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25

26 **Abstract**

27 The Philippine Archipelago is a complex island arc system, where many
28 regions still lack geopotential studies. This study aims to present a general discussion of
29 the Philippine gravity anomaly distribution. The high-resolution isostatic anomaly digital
30 grid from the World Gravity Map (WGM) was processed and correlated with the
31 Philippines' established geology and tectonics. This study also investigated the gravity
32 signatures that correspond to the regional features, e.g., geology, structures, sedimentary
33 basins, and basement rocks of the study area. Upward continuation, high-pass, and

34 gradient filters (i.e., first vertical derivative, horizontal gradient) were applied using the
35 Geosoft Oasis Montaj software. The interpreted gravity maps' results highlighted the
36 known geologic features (e.g., trench manifestation, ophiolite distribution, basin
37 thickness). They revealed new gravity anomalies with tectonic significance (e.g.,
38 basement characterization). The isostatic gravity anomaly map delineates the negative
39 zones. These zones represent the thick sedimentary accumulations along the trenches
40 surrounding the Philippine Mobile Belt (PMB). The Philippine island arc system is
41 characterized by different gravity anomaly signatures, which signify the density contrast
42 of subsurface geology. The negative anomalies (< 0 mGal) represent the thick
43 sedimentary basins, and the moderate signatures (0 to 80 mGal) correspond to the
44 metamorphic belts. The distinct very high gravity anomalies (> 80 mGal) typify the
45 ophiolitic basement rocks. The gravity data's upward continuation revealed contrasting
46 deep gravity signatures; the central Philippines of continental affinity (20 – 35 mGal) was
47 distinguished from the remaining regions of oceanic affinity (45 – 200 mGal). Local
48 geologic features (e.g., limestone, ophiolitic rocks) and structures (e.g., North Bohol Fault,
49 East Bohol Fault) were also delineated downward continuation and gravity gradient maps

50 of Bohol Island. The WGM dataset's effectiveness for geologic investigation was
51 achieved by comparing the established geologic features and interpreted gravity
52 anomalies. The processed gravity digital grids provided an efficient and innovative way
53 of investigating the Philippines' regional geology and tectonics.

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55 **Keywords**

56 World Gravity Map (WGM), Philippines, geology, basement, basin, subsurface structure

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1 Introduction

Gravity data is fundamental in understanding and modeling Earth's interior, e.g., subsurface, crust, especially in studying its relationship to geology and structures. With the advancement of technology, high-resolution satellite gravity data are being utilized for geologic exploration and tectonic studies. Satellite gravity data were processed and interpreted for bathymetry prediction (Majumdar and Bhattacharyya 2005), lineament investigation (Braitenberg et al. 2011), crust-mantle boundary study (Steffen et al. 2011), sediment basin survey (Vaish and Pal 2015), and geologic mapping (Pal et al. 2016). This emerging area of research was made possible by acquiring a more precise Earth gravitational model. The Earth Gravitational Model 2008 (EGM2008) is an Earth's geopotential model. This model integrates satellite gravimetry, satellite altimetry, and surface gravity measurements (Pavlis et al. 2008). Several studies already assessed and validated the accuracy of EGM2008 (Arabelos and Tscherning 2010; Pavlis et al. 2012). The gravity field data used in generating the high-resolution World Gravity Map 2012 (WGM) is derived from the EGM2008.

In the Philippines, regional gravity exploration began in the twentieth century when Teodoro (1970) compiled Luzon Island gravity surveys. Only a simple Bouguer anomaly map could have been generated in those years due to a lack of detailed topographic maps (Teodoro 1970). In 1982, the Philippines' first regional gravity anomaly map was presented, and different gravity anomalies were discussed relative to various geologic factors (Sonido 1981). Gravity surveys have undergone continuous development during the past twenty years. Ground and marine gravity surveys were employed by several studies focusing on specific regions, e.g., the crustal structure and tectonic evolution along Manila Trench (Hayes and Lewis 1984), the emplacement of

Bohol ophiolite (Barretto et al. 2000); the regional tectonics of northern Luzon (Milsom et al. 2006), the arc-continent collision in the central Philippines (Dimalanta et al. 2009), the crustal thickness of Central Philippines (Manalo et al. 2015), the upper crustal structure beneath Zambales Ophiolite Complex (Salapare et al. 2015), and the terrane boundary in northwest Panay (Gabo et al. 2015).

The historical overview of gravity surveys in the Philippines presents a wide range of gravity survey scales and applicability. Earlier studies generated and presented gravity maps based on limited point data from local to regional surveys (e.g., ground, marine). With the advent of satellite-derived gravity data and global gravity data sets, geologic studies' scope is no longer limited to the previously available point data. The recent isostatic anomalies from WGM were utilized to comprehensively investigate the gravity anomalies around the Philippine Islands' arc system. These may reveal regional features, e.g., geology, structures, sedimentary basins, and basement rocks. This work offers an innovative means of understanding the Philippines' geology and tectonics through the gravity signatures.

2 Tectonic and Geologic Setting

The Philippine Island arc system is a complex and tectonically active region. It was characterized by ophiolite accretion, arc magmatism, ocean basin closure, and other tectonic processes (Mitchell et al. 1986; Rangin 1991; Yumul et al. 2008a; Aurelio et al. 2013). The Philippine Archipelago consists of two general terranes: the Palawan-Mindoro Microcontinental Block and the Philippine Mobile Belt (PMB). The Palawan-Mindoro microcontinental block was once part of mainland Asia while the PMB originated from the sub-equatorial regions (MGB, 2010; Rangin et al., 1990). The PMB is an actively

deforming zone between two oppositely-dipping subduction systems (Fig. 1). The eastern side of the PMB is bounded by the west-dipping East Luzon Trough and the Philippine Trench. The Archipelago's western side is marked by east-dipping subduction zones: Manila Trench, Negros Trench, Sulu Trench, and Cotabato Trench. The left-lateral strike-slip Philippine Fault, which traverses the entire island arc system, accommodates the oblique convergence between the Philippine Sea Plate and Eurasian Plate (Barrier et al. 1991; Aurelio 2000). The amalgamation of different terranes paved the way to forming tectonic collage with diverse lithologic characteristics categorized into ophiolitic rocks, metamorphic rocks, magmatic arcs, and sediment basins (MGB, 2010). Ophiolitic and metamorphic basement rocks overprinted by relatively younger volcanic series and thick sedimentary basins define the Philippines' present geology.

