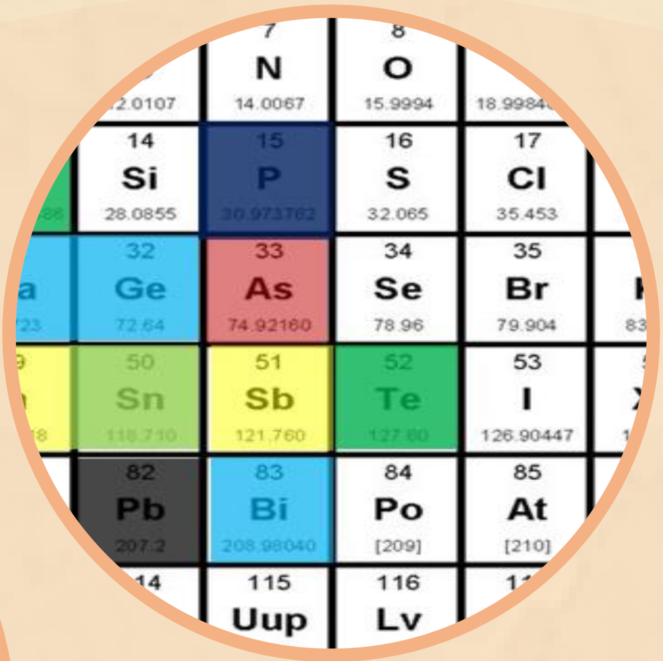
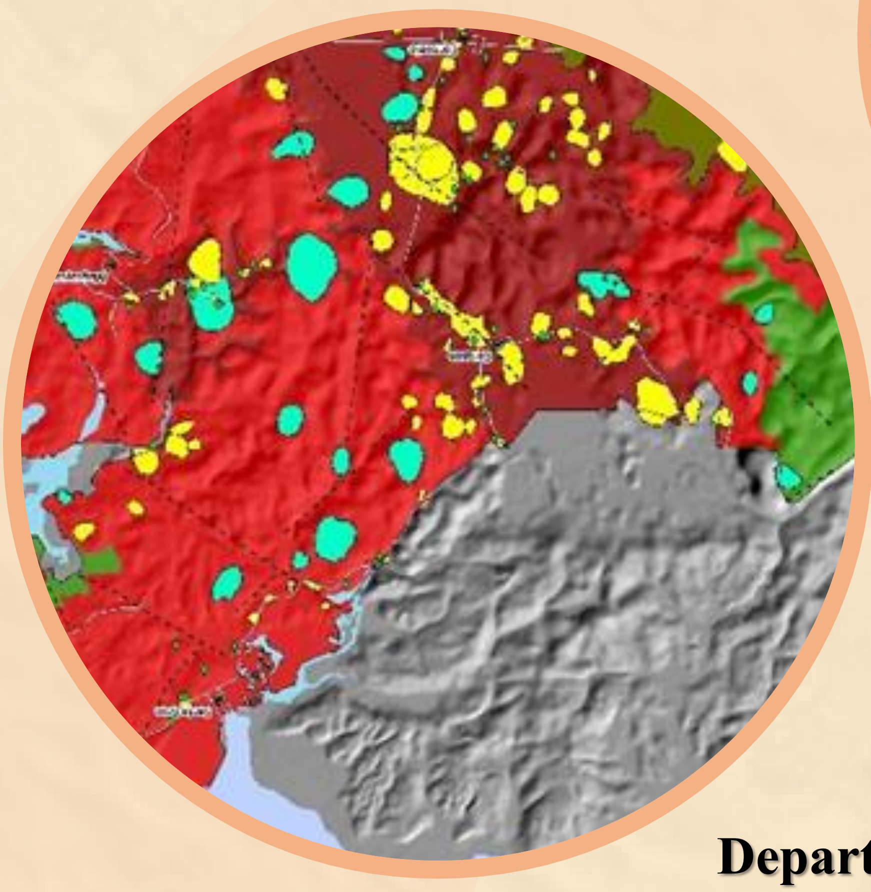
ISSN 2730-2695

THAI GEOSCIENCE JOURNAL

Vol. 4 No. 5 January 2023





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On the cover

1) Enhanced Karst Subsidence Susceptibility Map of General Luna, Province of Surigao del Norte based on the Weights of Evidence Analysis. *(Hugo, Marie Krystel D.*et al., *p.9, fig. 4)*

2) Metals or materials classified as critical in the United State of America; US, European Union; EU, Australia; AU, Canada; CU and Myanmar; MY. (Modify after KIGAM Critical Minerals Issue report, 2021-02). (*Thet tin nyunt* et al., *p.14, fig. 2)*

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Vol. 4 No. 5
January 2023

Published By
Department of Mineral Resources • Geological Society of Thailand
Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP)

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Vol. 4 No. 5
January 2023
ISSN 2730-2695

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Any opinions expressed in the articles published in this journal are considered the author's academic Autonomy and responsibility about which the editorial committee has no comments, and upon which the editorial committee take no responsibility.
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ISSN-2730-2695; DOI-10.14456/tgj.2023.1

Subsidence Susceptibility Mapping in Tropical Island Karst: A comparison of approaches used in the Municipality of General Luna in Siargao Island, Philippines

Hugo, Marie Krystel D.[1,2], Agot, Ross Dominic D. [1,2], Manzano, Liza Socorro J. [1*], Esmeralda, Aquila Kristian B.[1], Abracia, Aaron Miguel C.[1], Madrigal, Madonna Feliz B. [1,2], Ondona, April C. [1], Dela Torre, Angelo Ma. Gabriel P.[1], Isip, Marcius Elaeo G.[1], Rivera, John Michael D.[1], Umali, Julius Vincent P. [1], Belesario, Nelgie Ann C.[1]

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Received 26 December 2022; Accepted 8 June 2023.

Abstract

Karst subsidence hazard susceptibility mapping is an integral part of the National Geohazards Assessment and Mapping Program (NGAMP) initiated by the Mines and Geosciences Bureau (MGB) in 2013. It aims to comprehensively assess geohazards in karst regions in the Philippines. The mapping process involves three primary procedures: remote sensing interpretation of IfSAR-derived Sink Depth Maps using ArcGIS, geological and geomorphological assessment, and geophysical survey using Ground Penetrating Radar (GPR). This method considers sinkhole distribution, other karst features, ground movement evidence, and GPR survey results to identify subsidence-prone areas. The approach generates Karst Subsidence Susceptibility Maps indicating highly vulnerable regions, considering the unpredictable nature of sinkhole collapse.

To enhance the methodology and susceptibility classifications, the PhilKARST Program of MGB introduced the statistical Weights of Evidence (WoE) analysis and employed in General Luna, a prominent tourist destination in Siargao Island, Philippines. This approach ensures consistency and reproducibility by examining the correlation between hazard inventories and fifteen (15) conditional factors.

The resultant weights are determined to generate a subsidence susceptibility index map with Low, Moderate, High, and Very High ratings. Evaluation of true- and false-positive rates using available training data indicated an initial success rate of 82.2% for subsidence susceptibility modeling, signifying reliable results. The enhanced susceptibility map for General Luna in Surigao del Norte, displays lower susceptibility classifications in areas with fewer or no sinkhole occurrences. This differs from the output map of the previous method, which exclusively highlighted highly susceptible areas based on sinkhole distribution, other karstic features, and GPR surveys.

Keywords: Geohazards, Karst, Subsidence, Susceptibility Mapping, Sustainable Tourism

1. Introduction

Karst topography covers a significant land area in the Philippines. Previous studies such as that of Piccini and Rossi (1994) mention that about 10% of around 30,000 km^2 of the Philippine land surface is characterized by karst topography composed of outcrops that are generally smaller than 100 km^2. Most related published papers characterize and describe karst in the Philippines from speleological expeditions in Luzon, Samar, and Palawan in the 1970s and 1980s (Piccini and Rossi, 1994). In October 2013, the M_w7.2 Bohol earthquake struck and exposed numerous sinkholes in southwestern Bohol causing damages to communities, infrastructures, and the natural environment (Mines and Geosciences Bureau [MGB], 2015)

Responding to the need for a comprehensive geohazard assessment of areas characterized by karst topography as unraveled by the Bohol Earthquake, the MGB expands its National Geohazard Mapping and Assessment Program (NGAMP) to include Karst Subsidence hazards due to sinkhole collapse. It aims to identify areas that are susceptible to the said hazard, to make this information available to Local Government Units (LGUs) through the generation of karst subsidence hazard maps and technical reports, and to promote public awareness for proper prevention and mitigation measures against karst subsidence due to sinkhole collapse. As of 2022, the project targets 1,183 cities and municipalities identified to be underlain by carbonate rocks, formations with calcareous sedimentary members, and recent deposits based on compiled data in the Geology of the Philippines (MGB, 2010). One of the accomplished sites is the Municipality of General Luna, Surigao del Norte, which was assessed in 2019 following the established methodology discussed in the project guidebook. This includes gathering of anecdotal accounts, interpretation of satellite data from the Interferometric Synthetic Aperture Radar (IfSAR) and Light Detection and Ranging (LiDAR) Digital Elevation Models, geologic and geomorphic studies, establishment of a sinkhole inventory, Ground Penetrating Radar (GPR) surveys, and the conduct of an IEC Campaign to local authorities.

