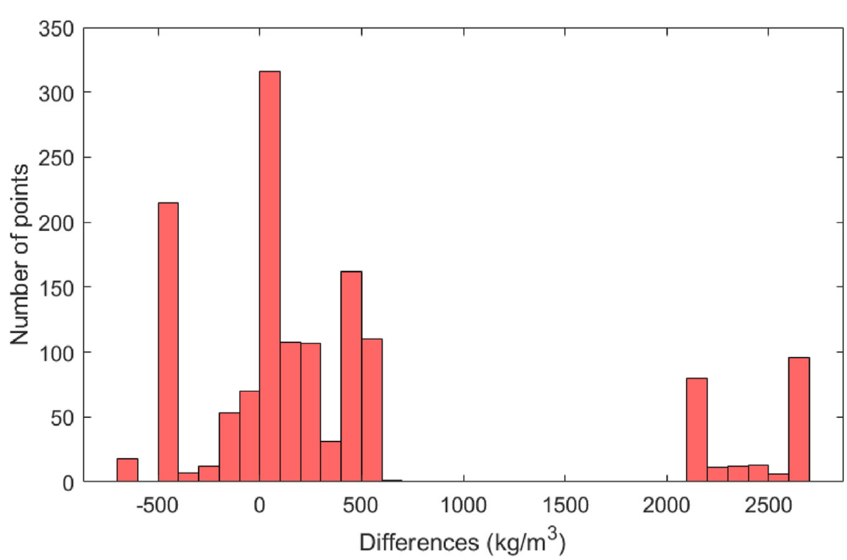


**Fig. 4.** Distribution of the differences between the Hong Kong digital rock density and the UNB_TopoDensT.

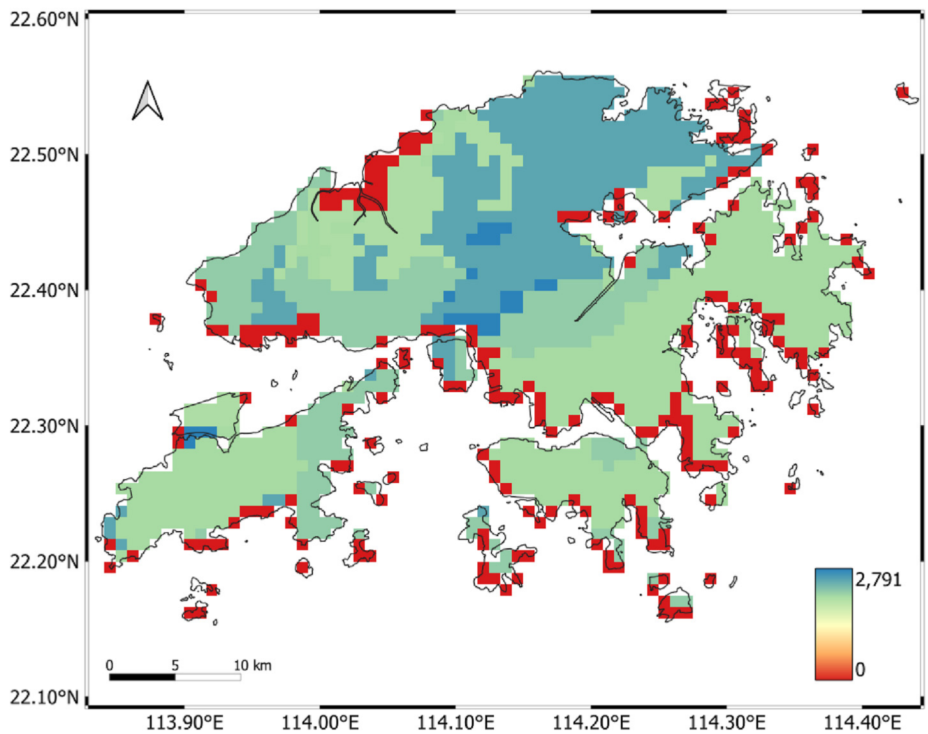


**Fig. 5.** The 30 arc-sec coverage of the UNB_TopoDensT at the Hong Kong territories.

zero density value in the UNB_TopoDensT due to the lack of a detailed geological map of the region. However, disregarding large coastal differences, we estimated the differences in the two models to range from −690 to 607 $kg \cdot m^{-3}$. This ascertains that the detailed lithological data plays a major role in the accurate modeling of topographic effect as compared with the 15 broadly categorized GLiM lithologies used in UNB_TopoDensT.

## 4. Conclusion

We have developed the new digital topographic density model for the Hong Kong territories and estimated respective average topographic density values. The model was derived from lithological units of the territory obtained from the published 1:100000 geological map and by assigning density values for particular rock types. The density model was compiled from existing rock density measurements recorded in various scientific sources. An estimated average topographic density value of the upper crust of 2303 $kg \cdot m^{-3}$ was obtained for the Hong Kong territories. This value significantly differs from the adopted value of 2670 $kg \cdot m^{-3}$. The computed model was spatially compared with the global UNB_TopoDensT topographic model. Moderate differences were observed inland. Large differences along some coastal areas and small surrounding islands were explained by variations in lithological details adopted in developing both models.