3 Methodology

3.1 Data Acquisition

The Philippines' isostatic anomaly digital grid was acquired from the World Gravity Map (WGM) of the Bureau Gravimetrique International (BGI). The BGI produced global gravity anomaly maps and digital grids considering an Earth model that accounts for the influence of most surface masses, e.g., atmosphere, land, oceans, lakes (Balmino et al. 2012). Different corrections were applied to the gravity data to remove the non-geologic effects; three WGM anomaly maps were produced (i.e., surface free air, Bouguer, isostatic) by BGI taking into account the elevation data from ETOPO1 Global relief (Bonvalot et al. 2012). The gravity anomalies were computed based on the spherical geometry of the isostatic equilibrium (Airy-Heiskanen model) model. The effects of deep isostatic roots and anti-roots were removed (Balmino et al. 2012) in this computation.

Thus, the isostatic anomaly map shows the gravity anomalies that correspond to the geologic features in the upper crust (Simpson et al., 1985; Lowrie and Fichtner, 2019). The isostatic anomaly grid has a gravity dataset with a 1' x 1' spatial resolution (Balmino et al. 2012). The high-resolution isostatic anomaly digital grid of WGM was processed to reveal the Philippines' geologic structures and features from surface to upper crustal depths. Bohol's elevation data was from the 30-m Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM). The geologic contacts and features were adapted from the 1:50,000 scale geologic maps of BMG (1987), and the geologic structures (e.g., fault) were delineated based on the active faults map of PHIVOLCS (2015). The distribution of the general geologic groupings was outlined from the 'Geology of the Philippines' (MGB, 2010). ArcGIS software was used to register and overlay secondary data (e.g., geology, structures) and visualize the features related to gravity anomaly. Geosoft Oasis Montaj software was utilized to process, filter, analyze, and generate gravity anomaly maps.

3.2 Processing and filtering

Upward continuation: The isostatic gravity anomaly was continued upward to investigate the Philippines' density distribution according to the depth. The digital grid was processed by applying an upward continuation filter at 5, 10, and 20 km depths. The upward continuation estimates and emphasizes the gravity anomaly at a minimum depth of half of the input filter (e.g., 10 km filter = 5 km minimum depth) (Jacobsen 1987). Since deep and large bodies produced long-wavelength and broad anomaly, upward continuation was applied to smooth out near-surface effects (e.g., Nabighian et al. 2005). The upward continuation produced sets of regional anomaly maps of the Philippines.

High-pass filter: In an isostatic gravity anomaly map, the broader/longer wavelength represents the signal at a deeper level (e.g., basement), while the finer/shorter wavelength is due to the shallow structures or features (e.g., Griffin 1949). The high-pass filter through Geosoft Oasis Montaj extension was applied to highlight the signal that corresponds to Bohol Island's shallow geologic features. With the high-pass filter operation, the regional effect can be suppressed when investigating gravity anomaly due to shallow crustal sources (Lowrie and Fichtner 2019). The high-pass filter generated the residual anomaly map.

Vertical derivative and horizontal gradient: Two filters (i.e., horizontal gradient, first vertical derivative) were applied to highlight edges of the gravity anomalies. The resulting maps of the two filters were compared and correlated to Bohol Island's established geology and structures. The horizontal gradient detects discontinuities in x and y directions, which are useful in exposing geologic lineaments, e.g., faults, contacts (Cordell and Grauch 1982; Hinze et al. 2013). Compared to other edge detection methods, the horizontal gradient is least affected by noise in a given data; it only requires calculating the two first-order horizontal derivatives of the gravitational field, as explained in Cordell and Grauch (1982). The highest values in the horizontal gradient map represent a gravity anomaly produced by a relatively vertical edge of an underlying feature. The first vertical derivative was applied to validate and help locate more structures represented by density contrast boundaries. The first vertical derivative presents the rate of change of the gravity field in a vertical direction. The resolution of the short-wavelength anomalies is significantly enhanced. The regional (long-wavelength) gravity field signal is attenuated when the first vertical derivative is applied (Nabighian et al. 2005). The shallow near-vertical contacts of the subsurface bodies in

Bohol Island are represented by the zones that correspond to the zero-value.

4 Results and Discussion

4.1 Regional Geology and Tectonics

Regional geologic and tectonic features were easily delineated and correlated in the isostatic gravity anomaly map (Fig. 2). The PMB (red to pink) is generally surrounded by very low negative anomalies (blue), correlating to the deep trenches and troughs bound the Archipelago. Areas underlain by denser materials reflect more positive anomalies, while lower density zones generate more negative signatures (Lowrie and Fichtner 2019). The two major terranes of the Philippine Archipelago, Philippine Mobile Belt (PMB) and Palawan-Mindoro microcontinental block, were outlined on the gravity anomaly maps. Non-linear color zoning was used in generating the isostatic anomaly map of the Philippines to represent the wide range of grid values (-280 to 200 mGal) efficiently.