Despite this, there is still a lack of understanding on their occurrence and the factors that contribute to sinkhole evolution that may lead to a largely overestimated hazard susceptibility zonation, which may hamper development or result in erroneous disaster risk reduction planning. Hence, to enhance its karst subsidence hazard assessment campaign, the Climate--responsive Karst Management for Sustainable Tourism (PhilKARST Program) is implemented from 2021 until 2023. This involves not only the updating of available subsidence hazard inventories, structural and geomorphological mapping but also statistical analyses and model validation. The outputs and methodologies formulated for hazard assessment seek to pave the way for objective decision-making, especially for sustainable tourism. This program has three (3) pilot study areas that are considered as developed and developing karst tourism sites in the country but highlighted in this paper is the Municipality of General Luna in Siargao Island, Surigao del Norte. This municipality is situated at the southeastern tip of the island facing the Pacific Ocean at its east.

Geology and Geomorphology of General Luna, Siargao Island

According to Fernandez, H. (1966), Siargao Island is underlain by the Cretaceous to Paleogene (?) Sapao Formation – the primary igneous rock sequence composed of spilitic basalt and diabase at the northern portion of the island – and the Miocene to Pleistocene Siargao Formation that comprises limestone and clastics underlying most of General Luna. The younger Pleistocene member was said to overlie the Miocene units without hiatus (MGB, 2019). The samples analyzed by PhilKARST, through petrographic and paleontological techniques, generally contain small and large benthic foraminifera, red algae, echinoid spine, coral fragments, gastropod, ostracod, and mollusk fragments deposited along the foreslope and shallow neritic environments. The occurrence of *Miogypsina sp.* suggests an Early to Middle Miocene age. Lastly, some portions of the municipality are capped by thick non-calcareous clastics.

Siargao Island is seismically active as it lies between two major structures namely the Mindanao segment of the Philippine Fault to its west and the Philippine Trench to its east (MMAJ-JICA, 1990). Moreover, major northwest-trending faults influenced the lithologic distribution along these islands and are complemented by northeast-trending lineaments. These are also observed in all lithologic units within the municipality. Movement observed along identified faults within the study area is evidenced by slickensides and displacement along reef flats (MGB, 2019).

General Luna is defined by old platform limestone ridges and cockpit topography at its west, undulating clastic hills, younger hillocks, valley flats towards its central portion, wide beaches, and reef flats along with distributed mangrove forests along its coastal zones to the east (MGB, 2019). This constitutes different levels or episodes of karstification that are also defined by the active seismicity in the area. Cave networks and sinkhole formation are also evident throughout the karst landscapes in the municipality.

2. Materials and Methods

NGAMP: Karst Subsidence Hazards Assessment and Mapping

Three (3) primary procedures were employed to generate a Karst Subsidence Susceptibility Map: (a) remote sensing interpretation of IfSAR-derived Sink Depth Map (Fig. 1) processed using ArcGIS tools, (b) geological and geomorphological assessment, and (c) geophysical survey using the Ground Penetrating Radar (GPR).

a. Remote Sensing Interpretation

Prior to the field assessment, MGB uses the IfSAR derived Digital Elevation Model (DEM) to determine the location of possible sinkholes and terrain attributes (MGB, 2015). Using the ArcGIS hydrologic toolset, raw elevation data was pre-processed or reconditioned to extract karst depression features through a step-by-step procedure. It starts with the generation of flow directions in the area. Then, the Watershed tool is utilized to determine sink areas or “catchments” from the steepest downslope neighbor of each cell. To achieve the raster of minimum and maximum elevations of the watershed for each sink, Zonal Statistics, and Zonal Fill tools are applied. Ultimately, using Minus, the minimum values will be subtracted to maximum values and generate a “fill-difference” raster that represents the varying depth of depressions in the original surface. The generated sinks are superimposed on the topographic map and classified into corresponding depth ranges suitable to the terrain of the study area (Garas et.al, 2020). These generated “sinks” were the basis during the field survey in all barangays.

b. Geological and Geomorphological Assessment

A field survey was conducted in all accessible villages (hereinafter referred to as barangays) and islands within the Municipality of General Luna. The extent and distribution of the different lithological units based on existing 1:50,000-scale Geologic Maps of Siargao were validated. The different karst and non-karst landforms were also delineated based on ground observations and DEM interpretation.

Following this, an inventory of karst features (i.e., sinkholes, cave openings, springs) was also established by ground validation. A matrix of karst features, including assessed and IfSAR-derived sinkholes and other observed features, was prepared with the following information: a) location, b) type of sinkhole, c) morphometry, d) observations on the geology and geomorphology of the vicinity.

c. Geophysical Survey using the Ground Penetrating Radar (GPR)

A Ground Penetrating Radar (GPR) survey was conducted in pre-selected sites based on the selection criteria established by MGB (MGB Karst Guidebook, 2015). Data is collected using the Geophysical Survey Systems, Inc. (GSSI) SIR 3000 paired with the Multiple Low Frequency (MLF) 80 MHz antenna reaching depths up to 25 meters. These are then processed using the RADAN 7 Software and finalized with Transfer Spectrum tool.

The generated radargrams show distinct subsurface layers, in differing sizes and depths, as indicated by the anomalies. These anomalies are represented by various colors assigned during radargram processing. Voids or cavities appear in red, saturated layers are green and yellow as solid material or carbonate rock units. The colors can also be representative of possible cave systems, subterranean drainage pathways, buried sinkholes, and geologic structures that transcend underneath the area of interest.

d. Generation of MGB’s Karst Subsidence Susceptibility Map

The results of the remote sensing interpretation and the geological and geomorphological datasets were combined to generate the susceptibility map. This method applied an expert’s opinion approach, such that the delineation of areas susceptible were based on the following:1) the distribution of karst features,

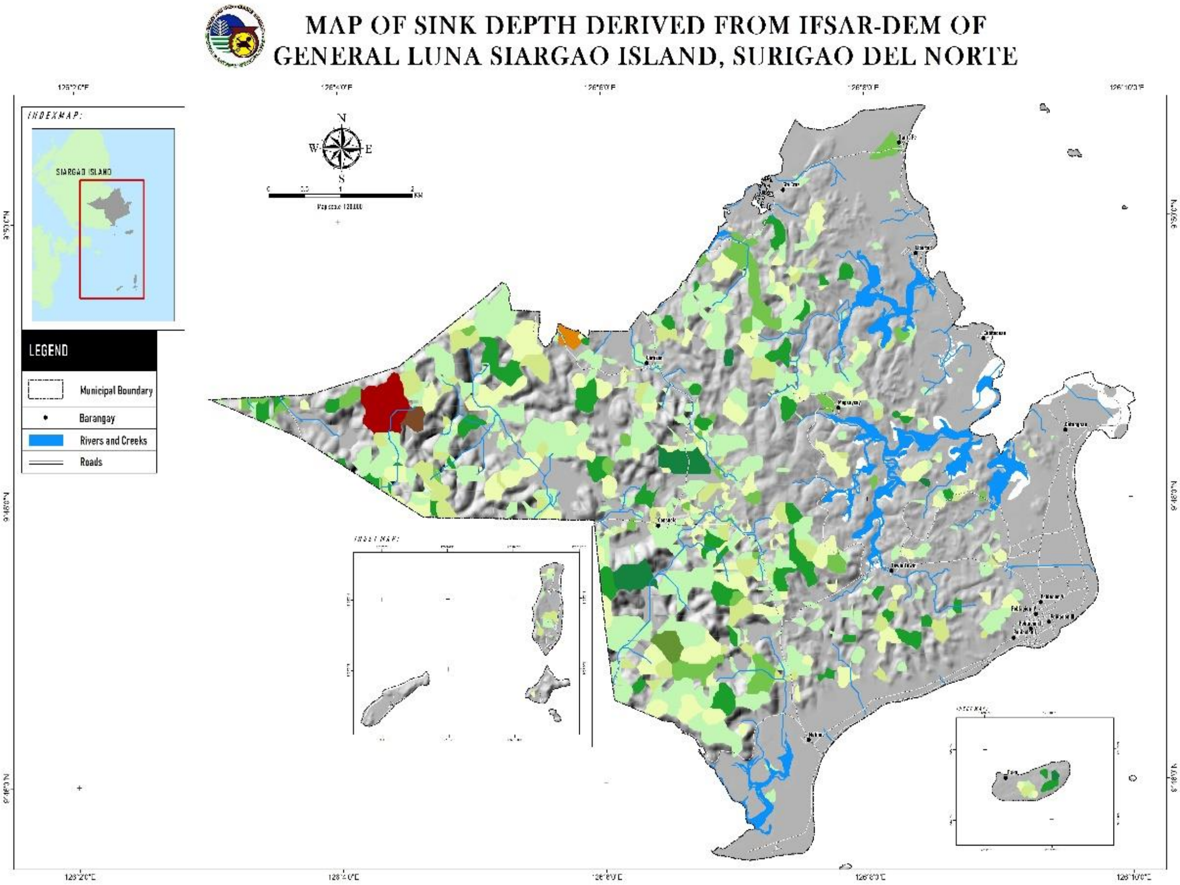

Fig. 1: Sink Depth Map of the study area generated from IfSAR-DEM.

2) subsurface configuration, 3) lithologic and geomorphic characteristics,4) surface mass movement (e.g., rock fall, slump), 5) shallow wells, and 6) other geologic structures (e.g., joints, faults, lineaments). Other parameters considered were the presence of differential settlements, heaving, progress-sing tension cracks, subsiding road surfaces, and staircase and horizontal cracks in concrete structures.