### Author statement

**Albertini Nsiah Ababio:** Conceptualization, Methodology, Software, Data curation, Investigation, Writing—original draft preparation, Visualization. **Robert Tenzer:** Supervision, Writing—Review and Editing, Funding Acquisition.

### Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to restrictions.

### Conflicts of interest

The authors declare that there is no conflicts of interest.

### Acknowledgment

The work presented in this article was supported by the Hong Kong GRF RGC project 15217222: “Modernization of the leveling network in the Hong Kong territories.”

### References

[1] F.R. Helmert, The mathematical and physical theories of higher geodesy, vol. 2, BG, Teubner, Leipzig, 1884.
[2] F.R. Helmert, Die Schwerkraft im Hochgebirge, insbesondere in den Tyroler Alpen, Veröff. Königl, No. 1, Preuss Geod Inst, Berlin, 1890.
[3] M.S. Molodensky, Fundamental problems of geodetic gravimetry (in Russian), TRUDY Ts NIIGAiK, vol. 42, Geodezizdat, Moscow, 1945.
[4] M.S. Molodensky, External gravity field and the shape of the Earth surface, Izv. CCCP, Moscow, 1948 (in Russian).
[5] W.J. Hinze, Bouguer reduction density, why 2.67? Geophysics 68 (5) (2003) 1559–1560.
[6] J.F. Hayford, The figure of the Earth and isostasy from measurements in the United States (No. 82), US Government Printing Office, 1909.
[7] M.B. Sheng, C. Shaw, P. Vaníček, R.W. Kingdon, M. Santos, I. Foroughi, Formulation and validation of a global laterally varying topographical density model, Tectonophysics 762 (2019) 45–60.
[8] R. Tenzer, P. Sirguey, M. Rattenbury, J. Nicolson, A digital bedrock density map of New Zealand, Comput Geosci 37 (8) (2011) 1181–1191.
[9] D.F. de Medeiros, G.S.A. Marotta, E. Yokoyama, I.B. Franz, R.A. Fuck, Developing a lateral topographic density model for Brazil, J. S. Am. Earth Sci. 110 (2021) 103425.