The broad north-trending negative anomaly characterizes Luzon Island's eastern offshore; it presents the East Luzon Trough (ELT) forearc basin. The very low negative anomaly zones (< -70 mGal) correspond to the thick accumulation of sediments, as confirmed by previous seismic and bathymetric surveys (Fig. 2b). Hayes and Lewis (1984) defined the plate boundary along eastern Luzon as a young active zone that decreases its activity towards the north. They also noted that gravity signatures do not follow ELT's trend, except the low anomalies south of 17 deg latitude. The ELT trace was delineated in the isostatic anomaly map, which propagates to the northeast (Fig. 2a). The discrepancy between the active tectonic zone and the ELT suggested that the ELT exemplifies a portion of past subduction episodes (Hayes and Lewis 1984). The northern,

very low gravity zone (< -70 mGal) was identified as the Sierra Madre Basin (SMB), with a maximum sediment thickness of 4.5 km (Hayes and Lewis 1984). The remnant of the Oligocene subduction zone was also delineated in the isostatic gravity anomaly map. The A- A' section on the map presents the pattern of the negative Sierra Madre Basin (forearc basin), positive Isabel Ridge (subduction complex), and linear East Luzon Trough (trench) (Fig. 2b). The ancient subduction zone of ELT was also recognized due to the absence of Early Miocene subduction-related magmatism in the eastern Luzon Island and Benham's accretion, exemplified by the circular high gravity region on the map (e.g., MGB 2010). To the south of the ELT, very low negative gravity anomaly zones may indicate very thick sediment accumulations, which defines the active tectonism along eastern Luzon (e.g., Hayes and Lewis 1984).

An active transform fault was interpreted as the structure that connects the southern part of the ELT system and the Philippine Trench (e.g., Lewis and Hayes 1983). The Philippine trench is described as a young subduction system with an accretionary prism that disappears towards the Mindanao area (Cardwell et al. 1980; Karig et al. 1986). The isostatic anomaly map showed that gravity signatures along the Philippine Trench were varying; the northern part (P1) has a higher gravity anomaly than the southern portion (P2). The very low negative gravity zone (< -70 mGal) along the southern part of the Philippine Trench system may correspond to very thick sediment accumulation along the forearc basin. The positive low (green) anomaly zones (0 to 20mGal) that sandwiched the negative gravity zone represent the elevated higher-density mantle rocks (seaward) and thinning of sedimentary deposits (landward) (e.g., Lewis and Hayes 1983; Lowrie and Fichtner 2019). The inconsistent gravity anomalies along the Philippine Trench

stretch also indicate a heterogeneous subduction zone morphology, similar to Manila Trench.

The east-dipping Manila trench shows a non-uniform negative gravity anomaly that generally corresponds to sedimentary deposits' thickness overlying basement rocks. Hayes and Lewis (1984) reported that the Manila trench's forearc basins have a maximum sediment thickness of 4.5 km. They also suggested that the thickness variation in the forearc basin is due to sediment accumulation and the accretionary prism's local uplift rate. The distinct negative gravity values (< -40 mGal) on the northern (M1) and southern (M3) portions of the Manila trench represent a balance between the local accumulation of sediments and the uplift rate of accretionary prisms (Fig. 2a). In contrast, the absence of very low negative gravity anomaly values in the central part (M2) corresponds to the lower rate of local sediment accumulation relative to the rate accretionary prism uplift (complex forearc) (Hayes and Lewis 1984). The very low negative gravity anomalies (< -70 mGal) at the northern and southern portions of the Manila trench correspond to the very thick sediment deposits; high sediment supply comes from the collision zones of Taiwan-Eurasia (north) and Mindoro-PMB (south) (Hayes and Lewis 1984). The very high and contiguous gravity anomaly along the offshore western Luzon Island was interpreted as the extension of Zambales Ophiolite (ZOE) (Hayes and Lewis 1984).

The isostatic gravity anomalies, which characterize the Negros, Sulu, and Cotabato Trenches, have a similar prominent gravity low associated with thick low-density sediments (e.g., Lowrie and Fichtner 2019). Based on the previously defined correlation between the processed isostatic gravity anomaly map and detailed ground surveys, these three trenches' complex forearc basin system (i.e., Negros, Sulu, Cotabato) can be understood. The peculiar, very low gravity zones were noted at the intersection of

Negros and Sulu Trenches (NS) and the southern side part of the Cotabato Trench (C) (Fig. 2a). Since there are no detailed studies about these three trenches, we can deduce the gravity anomalies based on the signatures of Manila and East Luzon Trough. The very low gravity zones suggest a very thick accumulation of sediments; these may indicate active local tectonics along the negative zones.

The isostatic anomaly map also revealed the subsurface geology, sedimentary basins, and basement rocks of the Philippines. The map reflects the variations of gravity fields caused by density differences of materials in the upper crust. Based on the gravity anomaly map, different regional lithologic units were also delineated according to the classification of MGB (2010) (Fig.3). The summary of the regional lithologic geologic groupings concerning the gravity anomaly map is presented in Table 1. Generally, negative gravity signatures represent the sediment basins (< 0 mGal), moderate gravity anomalies correspond to the metamorphic rocks (0 to 80 mGal), and very high gravity anomalies typify ophiolitic basement rocks (> 80 mGal).

Three major basins of the Philippines were delineated from the gravity anomaly map, namely, Ilocos-Central Luzon Basin (ICL), Cagayan Valley Basin (CV), and Agusan-Davao Basin (AD) (Fig. 3a). These sedimentary basins have distinct and defined north-trending negative anomalies (< -20 mGal). The isostatic gravity anomaly map only shows negative gravity anomalies on significantly thick sedimentary formations. Correlated with the established geology (MGB 2010), other portions of the basins do not show negative anomalies because of their shallow and/or very dense basement rocks; high gravity anomaly masks the gravity lows representing the sedimentary formations. Circular gravity lows were also delineated across the Bohol Sea (BS), signifying a very

thick sediment accumulation. This feature was previously interpreted as proto-Southeast Bohol Trench that bound the Western Visayan Block (Yumul et al. 2008b).

The distribution of metamorphic rocks generally coincides with moderate gravity anomaly values (0 to 80 mGal) (Fig. 3b). MGB (2010) classified metamorphic rocks into Pre-cretaceous (continental) and cretaceous (island arc) metamorphic zones. Pre-cretaceous metamorphic zones in the east-central Philippines (i.e., northern Palawan-Mindoro, Antique Range) are represented by lower gravity anomaly (0 to 30 mGal). The cretaceous metamorphic rocks, which are sparsely distributed in eastern Luzon (EL), southern Visayas (SV), and Mindanao (M) islands, have higher gravity signature (30 to 60 mGal). The cretaceous zones are characterized by mafic-to-ultramafic rocks (MGB 2010). The exemption to the positive correlation between the moderate gravity signatures and metamorphic rocks are those areas that are dominantly underlain by ophiolitic rocks. The very high gravity anomaly signature of ophiolitic rocks masks the gravity lows that represent the metamorphic regions. The documented metamorphosed ophiolitic rocks along the eastern Luzon (Geary et al. 1988; Billedo 1994) and eastern Mindanao (Pubellier et al. 1991; Quebral 1994) supported this concept.