Enhancement of the Subsidence Susceptibility Mapping using an integrated statistical approach

a. Preparation of sinkhole inventory

The sinkhole inventory of General Luna, Surigao Del Norte was compiled from existing records obtained in previous field investigations. The sinkhole dataset was split into training and testing subsets with a 70-30 ratio, respectively. The training subset was used to create the susceptibility model, while the testing subset was used for validation. These subsets were then converted into raster format. The raster pixels were assigned the values of 1 for the presence and 0 for the absence of sinkholes.

b. Generation of sinkhole-conditioning factor maps

Several factors identified from related literature were tested for their influence on sinkhole formation (Table 1). Most factor layers were derived from existing datasets from the government and other organizations, although some were obtained from publicly available sources. The factor layers in shapefile format were converted to .tiff format to allow for analysis of pixel distribution. Each factor was divided into classes based on their attributes and reclassified, with an assigned integer value for the pixels of each class (Table 2).

Table 1. Factors identified from related literature with the corresponding sources and processing data.

Factor	Source	Remarks
Geomorphological Factors (Elevation, Slope, Aspect, Curvature)	Derived from IfSAR-DEM (NAMRIA, 2013)	5-meter resolution
Sinkhole Density and Proximity	Existing MGB Central and Regional Offices inventories; other agencies	Processed using ArcMap tools
Lineament Density and Proximity		
Cave Density		
Springs and Wells Density		
Proximity to Drainage	IfSAR-DEM generated using ArcMap tools	
Geology/Lithology	PhilKARST Program Project 1	
Geomorphology		
Land Cover	ESA WorldCover	10-meter resolution
NDVI	Sentinel-2	

Table 2. Assigned integer value for the pixels of each factor class

		Factor class	
		Present	Absent
Hazard	Present	Npix1	Npix2
	Absent	Npix3	Npix4

c. Determination of factor significance

The factor map and inventory raster data prepared were then imported into the Integrated Land and Water Information System (ILWIS) program for statistical analysis. The hazard inventory was overlapped with the factor maps to determine the distribution of the hazard pixels for each class. The weights for each class are then calculated using the formula for Weight of Evidence as shown below:

$$W^{+} = ln\frac{\frac{Npix_1}{Npix_1 + Npix_2}}{\frac{Npix_3}{Npix_3 + Npix_4}} \qquad W^{-} = ln\frac{\frac{Npix_2}{Npix_1 + Npix_2}}{\frac{Npix_4}{Npix_3 + Npix_4}}$$

Where:

W^{+} = effect of the factor's presence
W^{-} = effect of the factor's absence
N_{pix} = number of pixels where both hazards and factor occur

$$W_{map} = W^{+} + W_{minSum} - W^{-}$$

The resultant weights were tabulated, and classes with positive values were considered favorable to hazard occurrence, while those with negative values were considered unfavorable. Favorable pixels that overlapped with hazard pixels were considered true positives, while those that overlapped non-hazard pixels were considered false positives. Likewise, unfavorable pixels that overlapped with non-hazard pixels were considered true negatives, while those that overlapped hazard pixels were considered false negatives. These values were used to compute True- and False-positive rates (TFR and TPR) using Microsoft Excel with the formulas below. These were then graphed to measure the Area-Under-the-Curve (AUC). Factors with AUC values above 0.6 were considered significant and included in the final calculation of susceptibility index values.

$$TPR = \frac{TP}{TP + FN}$$

$$FPR = \frac{FP}{FP + TN}$$

d. Generation of the enhanced karst subsidence susceptibility map

The weighted raster maps of the six (6) significant factors were superimposed on one another using ILWIS. Weight values were then added for each pixel to produce a raw susceptibility index map. These were subsequently normalized within 0 to 100 values. Using these, a test run was done to determine threshold values for susceptibility zonation based on the frequency of intersecting hazard pixels.

The very high and high susceptibility classes were then assigned 50% and 30% of the hazard pixels, respectively. Moderate Susceptibility was set to 15% of the hazard pixels, while low contained 5% hazard pixels. True- and False--positive rates were calculated using the training and testing subsets to obtain the AUC for the success and prediction rates. The output map was further cleansed and smoothened to provide a more logical and visual image for stakeholders.

3. Results and Discussion

Sinkhole and Karst Features Inventory

A total of 381 sinkholes based on ground validation, IfSAR interpretation, and the topographic map delineation by the National Mapping and Resource Information Authority (NAMRIA) was plotted in the MGB Karst Subsidence Susceptibility Map. The ground validated sinkholes included in the inventory are 302 karst sinkholes of various types and 20 pseudokarst sinkholes considering that there are areas with tuffaceous clastics underlain by limestone. The aperture sizes range from 1 meter to 300 meters while depths range from 0.1 to 3 meters (MGB, 2019). There were 161 caves and cave openings identified in different barangays. On the other hand, a total of 248 ground-validated karst sinkhole polygons comprised the hazard layer used in the enhanced subsidence susceptibility model. Fewer sinkholes were included in the said model due to the presence of sinkholes plotted as points which have limitations in the resolution.

The previous MGB susceptibility map considered geology, geomorphology, distribution of sinkholes and other karst features, and proximity to lineaments in the identification of areas susceptible to subsidence. These, however, were assigned generally equal weights based on ground observations. Meanwhile, for the model presented, six (6) factors were identified to have influence significantly in the distribution of karst features based on the threshold for computed AUC values - that is above 60% (Table 3).

Factor Maps

Table 3. Calculated AUC values for the significant subsidence factors

Factor	AUC
Sink density	86.69%
Cave density	80.98%
Lineament density	74.52%
Geomorphology	71.13%
Landcover	63.26%
Geology	60.39%

Sink density, cave density, lineament density, land cover, geomorphology, and lithology are essential factors in the formation of sinkholes (Fig. 2). Sink density refers to the concentration of sinkholes within a specific region, providing insights into their spatial distribution and prevalence. Similarly, cave density denotes the abundance and clustering of underground cavities, which can contribute to sinkhole development. Lineament density examines the frequency and arrangement of linear features, such as faults and fractures, that may influence the occurrence of sinkholes. Land cover plays a crucial role by influencing hydrological processes and erosion, thereby impacting sinkhole formation. Geomorphology investigates the landforms and processes responsible for shaping the Earth's surface, including sinkhole genesis. Lastly, lithology examines the composition, structure, and physical properties of rocks, which can dictate the susceptibility of an area to sinkhole formation. Understanding the complex interplay between these factors is crucial for understanding the multifaceted nature of sinkhole development.

For the influence of each factor, sinkhole and cave density had the largest AUC values. Further, the clustering of sinkholes and caves, in an area positively affected the computation. For lineaments, only the classes with lineament density greater than 0.89 sinks per square km had positive weights. In terms of geomorphology subsidence was more likely to occur along clastic hills, cockpit karst, and reef terrace. Tree cover and bare/sparsely vegetated areas were more like to experience subsidence. Then for geology, the limestone members of the Siargao Formation were identified to influence the susceptibility of an area.

The MGB Karst Subsidence Susceptibility Map (Fig. 3) delineated the whole municipality as highly susceptible to subsidence due to sinkhole collapse because of the presence of sinkholes (i.e., karst and pseudokarst), cave openings, as well as springs and wells, in all barangays. Delineation was also based on the underlying limestone and clastic formation, as well as the lineaments and observed localized faults, in the whole municipality. Anecdotal accounts and data on active seismicity and rainfall in the area were also considered.

The enhanced karst subsidence susceptibility map (Fig. 4) generated from the WoE method provided three (3) hazard susceptibility zonation within the municipality namely, moderate, high, and very high. These were identified based on the threshold values that corresponded to the percentage hazard pixels set for each classification (Table 4).

Multiple test runs were conducted using different training and testing subsets to obtain success and prediction rates based on the model, respectively. An initial test run using the available training data showed an initial success rate of 82.2% and another test revealed a success rate of 80.1%. Further tests produced success rates averaging to more than 80% and a prediction rate of 75.4% indicating a relatively good reliability based on available thematic and hazard datasets. The true positive (TPR) and false negative (FPR) rates were calculated following the equations below

Table 4. Sample values and the corresponding susceptibility zonation (Trial: SIAS-19).

Susceptibility	Values	0	1	True Positive Rate	False Positive Rate	Success Rate
Low	73	1006972	2081	0.921966674	0.319464533	80.13%
Moderate	80	567342	3904			
High	87	428216	27231			
Very High	100	310816	43482			

4. Conclusion

The MGB Geological Risk Reduction and Resiliency Program, along with the PhilKARST program, recognizes the importance of reliable and generally accurate hazard maps for government programs and plans, especially in land use and disaster risk management as well as sustainable tourism in karst areas. Thus, two (2) karst subsidence hazard susceptibility maps were generated in the process. The MGB-established methodology gave equal importance to the lithological distribution, subsurface and structural controls, as well as the climatological conditions in a more qualitative manner. On the other hand, the enhanced mapping methodology applied a more efficient statistics-based and data-driven process to consider the spatial distribution of karst features and karst-forming conditions to semi-automatically delineate and assign degrees of the susceptibility of areas that are vulnerable to subsidence through the inclusion of more factors. The latter produced success rates averaging to more than 80% and a prediction rate of 75.4% that entails relatively good method reliability. This approach also assures consistency and reproducibility. Hence, in contrast to that of previous methodology, the enhanced map generated through the WoE will be able to aid in the systematic identification and zoning of priority areas for development and recreation, settlement, protection, and hazard management.