[10] J. Huang, P. Vanicek, S. Pagiatakis, W. Brink, Effect of topographical mass density variation on gravity and geoid in the Canadian Rocky Mountains, J Geodyn 74 (2001) 805–815.
[11] R. Tenzer, P. Vaníček, M. Santos, W.E. Featherstone, M. Kuhn, The rigorous determination of orthometric heights, J. Geodyn. 79 (1–3) (2005) 82–92.
[12] R. Tenzer, P. Moore, P. Novák, M. Kuhn, P. Vaníček, Explicit formula for the geoid-to-quasigeoid separation, Studia Geophys. Geod. 50 (2006) 607–618.
[13] R. Tenzer, Ch Hirt, S. Claessens, P. Novák, Spatial and spectral representations of the geoid-to-quasigeoid correction, Surv Geophys 36 (2015) 627.
[14] R. Tenzer, Ch Hirt, P. Novák, M. Pitoňák, M. Šprlák, Contribution of mass density heterogeneities to the geoid-to-quasigeoid separation, J. Geodyn. 90 (1) (2016) 65–80.
[15] I. Foroughi, R. Tenzer, Comparison of different methods for estimating the geoid-to-quasigeoid separation, Geophys J Int 210 (2017) 1001–1020.
[16] N. Kühtreiber, Precise geoid determination using a density variation model, Phys Chem Earth 23 (1) (1998) 59–63.
[17] S.D. Pagiatakis, C. Armenakis, Gravimetric geoid modelling with GIS, Int. Geo. Serv. Bull. 8 (1999) 105–112.
[18] R. Kiamehr, The impact of lateral density variation model in the determination of precise gravimetric geoid in mountainous areas: a case study of Iran, Geophys J Int 167 (2006) 521–527.
[19] R.A. Abbak, Effect of a high-resolution global crustal model on gravimetric geoid determination: a case study in a mountainous region, Studia Geophys. Geod. 64 (2020) 436–451, https://doi.org/10.1007/s11200-020-1023-z.
[20] J. Hartmann, N. Moosdorf, The new global lithological map database GLiM: a representation of rock properties at the Earth surface, G-cubed 13 (2012) 431.
[21] A. Nsiah Ababio, R. Tenzer, The use of gravity data to determine orthometric heights at the Hong Kong territories, J. Appl. Geodesy 16 (4) (2022) 401–416.
[22] A. Nsiah Ababio, R. Tenzer, Compilation of the new detailed geoid model HKGEOID-2022 for the Hong Kong territories, Mar. Geodesy 45 (6) (2022) 688–709.
[23] S.G. Davis, The geology of Hong Kong, Government Printer, Hong Kong, 1952, p. 231.
[24] C.W. Lee, R.J. Sewell, in: On-line Geological Memoir of Hong Kong: Episodes, 30, 2007, p. 59.
[25] S.D.G. Campbell, R.J. Sewell, Structural control and tectonic setting of Mesozoic volcanism in Hong Kong, J. Geol. Soc. 154 (1997) 1039–1052.
[26] R.L. Langford, K.W. Lai, R.S. Arthurton, R. Shaw, Geology of the western new territories, Hong Kong geological survey memoir No. 3, geotechnical control office, Hong Kong Government, 1989, p. 140. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_3.
[27] K.W. Lai, S.D.G. Campbell, R. Shaw, Geology of the Northeastern new territories, Hong Kong geological survey memoir No. 5, geotechnical engineering office, Hong Kong, 1996, p. 143. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_5.
[28] D.V. Frost, Geology of Yuen Long, Hong Kong geological survey sheet report No. 1, geotechnical engineering office, Hong Kong Government, 1992, p. 69. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/sheet_g1.
[29] N.S. Jones, J.A. Fyfe, R.J. Sewell, K.W. Lai, C.M. Lee, Devonian fluviodeltaic sedimentation in Hong Kong, J Asian Earth Sci 15 (1997) 533–545.
[30] P.M. Allen, E.A. Stephens, Report on the geological survey of Hong Kong 1967-1969, Hong Kong Government Printer, 1971, p. 107, p, plus 2 maps.
[31] J.D. Bennett, Review of superficial deposits and weathering in Hong Kong, Geotechnical Control Office, Hong Kong, 1984, p. 51 [p (Unpublished)].
[32] R. Addison, Geology of sha Tin, Hong Kong geological survey memoir No. 1, geotechnical control office, Hong Kong, 1986, p. 85. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_1.
[33] P.J. Strange, R. Shaw, Geology of Hong Kong island and Kowloon, Hong Kong geological survey memoir No. 2, geotechnical control office, Hong Kong, 1986, p. 134. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_2.
[34] P.J. Strange, R. Shaw, R. Addison, Geology of sai Kung and clear water bay, Hong Kong geological survey memoir No. 4, geotechnical control office, Hong Kong, 1990, p. 111. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_4.
[35] R.L. Langford, J.W.C. James, R. Shaw, S.D.G. Campbell, P.A. Kirk, R.J. Sewell, Geology of Lantau District. Hong Kong geological survey memoir No. 6, geotechnical engineering office, Hong Kong Government, 1995, p. 173. https://www.cedd.gov.hk/eng/publications/geo/hong-kong-geological-survey/memoir_no_6.
[36] C. Annen, B. Scaillet, Thermal evolution of Leucogranites in extensional faults: implication for miocene denudation rates in the Himalaya, vol. 268, Geological Society, London, 2006, pp. 309–326 (Special publications).
[37] W. Hildreth, M. Lanphere, D. Champion, J. Fierstein, Rhyodacites of Kulshan caldera, North Cascades of Washington, Postcaldera lavas that span the Jaramillo, J. Volcanol. Geoth. Res. 130 (2004) 227–264.
[38] R.S. Carmichael, Handbook of physical properties of rocks, CRC Press, 1982, https://doi.org/10.1201/9780203712115.
[39] P. Vaníček, E.J. Krakiwsky, Geodesy: the concepts, second ed., 1986. North-Holland, Amsterdam (Second Edition).

Albertini Nsiah Ababio is a Ph.D. student in Physical Geodesy at the Department of Land Surveying and Geo-Informatics at the Hong Kong Polytechnic University. He obtained his B.Sc. degree in Geomatic Engineering from Kwame Nkrumah University of Science and Technology, Ghana, in 2017. He received his M.Sc. in Engineering Surveying in 2019 from The University of Nottingham. His research interests are precise geoid determination, gravity field modeling, height systems, and least-squares adjustment.

Robert Tenzer is an associate professor at the Department of Land Surveying and Geo-Informatics at the Hong Kong Polytechnic University. He received an M.Sc. in Geodesy and Cartography (in 1995) and a Ph.D. in Physical Geodesy (in 1999) at the Slovak Technical University, as well as a Ph.D. in Satellite Geodesy (in 2008) at the Czech Technical University. Between 2001 and 2008, he held research positions at the University of New Brunswick, the University of Newcastle upon Tyne, and the Delft University of Technology. Between 2009 and 2012, he taught at the University of Otago. Between 2012 and 2016, he was a visiting professor in the School of Geodesy and Geomatics at Wuhan University. His research interests cover broad areas of Geodesy, Geophysics, Geodynamic, and Planetary Science, with a major focus on geospatial modeling techniques and interpretations, theoretical geodesy and geophysics, geo-referencing, planetary inner structure and processes.