The regional groupings of ophiolitic rocks, delineated by MGB (2010), exactly coincide with areas having very high gravity anomalies ($> 70\text{mGal}$). The occurrence of ophiolitic rocks, which serve as basement rocks of most islands, is extensive within the Philippines. Lower gravity anomalies are due to metamorphism in some ophiolitic zones (e.g., south-eastern Luzon). Among the identified ophiolitic regions, the gravity anomaly map presents clusters of very high gravity zones. These clustered regions have distinguishable massive outcrops of ultramafic rocks, 1) northern Luzon (Ilocos Ophiolite), 2) western Luzon (Zambales Ophiolite), 3) eastern Luzon (Isabela-Aurora

Ophiolite), 4) southern Palawan (Palawan Ophiolite), 5) Samar-eastern Mindanao (NE Leyte, Samar, SW Leyte, Dinagat, Surigao, Pujada ophiolites), 6) Central Mindanao (Central Mindanao ophiolites), and 7) western Mindanao (Zamboanga Ophiolite). These regions were described in McCabe et al. (1982), Schweller et al. (1984), Rangin et al. (1985), Mitchell et al. (1986), and MGB (2010). The majority of these zones have known ophiolite-related occurrences of chromite and nickel deposits (MGB 2004). The shallowness of the ophiolite exposures and the massive occurrence of ultramafic rocks resulted in highly positive anomalies. The complete ophiolite suites were also reported in some areas (i.e., Zambales, Isabela, southern Palawan, Pujada). The comprehensive and regional gravity signatures provide a better picture of the complex Philippine island arc system in correlation with available ground data. This new gravity information is essential in narrowing down specific areas of interest (e.g., mineral exploration), especially in inaccessible regions.

4.2 Basement Rocks and Basins

In understanding deeper large-scale crustal features, gravity anomalies due to smaller local small structures are less important than the regional anomalies. The deeper and regional signals can be enhanced (Lowrie and Fichtner 2019). The upward continuation was implemented to further investigate the high-density ophiolitic basement rocks and low gravity sediment basins at depth. The 5, 10, and 20 km continuation depths represent a minimum depth of 2.5, 5, and 10 km, respectively (Fig. 4).

The Philippines' upward continuation maps show that the very high gravity anomalies (> 75 mGal), associated with the dense features, are distributed in Luzon, southern Visayas islands, Mindanao, and southern Palawan. The 2.5 km upward

continuation delineates areas underlain by very dense ophiolite rocks or may indicate the occurrence of massive magmatic arcs, e.g., Negros, Daguma Range. Very high (> 90 mGal) gravity anomaly signatures coincide with the well-known massive ophiolitic outcrops (e.g., Tamayo et al. 2004; Yumul 2007). The 2.5 km upward continuation of gravity anomaly can be clustered into four regions: western Luzon, eastern Visayas-Mindanao, western Mindanao, and southern Palawan (Fig. 4a). In Luzon Island, very high gravity anomalies were recognized in south-eastern Luzon - representing the Zambales Ophiolite (e.g., Abrajano and Pasteris 1989; Yumul and Dimalanta 1997), and offshore of northeastern Luzon - signifying the Ilocos Ophiolite (e.g., Arai et al. 1997; Pasco et al. 2019). These gravity anomaly peaks characterize the dense ultramafic rocks separated by the thick Ilocos-Central Luzon basin (Fig. 5a). In southern Palawan, the very high gravity anomaly corresponds to the Palawan Ophiolite (e.g., Rammlmair et al. 1987; Aurelio et al. 2014) perceivable at the eastern offshore of central Palawan. High gravity signatures of Zamboanga Ophiolite (i.e., Polanco, Titay) (Yumul et al. 2004) are apparent in western Mindanao. Finally, the continuous very high gravity anomalies along the Leyte and Samar islands due to Tacloban and Samar ophiolites (e.g., Balmater et al. 2015; Guotana et al. 2017) are very prominent on the 5 km upward continuation map (Fig. 4b). The same anomalies are also remarkable along the easternmost Mindanao due to Dinagat and Surigao ophiolites (Yumul, 2007; MGB, 2010). Similar to the case in northern Luzon, the signatures of the very high anomaly zones in western Mindanao and northcentral Mindanao (Central Mindanao Ophiolite) are separated by the negative anomaly signature of the ~ 4.5 km thick Agusan Davao Basin (Ranneft et al. 1960). The 10 km upward continuation map shows lesser areas with very high gravity anomalies (> 90 mGal), which correspond to thicker and more massive ophiolitic basement rocks; these regions were

353 recognized in western Luzon (i.e., Zambales), easternmost Visayas-Mindanao (i.e., Samar,
354 Dinagat, Surigao), and western Mindanao (i.e., Zamboanga) (Fig. 4b). High gravity
355 signatures of the massive Negros and Daguma magmatic arcs that persist at deeper levels
356 may indicate dense ophiolitic basement rocks. Limited regional studies of southern
357 Mindanao mentioned the occurrence of serpentinitized peridotite as part of the Basement
358 Complex of western Mindanao (e.g., Ranneft et al. 1960). After applying the 20 km
359 upward continuation (Fig. 4c), the exceptionally high anomalies (> 90 mGal) are only
360 recognizable in western Visayas-Mindanao and southwest Mindanao. These anomalies
361 indicate that the source of the signal may be located at a deeper level. The persistence of
362 the very high gravity anomaly values in the southern Mindanao may suggest a very
363 massive and dense ophiolitic basement complex. Due to the lack of detailed geologic
364 mapping in southern Mindanao, this very high gravity region remains an enigma. It is
365 also interesting to note that the central Philippines (CP) has generally lower gravity
366 signatures (20 – 35 mGal) compared to the distinct very high gravity values (45 – 200
367 mGal) in Luzon and Mindanao (Fig. 4c). This is a significant indication of dissimilar
368 major basement rocks (i.e., continental and oceanic origins) of the Philippine Archipelago,
369 revealed by their characteristic gravity signatures.