Lastly, the results of the WoE method and the enhanced karst subsidence susceptibility map will be validated through follow-up fieldworks. This approach and its applicability to the mapping of the remaining targets under the NGAMP shall be explored. Expanding the size of the hazard inventory, as well as improving the resolution of the thematic factor maps, shall also be delved into.

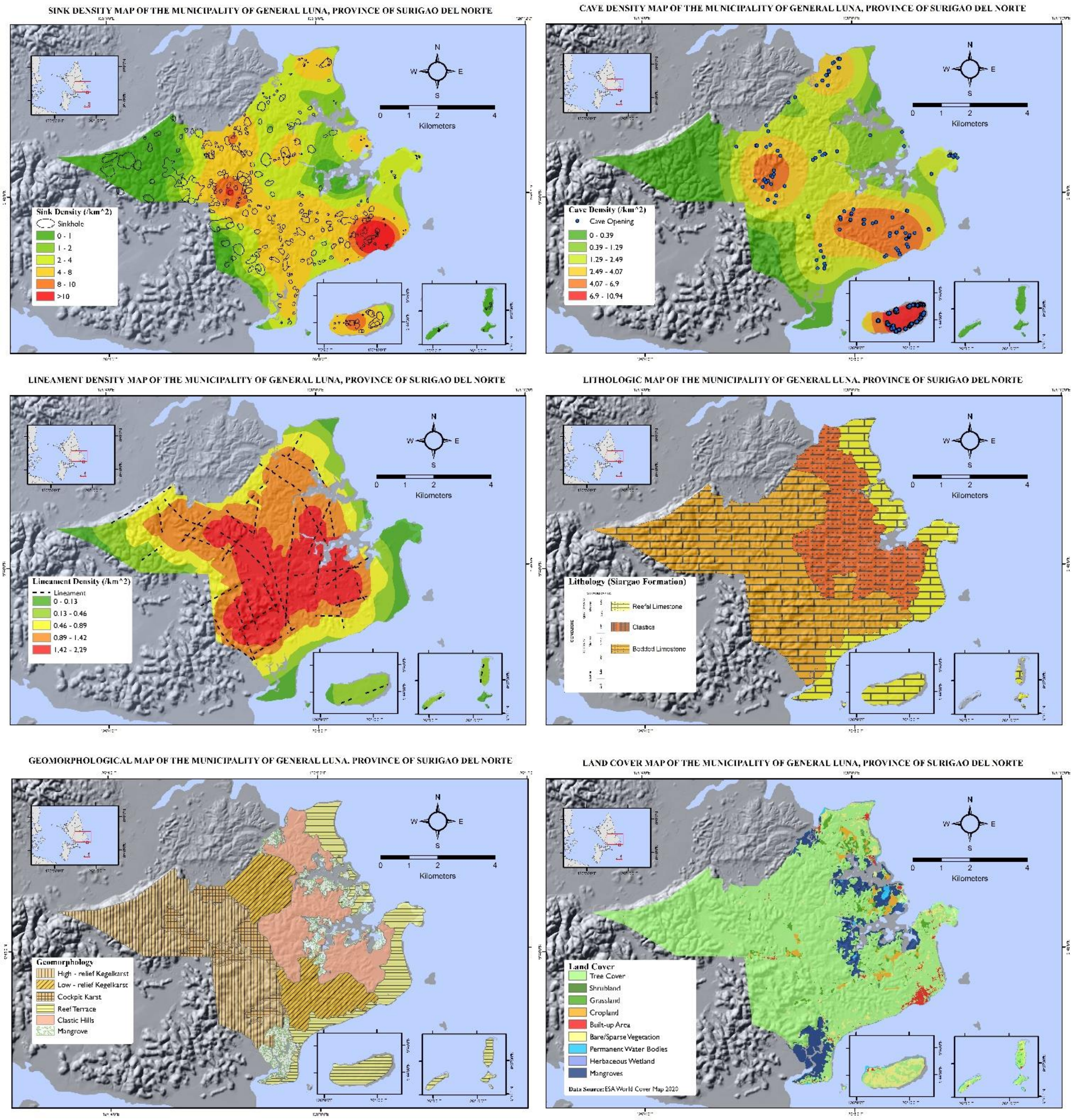

Fig. 2: Thematic maps of the factors used in the model. (Top left) Sink Density; (top right) cave density; (middle right) lineament density; (middle left) lithologic map; (bottom left) geomorphologic map; (bottom right) land cover

Karst Subsidence Susceptibility Maps

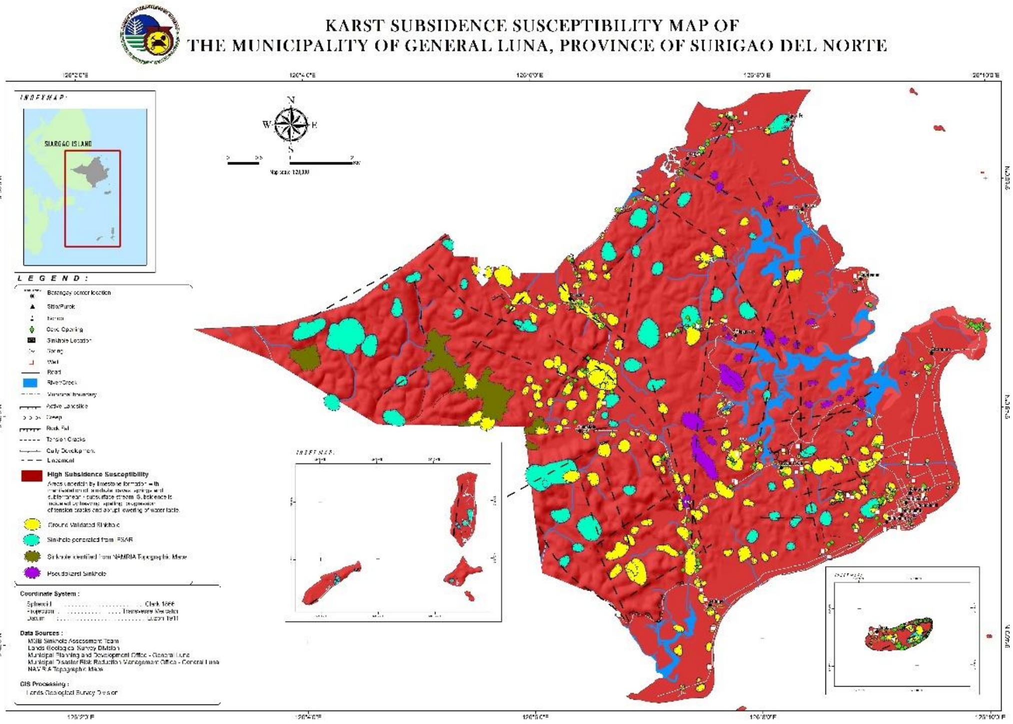

Fig. 3: Karst Subsidence Susceptibility Map of General Luna, Province of Surigao del Norte based on the MGB Karst Subsidence Hazards Assessment and Mapping Methodology. (Left) Enlarged Legend section.

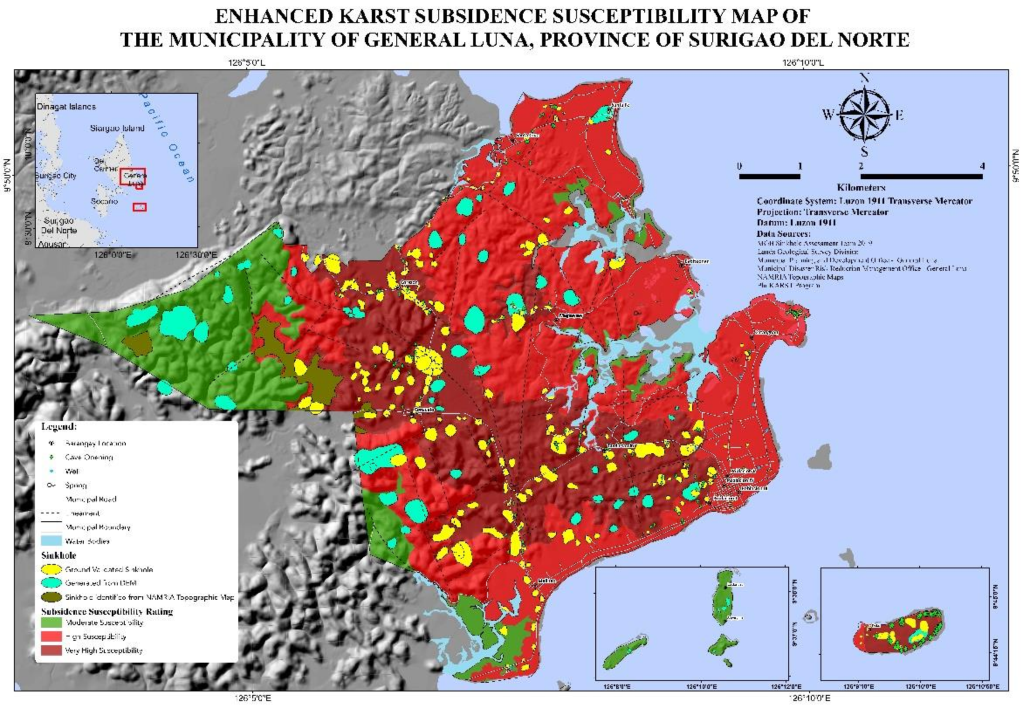

Fig. 4: Enhanced Karst Subsidence Susceptibility Map of General Luna, Province of Surigao del Norte based on the Weights of Evidence Analysis

Acknowledgment

The authors would like to thank the Department of Science and Technology - Philippine Council for Industry, Energy, and Emerging Technology Research and Development (DOST-PCIEERD) for providing the funding for this study. Lastly, the assistance of the local government unit of General Luna, whom the authors are grateful for their time and effort during the field assessment.