370 In contrast to the high anomaly zones of dense and massive basement rocks,
371 the sedimentary basins manifest a strong negative anomaly due to the mass deficiency of
372 the underlying thick sedimentary rocks and quaternary alluviums. The gravity anomaly
373 data from Luzon's land were separately presented to understand the range of gravity
374 anomaly values that correspond to the sedimentary basin. Figure 5a shows Luzon Island's
375 gravity signatures after the 5 km upward continuation filtering; negative gravity
376 anomalies characterize the Philippines' two major basins i.e., Ilocos-Central Luzon Basin

(ICL), Cagayan Valley Basin (CV). The two basins are generally divided by the Oligo-Miocene magmatic belts along Central Cordillera (MGB, 2010) (Fig. 5b). The main north-trending negative anomalies (-15 to -37 mGal) are still present until the 20 km upward continued depth (Fig. 5c). The Ilocos-Central Luzon Basin (west) exemplified a larger negative anomaly zone than the Cagayan Valley Basin (east). The maximum thickness of the Oligocene to Pleistocene sedimentary deposits underlying the Ilocos-Central Luzon Basin (14 km) is thicker than the Cagayan Valley Basin (10 km) (Tamesis 1976; Bachman and Lewis 1983). The portions dominated by very low anomalies (< 5 mGal) gave us a regional knowledge of the portions' thickest sediment accumulation. At a depth of 10 km upward continuation, the lowest gravity anomalies were delineated in the central portion of the Cagayan valley basin and the southern part of the Ilocos-Central Luzon Basin. The 20 km upward continuation map shows the negative gravity anomaly diminished in the northern part of the Ilocos-Central Luzon Basin; it implies that the dense basement rock is shallower in the northern Ilocos Region south-central Luzon. These new regional processed data have provided additional knowledge in understanding the Philippines' understudied basins and basement.

4.3 Local Geology and Structures

The gravity anomalies that correspond to shallow features and structures were characterized by suppressing regional gravity signals, using the high-pass filtering (e.g., Lowrie and Fichtner 2019). Bohol Island was chosen as the representative area for correlating the high-pass filtered gravity map and local geology because it has diverse geology and lithology that reflects a density contrast. Maps are shown as illuminated from the northwest to emphasize the significant areas that manifest gravity lows and highs. The

high-pass filtered gravity map of Bohol Island shows values that range from (-4 to 145 mGal) (Fig. 6); it helps delineate geologic formations and lithological units concerning their inherent physical characteristics (e.g., density). The summary of the correlation between the high-pass filtered gravity map and the geologic map of BMG (1987) was presented in Table 3.

The local sedimentary basin (Cebu Strait Sub-basin), which separates the Bohol and Cebu islands in the northwestern portion of the map, exhibits a low gravity anomaly (< 20 mGal). This northeast-trending feature (L0) represents a part of the Visayan Sea Basin, which is generally underlain by thick Miocene to Pleistocene sediment formations, e.g., carbonates, clastics, volcanoclastics (MGB, 2010). Within Bohol Island, patches of very low anomalies (< 25 mGal) can also be recognized in the southern portion, represented by L1, L2, L3, and L4. Very low gravity anomaly zones (< 5 mGal) are distributed in areas underlain by thick, highly porous, and karstic Pliocene Maribojoc Limestone (L1) and rubbly Late Miocene Sierra Bullones Limestone (L3, L4) (Corby et al. 1951; Arco 1962). Gravity highs (> 70 mGal) were noted on the eastern (H1) and western portions of the map (H2, H3, H4). The H1 gravity anomaly represents the thick clastic exposures (e.g., sandstone, conglomerate) of the older and relatively dense Middle Miocene Carmen Formation underlies the area (e.g., Corby et al. 1951). Bohol island's eastern side is remarkably represented by very high gravity anomaly zones (> 75 mGal), signifying the subsurface lithology's sharp density contrasts. According to the geologic map of MGB (2010), H2 and H3 are areas dominated by Boctol Serpentinite outcrops representing parts of the Bohol Ophiolite (Fig. 8). The southern H2, central H3, and northern H4 generally correlate to the northeast-trending exposures of the Duero Massif, Guindulman Massif, and Alicia Massif, respectively (e.g., Faustino 2003). Interestingly,

the very high gravity anomaly in southern H3 marks the lone exposure of the very dense harzburgite of the southeast Bohol Ophiolite Complex (SEBOC), as reflected on the detailed geologic map of Faustino et al. (2003). The moderate gravity anomaly (25 to 55 mGal) on northwestern Bohol Island is associated with the signatures of the Eocene Ubay Volcanics (Arco 1962); some portions are related to the Carmen Formation and thin exposures of Maribojoc Limestone. Positive correlations between the established geologic studies and the high-pass filtered gravity map confirm the WGM dataset's applicability for reconnaissance surveys, e.g., medium-scale geologic mapping. The analysis of gravity data is also very advantageous in exploring mineral deposits with very distinct density characteristics, e.g., chromite in ophiolitic rocks.

The first vertical derivative (1VD) and horizontal gradient (HG) maps were prepared to delineate geologic features, e.g., fault, lithologic contact (Fig. 7). For the horizontal gradient, the map's values are represented by the amplitude of the horizontal component of the gravity anomaly map (Cordell and Grauch 1982). Geologic contacts and faults were interpreted based on the features with the highest value and defined orientation. The qualitative interpretation of the horizontal gradient map is presented in Fig. 7a. High amplitude anomalies have a general NE-SW orientation, parallel to the major structures within Bohol Island, e.g., East Bohol Fault (EBF), the North Bohol Fault (NBF). Other minor peaks were delineated on the map, representing lineaments related to geologic contacts or minor structures (e.g., thrust faults). The EBF is a NE-SW-oriented fault that triggered the 1990 Bohol Earthquake; there was no mapped surface rupture (e.g., Besana-Ostman et al. 2011; PHIVOLCS 2015). The trace of EBF on the horizontal gradient map is represented by the very high NE-SW anomaly (F1) on Bohol Island's south-eastern side (Fig. 7a). The long but minor gravity anomaly (F2) adjacent and

concordant to the EBF may also be a structure-related lineament. On the western side of the map, a strong gradient anomaly (F3) was correlated to the northeast-trending NBF, which generated the 2013 Bohol Earthquake (e.g., Kobayashi 2014; Lagmay and Eco 2014). Linear parallel gravity anomalies (F4, F5), with a similar orientation of the NBF, were traced on the northeast and southwest of NBF; these anomalies may suggest major NBF-related structure. Some minor lineaments were also identified in the horizontal gradient map, particularly in south-eastern Bohol Island (Fig. 8). These minor anomalies correspond to the lineaments and features delineated by the (MGB 1987). High amplitude linear feature (F6), which may represent a geologic contact or a major submarine structure, was also recognized along the offshore of southern Bohol.

The First Vertical Derivative map was also prepared to validate and supplement Bohol Island structures delineated on the horizontal gradient map (Fig. 7b). Vertical derivative maps are more influenced by shallow local structures than deeper features (Nabighian et al. 2005). The first vertical derivative map generally presents how much the gravity potential changes in the vertical direction. Steep and semi-vertical features, where potential does not change, are represented by zero or near-zero values. The majority of traced features (e.g., F7, F8) accurately correlate with high amplitude lineaments on the horizontal gradient map. Gravity anomaly features, which indicate shallow structures, also have a general NE-SW orientation (e.g., F9). These features are parallel with previous studies' geologic contacts (MGB, 2010; PHIVOLCS, 2015). Additional geologic structures, e.g., geologic contacts, lineaments were delineated on the first vertical derivative map (e.g., F10). Table 2 summarizes the delineated geophysical lineaments based on the horizontal gradient and first vertical derivative maps. Other lineaments, which were revealed by the gravity gradient maps, can be considered starting

points for future detailed structural and geologic surveys. Geological features, revealed by the gravity gradient maps, are generally parallel to known structures, e.g., major fault and geologic contact.

The prominent gravity highs and lows (delineated on the high-pass filtered gravity map) and the lineaments (defined on the gradient maps) were overlaid on the established geologic map of Bohol (Fig. 8) (BMG, 1987). The map shows a positive correlation between the high gravity anomaly value and the distinctive density of the subsurface lithology (e.g., high anomaly corresponds to ultramafic rock). It highlights parallel gravity anomaly lineaments and known structures, e.g., fault, geologic contact. These good correlations present us with a new and supplementary way of deducing subsurface geologic structures and features, especially in remote areas without available ground data.

5 Conclusions

The isostatic anomaly World Gravity Map (WGM), derived from the EGM2008, has been utilized efficiently and effectively for understanding the geologic and tectonic features of the Philippine Islands arc system. The processed gravity anomaly dataset provided significant constraints in evaluating the structures from subsurface to upper crustal depth (e.g., basin, basement). The complete and regional gravity data were significant in studying the Philippine Archipelago's composite terranes by correlating with ground geologic data. Negative gravity anomaly zones correspond to the surrounding trenches that bound the PMB and thick sedimentary basins. Areas with moderate gravity anomalies are associated with metamorphic belts. Lastly, the very high gravity anomaly regions define the ophiolitic basement rocks. The processed gravity

anomaly maps serve as a scientific basis in narrowing down the specific area of interest (e.g., geologic investigation) and as a background in understanding the geology, basins, and basement of the understudied regions of the Philippines. The gravity data's upward continuation reveals a relatively low gravity (20 - 35 mGal) in continental central Philippines compared to the gravity highs (45 – 200 mGal) of the island arc PMB. This study also confirms an excellent correlation between the high-pass filtered gravity map and established geologic features and structures. The WGM digital grid could be utilized in reconnaissance surveys and very useful in regional mineral exploration (e.g., chromite). The gravity gradient analysis of the WGM data provides a promising scientific supplement in delineating subsurface structures (e.g., fault, geologic contact). With the availability and proved efficiency of the WGM data, these techniques are applicable and valuable in future structural and geologic explorations in the Philippines.

Abbreviations

WGM: World Gravity Map; PMB: Philippine Mobile Belt; EGM2008: Earth Gravitational Model 2008; BGI: Bureau Gravimetrique International; SRTM: Shuttle Radar Topographic Mission; DEM: Digital Elevation Model; MGB: Mines and Geosciences Bureau; PHIVOLCS: Philippine Institute of Volcanology and Seismology; ELT: East Luzon Trough; SMB: Sierra Madre Basin; ZOE: Zambales Ophiolite Extension; NS: Negros and Sulu Trenches; C: Cotabato Trench; ICL: Ilocos-Central Luzon Basin; CV: Cagayan Valley Basin; AD: Agusan-Davao Basin; BS: Bohol Sea; EL: eastern Luzon; SV: southern Visayas; M: Mindanao; SEBOC: southeast Bohol Ophiolite Complex's; 1VD: first vertical derivative; HG: horizontal gradient; EBF: East Bohol Fault; NBF: North Bohol Fault

Declarations

Availability of data and materials

The gravity digital grids and data used in this study are available online at <https://bgi.obs-mip.fr/data-products/grids-and-models/wgm2012-global-model/>. The DEM from the SRTM can be downloaded at <https://www2.jpl.nasa.gov/srtm/cbanddataproduts.html>.