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Thai Geoscience Journal 4(5), 2023, p. 11–32
Copyright © 2023 by the Department of Mineral Resources of Thailand
ISSN-2730-2695; DOI-10.14456/tgj.2023.2

Some critical mineral and element occurrences and potential in Myanmar

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Received 28 December 2022; Accepted 12 June 2023.

Abstract

Critical minerals and elements are naturally formed materials that are essential to modern society for technology. Although the classification of critical minerals and elements varies among some countries, organizations, and industries, their importance is central to high-tech sectors. Some critical minerals and elements are important for energy production and storage, some for high-tech communication, and entertainment, and some for security and defense. Most of the critical minerals and elements are primary ore (or) elements, but some are the by-product of refining and smelting of the metal produced. Myanmar has a stratigraphic unit ranging from Precambrian? to Recent and its morphology and tectonic feature follow a general north-south trend. It is endowed with an extensive variety of mineral resources. Generally, it can be stated that critical minerals of Myanmar are rich in copper, lead, zinc, tin, and tungsten, fairly rich in antimony, nickel, and iron, and poor in chromite, manganese, platinum group minerals (PGMs), radioactive minerals, rare earth elements (REEs), bauxite, mercury, lithium, and uranium. In Myanmar, REEs, PGMs, titanium, and zircon are regarded as restricted metals/ elements. Most of the critical minerals such as REEs and lithium minerals, uranium and radioactive minerals are associated with the Mogok Metamorphic Belt (MMB), especially in the northeastern part, and the other 7 areas, the eastern and central granitoid belt of Myanmar. PGMs are mainly found in secondary placers of the Chindwin basin; titanium and zircon in placers and beach sand in southern parts of Myanmar; lithium in lepidolite mica and petalite in pegmatite dykes of the MMB; copper in the central volcanic belt, and Tagaung-Myitkyina belt; nickel and chromite ultramafic rocks of ophiolite suite of western fold belts; lead-zinc-silver-copper in stratabound & stratiform deposits in Paleozoic carbonate sediments and volcanic rocks of Sibumasu; tin-tungsten primary deposits associated with S-type granitoid belts in the Tanintharyi Region and SW of the Kayah State in Myanmar while occurs as placers at surrounding areas. The stibnite ores are generally found in veins or lenses and pockets as epithermal origin in clastic sediments of Carboniferous age and Paleozoic carbonate rocks. This study focuses on the potential for critical minerals exploration areas and discusses the need for special collaboration and research work on critical minerals exploration and production in Myanmar.

Keywords: Critical minerals, Mogok Metamorphic Belts, Rare Earth Elements, restricted metals/elements, secondary placer

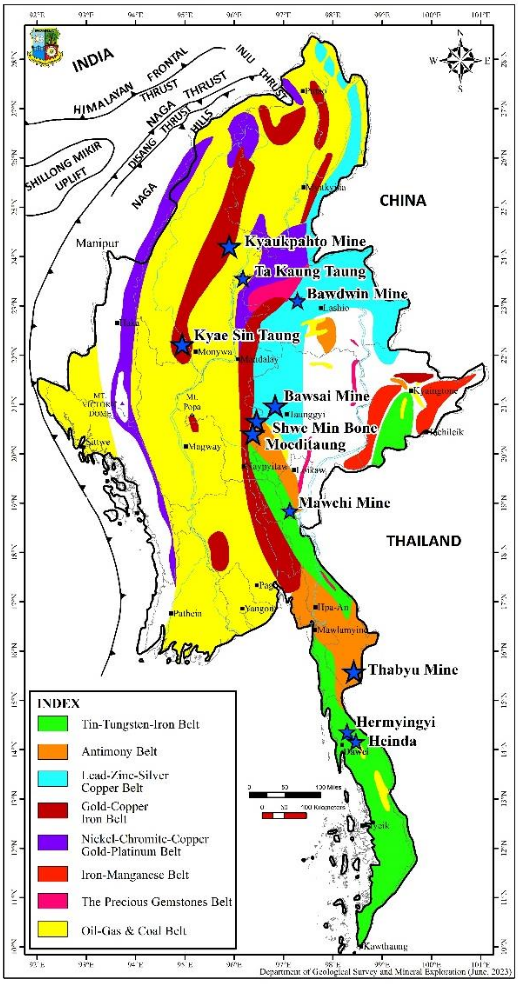
1. Introduction

Critical minerals and elements are naturally formed materials that are essential to modern society for technology. Although the classification of critical minerals and elements among countries, organizations, and industries varies, their importance is central to high-tech sectors. Some critical minerals and elements are important for energy production and storage, some for high-tech communication including entertainment, and some for security and defense. Most of the critical minerals and elements are primary ore constituents but some are the by-product of refining and smelting of the major metal produced.

2. Brief Geology of Critical Mineral Exploration in Myanmar

Mineral exploration and potential mining had been undertaken for centuries with old mining history in Myanmar. By comparing the distribution of the mineral occurrences with background geology, mineral provinces can be easily defined and their relationship to the tectonic provinces becomes more evident. The ages of rock units in Myanmar range from Precambrian? to Recent and morphologic and tectonic features of these units follow a general north-south trend. There are similarities with the stratigraphy and tectonic settings in neighboring countries of India, China, Thailand, Malaysia and Indonesia. The territory of Myanmar is traditionally divided into five parallel north-south trending morpho-tectonic belts from east to west. They are the Eastern High Lands & Upper Irrawaddy Province, the Central Lowlands, the Western Ranges or Western Fold Belts and including the Arakan Coastal Belts, where each belt has its own outstanding stratigraphic succession, geological structures and metallogenic characteristics and this is endowed with extensive varieties of mineral resources.

There have been various accounts on the distribution of minerals in Myanmar such as geographical groups or regions of mineral occurrences; metallogenic provinces and mineral belts. Brown (1924), Haq (1970,1972 & 1981), Goossens (1978), Bender (1983) and Thein (1986). Among them, the classification of Thein (1986) is more appropriate, and he synthesized the mineralization proposing six mineral belts and eleven mineral epochs (Fig. 1).



1. Tin-Tungsten-Iron Belt of Tanintharyi, Southwestern Kayah State, Western marginal zone and northern (including Manmaw deposit) and southeastern part of Shan Plateau.

2. Antimony Belt of part of Shan, Kayah, Mon States, and Mandalay Region**.**

3. Lead-Zinc-Silver-Copper Belt of Shan State (Stratabond & Stratiform Deposits in Carbonate, Sediments and volcanic Rocks.)

4. Gold-Copper-Iron Belt of Monywa and Wuntho Massif Area (Central Volcanic Arc) and Western Shan Scarp Region.(within MMB, Slate Belt, and Mesozoic Turbidite)

5. Nickel-Chromite-Iron-Copper-Gold-Platinum and Jade Belt of Chin Hills, Jade Mines Area and Tagaung-Shwegu Region associated with ultrabasic and meta-sediments**.**

6. Iron–Manganese-Gold Belt of Eastern Shan State in meta-sedimentary, granitic and volcanic rocks. (e.g. Tar-lay & Mong Yu epithermal gold, and Ar Ye SEDEX? manganese deposits)

7. The Precious Gemstones Belt of Madaya-Mogok Tract, Northernmost Shan State and Thanlwin River Tract of Eastern Shan-Kayah-Kayin Regions related with marble, calc-silicates, gneiss, granulite and major granite emplacement.

8. Oil-Gas and Coal Belt of Central Myanmar, Ayeyarwaddy Delta, Rakhine Coastal Region and small structural Basins in Tanintharyi Region and Shan States of Tertiary and a few are of Jurassic age.

Fig. 1: Mineral belts of Myanmar (Modified after Maung Thein, 1986) (Although coloured minerals are non-critical minerals, the map shows the associated occurrences as the belts).

3. Occurrence and Potential of Critical Minerals

Thein (1986) generally stated that minerals occurrences in Myanmar are rich in copper, zinc, tin, and tungsten, fairly rich in antimony, and poor in chromite, manganese, platinum group minerals (PGMs), radioactive minerals, rare earth elements (REEs), lithium, and uranium. According to the commodity, usefulness, potential and abundance in Myanmar, the following minerals can be regarded as critical minerals by Department of Geological Survey and Mineral Exploration (D.G.S.E.) (Table 1, Fig. 2). In Myanmar, REEs, PGMs, titanium, and zirconium are regarded as restricted metals/ elements.

Most of the critical minerals such as lithium and REE minerals including uranium and radioactive minerals in Myanmar are mostly found in the Mogok Metamorphic Belt (MMB) (Chhibber, 1934; Searle and Haq, 1964;Bender, 1983; Mitchell, 1993, 2018; Barley et al., 2003; Zaw, 2017; Barber et al., 2017; Searle et al., 2007, 2020). The belt is composed of high-grade metamorphic rocks and collision-related granitic rocks with late-stage crustal melt-derived granitic rocks (Searle et al., 2007), and the southern part of the belt which is pinch-outs while mainly composed of the Carboniferous Mergui Group. The MMB is also an important geotectonic setting for gold, lead-zinc, and copper (Mitchell, 1993, 2018).

Table 1. Criteria for critical minerals selection in the US, EU, Australia, Canada and Myanmar (Modify after KIGAM Critical Minerals Issue report, 2021-02).