534 **Competing interests**

535 The authors declare that they have no competing interests.

536

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540 **Authors' contributions**

541 MAAC drafted the manuscript. HM, TT, and CBD revised the paper. All authors read

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781 **Figure Legends**

782 Figure 1. General tectonic map of the Philippine island arc system (modified from Rangin,
783 1991; Yumul et al., 2008). The continental Palawan-Mindoro microcontinental block and
784 island arc Philippine Mobile Belt (PMB) characterize the Philippine Archipelago. The
785 mentioned islands are represented by green labels: LZN = Luzon, MNDR = Mindoro,
786 PLW = Palawan, PNY = Panay, SMR = Samar, NGR = Negros, BHL = Bohol, MNDN =
787 Mindanao.

788 Figure 2. (a) Isostatic gravity anomaly map of the Philippines showing the Philippine
789 Mobile Belt (PNB) bordered by negative anomalies corresponding to the deep trenches.
790 Traces of major structures (e.g., fault, trench) and features (e.g., Palawan-Mindoro
791 microcontinental Block, PNB) were overlaid on the map. SBM= Sierra Madre Basin, IR

792 = Isabela Ridge, ELT = East Luzon Trough, BR = Benham Rise, P1 = northern Philippine
793 Trench, P2 = southern Philippine Trench, M1 = northern Manila Trench, M2 = central
794 Manila Trench, M3 = southern Manila Trench, ZOE = Zambales Ophiolite extension, NS
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796 Interpretation of seismic reflection profile across the SMB, IR, and ELT (modified from
797 Hayes and Lewis 1984). The A-A' on the map marks the location of the seismic reflection
798 profile.

799 Figure 3. Isostatic anomaly map of the Philippines showing the general distribution of (a)
800 sedimentary basins, (b) metamorphic rocks, and (c) ophiolitic rock (modified from MGB
801 2010). White outline represents the shoreline of the Philippine Archipelago. Numbers
802 represent the sedimentary basins of PMB affinity: 1 = Ilocos-Central Luzon (ICL), 2 =
803 Cagayan Valley (CV), 3 = Mindoro, 4 = Southern Luzon-Bicol, 5 = Iloilo, 6 = Visayan
804 Sea, 7 = Samar, 8 = Agusan-Davao (AD), 9 = Cotabato. BS = Bohol Sea, NPM =
805 Northern Palawan-Mindoro block, AR = Antique Range. Circles symbolize the
806 occurrences of nickel (black) and chromite (white) deposits in the Philippines (MGB
807 2004).

808 Figure 4. Upward continued maps of the Philippines at (a) 5, (b) 10, and (c) 20 km. White
809 outline represents the shoreline of the Philippine Archipelago. (a) Massive ophiolitic
810 outcrops coincide with very high gravity anomaly signatures (> 90 mGal). Representative
811 ophiolites and ophiolite complexes are labeled on the map: I = Ilocos, ZBL = Zambales,
812 P = Palawan, ZBN = Zamboanga, T = Tacloban, SM = Samar, D = Dinagat, SR = Samar,
813 CM = Central Mindanao (modified from Tamayo et al. (2004) and Yumul et al. 2007. (b)
814 Three remaining zones (> 90 mGal) suggest thicker and more massive ophiolitic
815 basement rocks. (d) Generally, the central Philippines has lower gravity anomalies ($20 -$
816 35 mGal) than the rest of the Archipelago ($0 - 45$ mGal). CP = Central Philippines, LZN=
817 Luzon, MND = Mindanao.

818 Figure 5. Upward continued maps of Luzon Island at (a) 2.5, (b) 5, and (c) 10 km. (a)
819 Ilocos-Central Luzon Basin (ICL) and Cagayan Valley Basin (CV) are divided by the (b)
820 Oligo-Miocene Magmatic belts along Central Cordillera (CC) (MGB, 2010). (c) Very low
821 gravity anomaly zones (< 5 mGal) indicate portions of the basins with the thickest
822 sediment accumulation (e.g., Tamesis, 1976; Bachman et al., 1983).

823 Figure 6. High-pass filtered gravity map of Bohol Island overlaid by the geologic map

outline (MGB 1987). White dashed circles show gravity lows (L1, L2, L3, L4), signifying very thick low-density lithology (e.g., porous limestone). Black dashed circles represent gravity highs (H1, H2, H3, H4), indicating very dense rocks (e.g., peridotite). CSSB = Cebu Straight sub-basin. See text for discussion.

Figure 7. Overlay maps of both horizontal gradient (upper) and the first vertical derivative (lower). The political boundary of Bohol Province is outlined in black. F represents significant features delineated from the gravity gradient maps. See text for discussion.

Figure 8. Geologic map of Bohol overlaid by delineated gravity anomaly lineaments and prominent gravity highs (black oval) and lows (white oval) (modified from BMG, 1987). Interpreted gravity anomalies generally coincide with the established geologic features (e.g., fault, geologic contact). See text for discussion.

Tables

Table 1. Significant regional geologic features delineated on the isostatic anomaly map of the Philippines.

General Anomaly	Correlation	Location
Low gravity anomaly	Sedimentary Rocks	Ilocos-Central Luzon Basin (ICL), Cagayan Valley Basin (CV), Mindoro Basin (M),

(< 0 mGal)		Southern Luzon - Bicol Basin (SLB), Iloilo Basin (I), Visayan Sea Basin (VS), Samar Basin (S), Agusan-Davao Basin (AD), Cotabato Basin
Moderate gravity anomaly (0 to 80 mGal)	Metamorphic Rocks	Continental: Northern Palawan-Mindoro Block (NPM), Antique Range (AR) Island Arc: Eastern Luzon (EL), Southern Visayas(SV), Mindanao (M)
High gravity anomaly (> 80 mGal)	Ophiolitic Rocks	Western Luzon (Zambales Ophiolite), Northeast Luzon (Ilocos Ophiolite/ Peridotite), Eastern Luzon (Isabela Ophiolite), Southeastern Luzon (Cadig Ophiolitic Complex, Lagonoy Ophiolite, Cagraray Peridotite, Pangarinan Peridotite), Mindoro (Amnay Ophiolite), Antique (Antique Ophiolite), Eastern Visayas-Mindanao (Dinagat Ophiolite), Central Mindanao (Awang Ultramafic Complex, Pantaron Ultramafic Complex), Western Mindanao (Polanco Ophiolite), Southeastern Mindanao (Pujada Ophiolite)

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840

841

842 Table 2. Significant local geologic features and structures delineated on the high-pass
843 filtered gravity map of Bohol. HG and 1VD represent the anomalies traced from
844 horizontal gradient and first vertical derivative maps, respectively.