Country	Name	Criteria
United States	Critical mineral resources	1. 1. A non-fuel mineral or mineral essential to the economic and national security of the US; 2. 2. The supply chain of which is vulnerabe to disruption; and 3. 3. Serves an essential function in the manufacturing of a product, the absence of which would have significant consequence for the economy or national security
European Union	Critical raw materials	1. Link to industry (Linked to all industries across all supply chain stages). 2. Modern technology (dependency of technological progress & quality of life on access to a growing number of raw materials) 3. Environment (indispensable role of CRMs in clean technologies).
Australia	Critical minerals	1. The level of criticality assigned by the United Kingdom, European Union, United States of America, Japan and Republic of Korea. 2. Australia's know resources as well as potential for discovery of new resources. 3. Demand in terms of global market size; and 4. Growth outlook.
Canada	Critical minerals	1. Essential to Canada's economic security. 2. Required for Canada's transition to a low-carbon economy. 3. A sustainable source of critical minerals for our partners.
Myanmar	Critical minerals	1. Commodity, potential, abundance and common usage as accepted by ASEAN and neighboring countries.

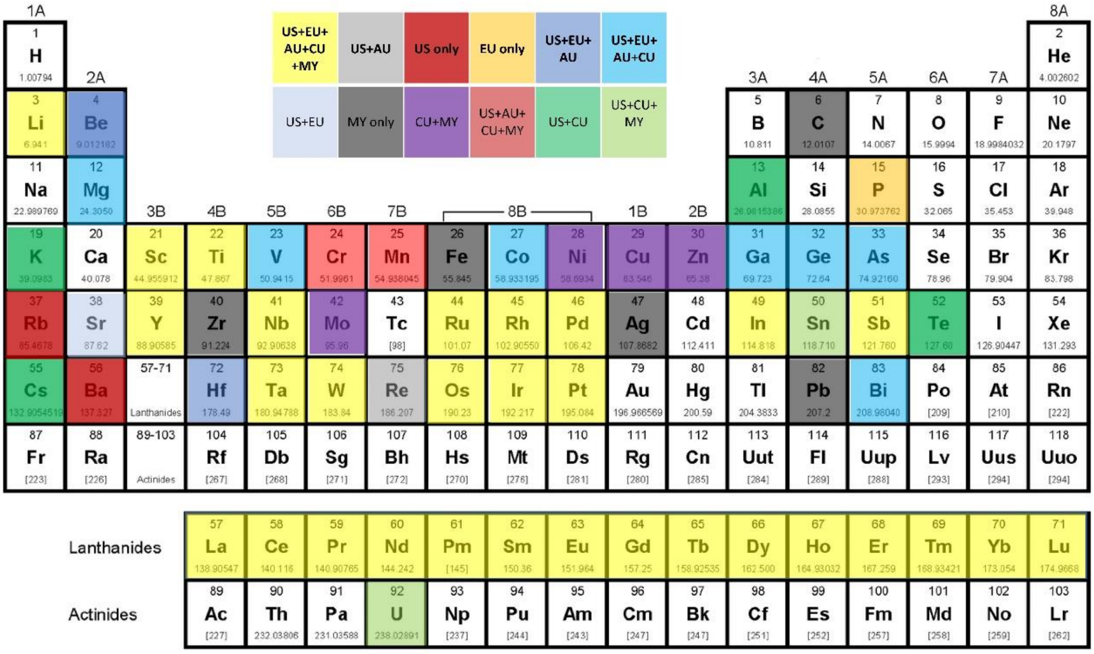


Fig. 2. Metals or materials classified as critical in the United State of America; US, European Union; EU, Australia; AU, Canada; CU and Myanmar; MY. (Modify after KIGAM Critical Minerals Issue report, 2021-02).

Lithium: Lithium is currently an important critical mineral that can be found in Myanmar although detailed exploration works have not yet been done. The lithium occurrences in Myanmar are in lithium-bearing micas such as lepidolite, and lithium-bearing minerals such as petalite and spodumene. Most lithium-bearing minerals are associated with and found in granitic pegmatites. The possible areas for the occurrence of lithium minerals in Myanmar (Fig. 3) are:

1. Shan State, Molo-Momeik region (Petalite in pegmatites intruded into ultramafic igneous rocks)

2. Mandalay Region, Mogok Township, Sakan Gyi Area (Lepidolite, petalite and spodumene in pegmatites of Mogok metamorphic rocks)

3. Mandalay Region, Singu-Thabeikkyin Township Area (Pegmatites intruded into Mogok metamorphic rocks).

4. Mandalay Region, Singu Township, Pyingyi Taung Area (Petalite and lepidolite in pegmatites intruded into Mogok metamorphic rocks)

5. Mandalay Region, Tharzi-Pyawbwe Township Area (Pegmatites intruded into Mogok metamorphic rocks and saline development areas)

6. Tanintharyi Region, Dawei Township, Harmyingyi Area (Pegmatite dykes in granitic rocks)

7. Tanintharyi Region, Tanintharyi Township, Tagu Area (Pegmatite dykes in granitic rocks).

Rare Earth Elements: In Myanmar, REEs are mostly associated with granitic rocks which intruded into the Mogok Metamorphic Belt (MMB) especially at the eastern and northeastern part of Myanmar. Other REEs occurrences are associated with volcanic rocks. Swe (2012) proposed eight possible potential areas for the occurrence of REEs in Myanmar (Fig. 4) are:

Area I. Around Chipwi-Panwa, Hpimaw, Kanpant areas (Weathered coarse-grained granite (porphyry granite) occurrences at Kachin State)

Area II. Around Singu, Thabeikkyin, Mogok, Momauk, Lweje areas (Granite, pegmatite and Thachileik district, Eastern Myanmar) related

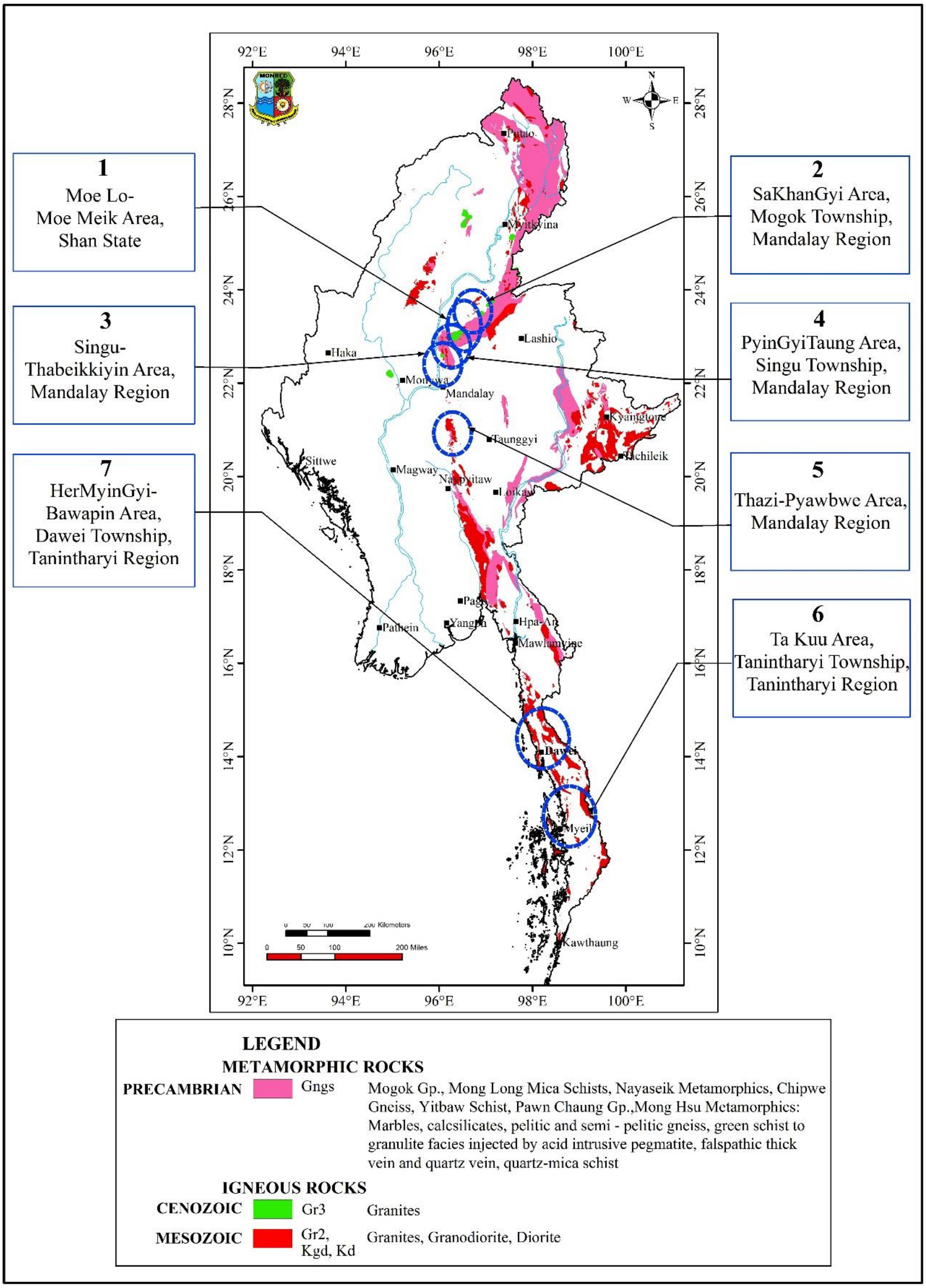


Fig. 3: The location of possible areas for lithium occurrences in Myanmar.