Anomaly	Description	Correlation/ Interpretation
L0	NE-trending (< 20 mGal)	Cebu Strait Sub-basin (thick Miocene to Pleistocene sedimentary formations)
L1	NE-trending (< 5 mGal)	Maribojoc Limestone (thick, highly porous, and karstic Pliocene limestone)
L2	Circular (< 20 mGal)	Maribojoc Limestone (thick, highly porous, and karstic Pliocene limestone)
L3	Circular (< 5 mGal)	Sierra Bullones Limestone (thick, massive to rubbly Late Miocene limestone)
L4	Circular (< 5 mGal)	Sierra Bullones Limestone (thick, massive to rubbly Late Miocene limestone)
H1	N-trending (65 to 70 mGal)	Carmen Formation (thick exposures of older and denser Middle Miocene clastic rocks)
H2	Circular (65 to 70 mGal)	Boctol Sepentinite/ Bohol Ophiolite Complex (Duero Massif)
H3	NE-trending (>70 mGal)	Boctol Sepentinite/ Bohol Ophiolite Complex (Guindulman Massif)
H4	E-trending (>70 mGal)	Bohol Ophiolite Complex (Alicia Massif)

F1	NE-trending (HG)	East Bohol Fault (EBF)
F2	NE-trending (HG)	EBF-related structure
F3	NE-trending (HG)	North Bohol Fault (NBF)
F4	NE-trending (HG)	NBF-related structure
F5	NE-trending (HG)	NBF-related structure
F6	E-trending (HG)	Significant offshore structure (?)
F7	ENE-trending (1VD)	Geologic contact between Ubay Volcanics and Quaternary Alluvium
F8	N and NW- trending (1VD)	Geologic contact between Sierra Bullones Limestone and Carmen Formation
F9	NE-trending (1VD)	NBF-related structure
F10	E-trending (1VD)	Geologic contact between Maribojoc Limestone and Ubay Volcanics

Figures

Figure 1

General tectonic map of the Philippine island arc system (modified from Rangin, 1991; Yumul et al., 2008). The continental Palawan-Mindoro microcontinental block and island arc Philippine Mobile Belt (PMB) characterize the Philippine Archipelago. The mentioned islands are represented by green labels:

a

120° 125°

20°

M1 M2 M3

SMB IR ELT

A A' BR

P1 P2

NS

C

0 200 Kilometers

N

mGal

100.0 80.0 70.0 60.0 50.0 40.0 30.0 20.0 10.0 0.0 -10.0 -20.0 -40.0 -70.0

b

20 km

V.E. = 3:1

SIERRA MADRE BASIN (SMB)

ISABELA RIDGE (IR)

EAST LUZON TROUGH (ELT)

Thrust Faults

Subduction Complex

Underthrusting Basement

Subduction Complex (Inactive)

Normal Faults (Inactive)

Oceanic Basement

Reflection time (sec)

A A'

(a) Isostatic gravity anomaly map of the Philippines showing the Philippine Mobile Belt (PNB) bordered by negative anomalies corresponding to the deep trenches. Traces of major structures (e.g., fault, trench) and features (e.g., Palawan-Mindoro microcontinental Block, PNB) were overlaid on the map. SBM= Sierra Madre Basin, IR = Isabela Ridge, ELT = East Luzon Trough, BR = Benham Rise, P1 = northern Philippine Trench, P2 = southern Philippine Trench, M1 = northern Manila Trench, M2 = central Manila Trench, M3 = southern Manila Trench, ZOE = Zambales Ophiolite extension, NS = Negros and Sulu Trenches intersection, C = southern Cotabato Trench. (b) Interpretation of seismic reflection profile across the SMB, IR, and ELT (modified from Hayes and Lewis 1984). The A-A' on the map marks the location of the seismic reflection profile.

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Figure 4

Upward continued maps of the Philippines at (a) 5, (b) 10, and (c) 20 km. White outline represents the shoreline of the Philippine Archipelago. (a) Massive ophiolitic outcrops coincide with very high gravity anomaly signatures (> 90 mGal). Representative ophiolites and ophiolite complexes are labeled on the map: I = Ilocos, ZBL = Zambales, P = Palawan, ZBN = Zamboanga, T = Tacloban, SM = Samar, D = Dinagat, SR = Samar, M = Central Mindanao (modified from Tamayo et al. (2004) and Yumul et al. 2007. (b) Three remaining zones (> 90 mGal) suggest thicker and more massive ophiolitic basement rocks. (d) Generally, the central Philippines has lower gravity anomalies (20 – 35 mGal) than the rest of the Archipelago (0 - 45 mGal). CP = Cental Philippines, LZN= Luzon, MND = Mindanao.

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Figure 6

High-pass filtered gravity map of Bohol Island overlaid by the geologic map outline (MGB 1987). White dashed circles show gravity lows (L1, L2, L3, L4), signifying very thick low-density lithology (e.g., porous limestone). Black dashed circles represent gravity highs (H1, H2, H3, H4), indicating very dense rocks (e.g., peridotite). CSSB = Cebu Strait sub-basin. See text for discussion.

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Overlay maps of both horizontal gradient (upper) and the first vertical derivative (lower). The political boundary of Bohol Province is outlined in black. F represents significant features delineated from the gravity gradient maps. See text for discussion.

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Geologic map of Bohol overlaid by delineated gravity anomaly lineaments and prominent gravity highs (black oval) and lows (white oval) (modified from BMG, 1987). Interpreted gravity anomalies generally coincide with the established geologic features (e.g., fault, geologic contact). See text for discussion. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any

country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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