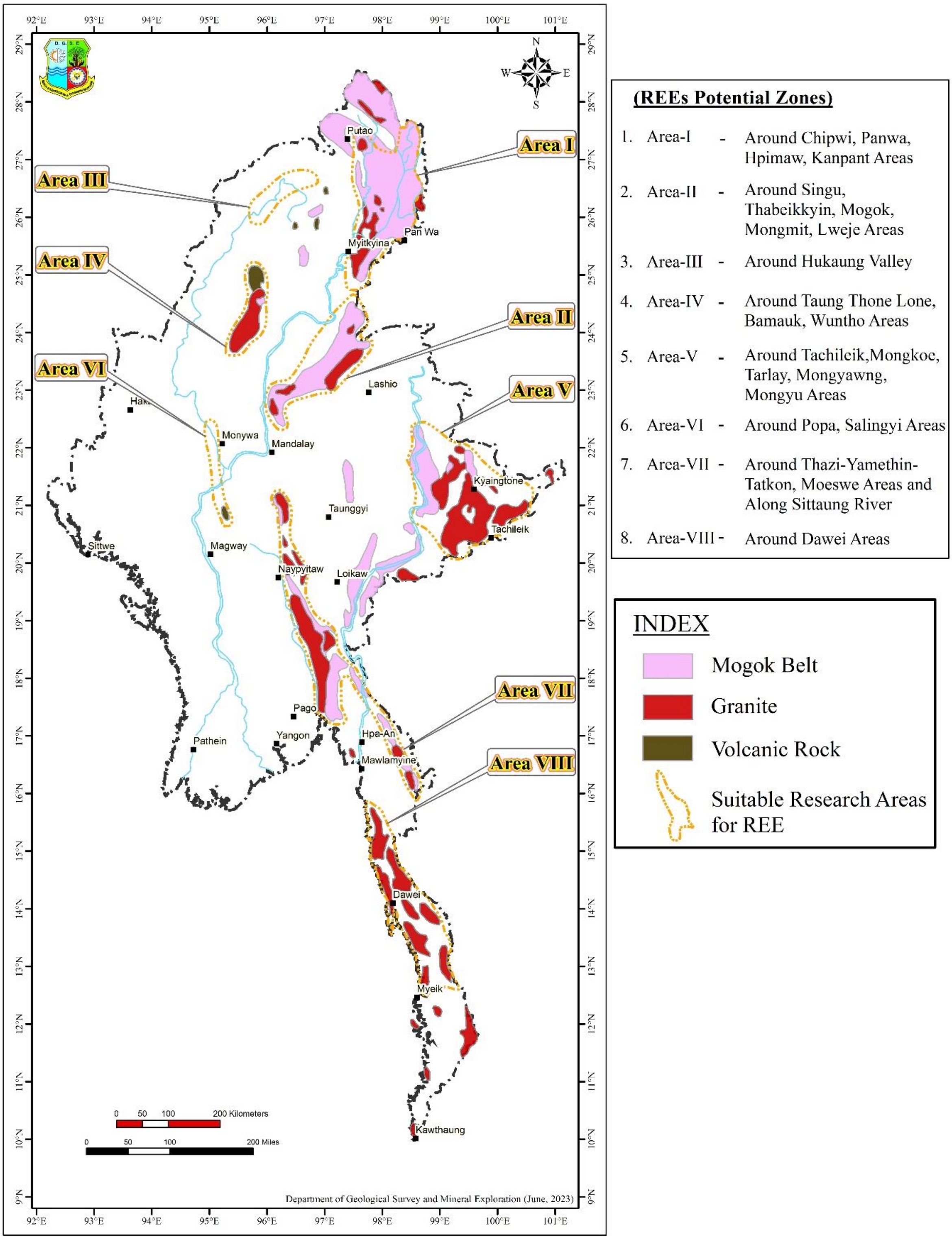


Fig. 4: Potential areas for REEs occurrences in Myanmar (After Ye Myint Swe, 2012).

meta-sediment along the Mogok Metamorphic Belt)

Area III. Around Hukaung Valley (Placer deposit at Hukaung Valley at the northern part of Myanmar)

Area IV. Around Taung Thone Lone, Banmauk, Wuntho areas (Along the Central Magmatic Arc at the central part of Myanmar)

Area V. Around Tachileik, Mongkoe, Tarlay, Mongyawng, Mongyu areas (SEDEX iron-manganese, and epithermal gold deposits at

Area VI. Around Popa, Salingyi areas which consist in the Central Magmatic Arc

Area VII. The distribution of laterite, bauxite and kaolinite occurrences in Shwegyi, Minlan-ThanZeik, Kyeikhto-Mokepalin and in the vicinity of Sittaung River (laterite-bauxite with clay occurrences at Mon State)

Area VIII. Weathering crust of tin-tungsten bearing granite belt in Dawei region along Thai-Myanmar borderline (associated with granite-related Sn-W deposits).

Platinum Group Minerals: Nearly a million tons of PGMs with an average value of 0.53 gm/t of Pt was discovered 20 years ago in Kachin State, northern Myanmar in the mafic and ultramafic Terrane (D.G.S.E., 1994). Local small alluvial deposits of Platinum and Palladium have been worked for more than 25 years in that area. Moreover, secondary placer PGMs are found in the Chindwin basin (Fig. 5).

Zirconium and Titanium: Zirconium and titanium are found in placers and beach sand as zircon and rutile in southern parts of Myanmar. The primary sources of titanium are found in Mogok Metamorphic rocks, Kachin State and Htee Chaint area of Sagaing Region, rarely (D.G.S.E., 2011). Zircon is also found in the placers and beach sands in Bokye Pyin area, Tanintharyi Region is 0.2 to 4 Lb/ton (D.G.S.E., 1993a), May Yu beach, Maung Daw area, Rakhine State is 0.017 Lb/ton (D.G.S.E., 1993b) and Chaungzone area, Mon State is 0.035 Lb/ton (D.G.S.E., 2022) (Fig. 5).

Copper: Myanmar had a long history of the existence of the Bronze Age which proved that copper mineralization and culture are inseparable. Several copper occurrences are known in Myanmar (Zaw et al., 2017b) and the most important is the high-sulphidation copper deposit on the west bank of the Chindwin River, opposite of Monywa City (Soe et al., 2017). The copper mineralization within the central volcanic arc is found from Mt. Popa and passes through the lower Chindwin area where the volcanic rocks are hosted to the high sulphidation deposits at the Sabe Taung, Kyesin Taung, & Lepadaung Taung, Monywa area of the Northern part of Myanmar (Fig. 6). This copper mineralization occurs as high sulphidation epithermal deposit with Letpaduang: 1478 Mt@ 0.37% Cu, Sabetaung and Sabetaung south 213 Mt @ 0.26% Cu, Kyisintaung 391 Mt @ 0.31% Cu (Mitchell et al., 2010; Zaw et al., 2017a, b). The other major deposits of copper deposits are located in Wuntho Massif area of central volcanic arc and Western Shan Scarp Regions. The porphyry style Cu-Au & its related epithermal Au along the central volcanic arc of Kawlin, Wuntho, Banmauk areas with possible ore reserve is about 9 Mt @ 0.23% Cu, 0.17% Au with traces of Mo in Shangalon mine (Gardiner et al., 2016; Zaw et al., 2017a, b) and Mahar San (Cu–Pb–Zn–Ag) prospect which contained 7.35% Cu, 5.58% Pb, 7.56% Zn, 3.8 g/t^{-1} Au and 68.6 g/t^{-1} Ag (Zaw et al., 2017a, b). The Au (Cu) skarn & mesothermal veins are found in marble, gneiss and granite within the Mogok Metamorphic Belt of Pyinmana, Singu and Thabeikkyin areas and Au-Cu skarn & mesothermal veins in marble within Jurassic turbidites of Kalaw area. More than 100 copper occurrences are recorded in Myanmar but most of them are of minor importance. Copper is found in Mandalay Region at Sabe Taung with 0.09 Mt @ 0.85–1.5% Cu at Main zone and 0.34 Mt @ 0.69% Cu at Sabe extension zone (Zaw et al., 2017b) and Leymyetna (Cu–Au) prospect in Western Ophiolite Belt which minera-lization occurs in submarine mafic–ultramafic volcanic rocks associated with predominantly shale, limestone, chert and sandstone, up to 100 000 tonnes @1.06–2.53% Cu (Htay et al., 2017; Zaw et al., 2017a, b).

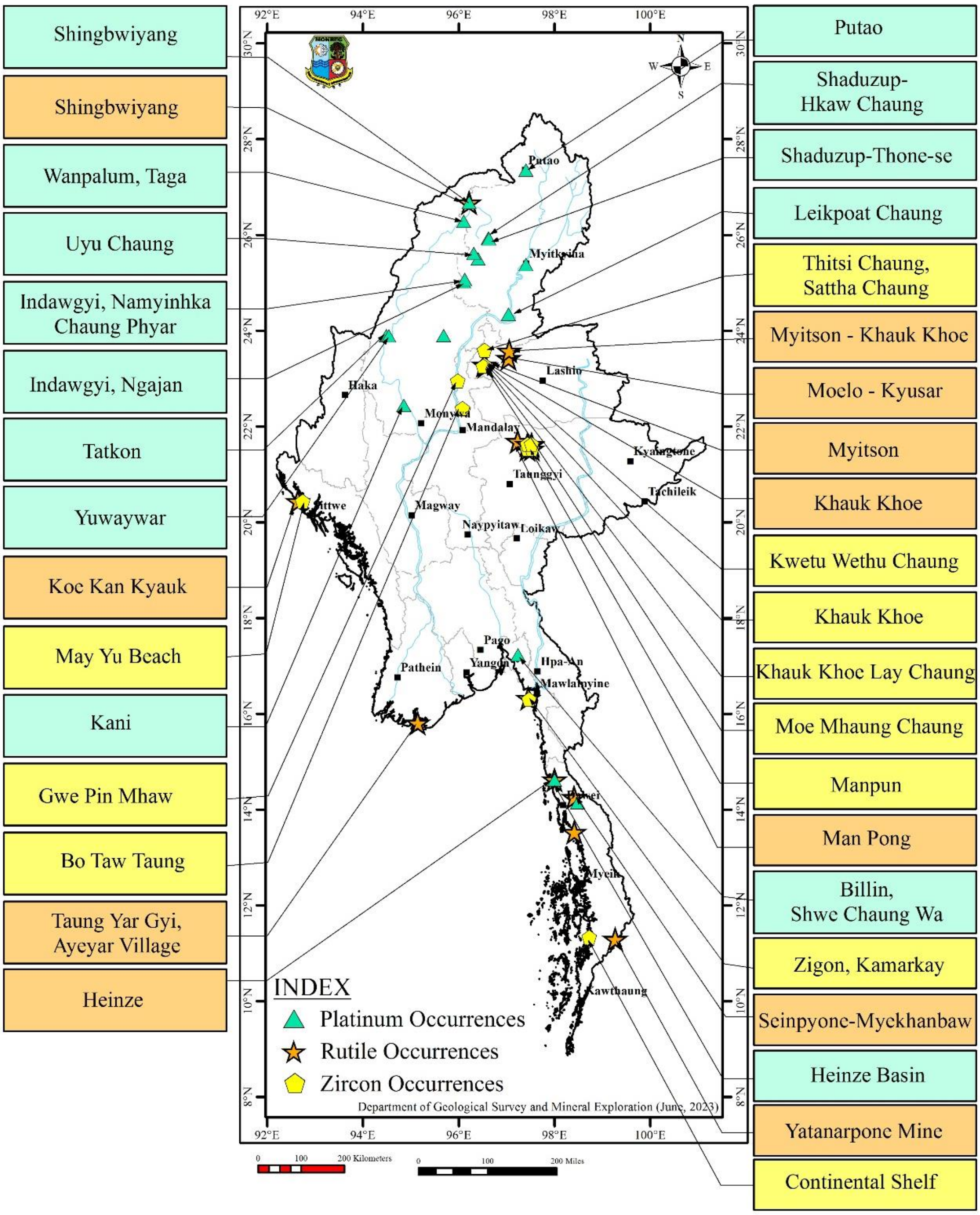


Fig. 5: The location of platinum group minerals and zirconium and titanium in Myanmar.

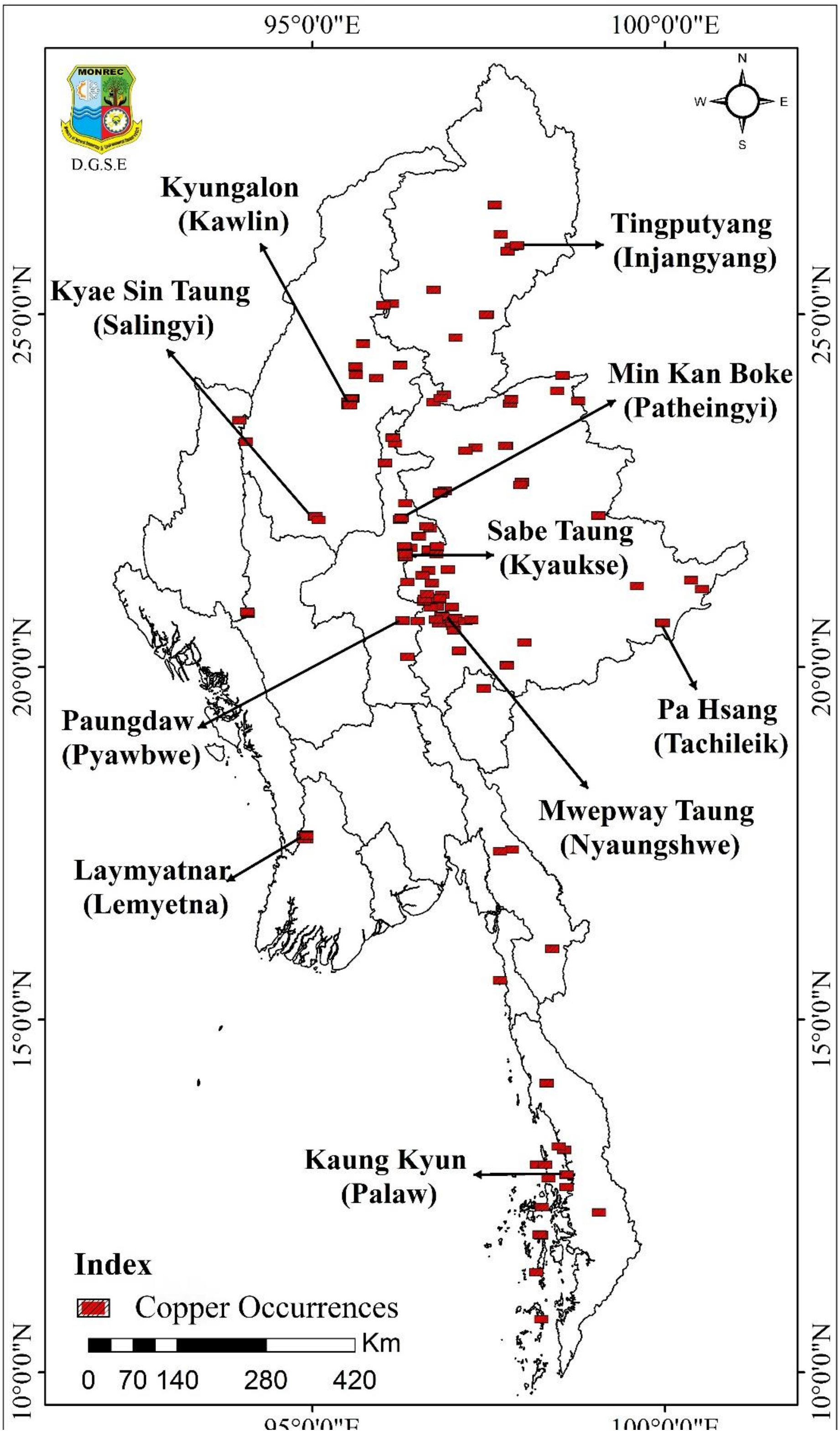


Fig. 6: The location of copper occurrences in Myanmar

Nickel and Chromium: Nickel and Chromium (Ni-Cr) are not common and mainly found at the Jade Mine area, Chin Hills and Tagaung-Shwegu regions associated with ultramafic rocks of ophiolite suite of western folded belts (Late Cretaceous-Early Eocene) and some metasediments. At Mwetaung & Tagaung Taung, the deposits have formed as a result of the tropical weathering of ultramafic rocks (Ni laterite deposits) (Fig. 7). The most significant lateritic nickel deposits occur at Tagaung Taung and Mwetaung (Zaw et al., 2017b). Tagaung Taung deposit is a residual lateritic type in serpentinized ultramafic bodies of dunite, harzburgite, partly cumulate peridotite which contains 40 Mt @ 2% Ni (Htay et al., 2017) and Mwetaung deposit is about 36 Mt @ 1.48% Ni which is regarded as national reserve area (Lynn 2016; Htay et al., 2017).

Chromium deposits are widespread in Myanmar being related to north-south trending ophiolite lines close to nickel deposits (Fig. 8). They are found as podiform chromite and residual deposits dispersing near the primary sources about 38200 Ton @ 11.8% to 37.96 % Cr with 0.07 to 0.34% Ni at Bhopi Vum area, Tidim Township, Chin State and is regarded as a national reserve area (D.G.S.E., 2020) (Fig.8).

Lead-Zinc-Silver: Lead-zinc-silver are found in stratabound & stratiform deposits in Paleozoic carbonates sediments and volcanic rocks of Sino-Sium, Burma, Malaysia Sumatra (Sibumasu) terrane, especially in the Southern and Eastern Shan States. More than 300 occurrences of lead-zinc-silver mineralization are recorded in Myanmar. Mineralization occurs in five different styles such as volcanogenic massive sulphides type (VMS) at Bawdwin. The mineralization is bound to an approximately 4 km long and about 100 m wide NW-SE oriented Bawdwin Fault Zone (Zaw, 2003, 2004; Zaw et al., 1999, 2014a, b; Htun et al., 2017a; Gardiner et al., 2017). The possible ore grade tonne of the Bawdwin deposit is 10.8 Mt consisting of 22.8% Pb, 13.9% Zn, 1.1% Cu, 670 g/t Ag with Co and Ni. Mohochaung lead occurrence approx.-imately 30 km north of Namtu is stockwork mineralization of galena in calcite gangue (D.G.S.E, 2001). Mississippi valley type (MVT) deposit at Bawsaing mine occurs in the Ordovician limestone, the sulphide ores are found in numerous small occurrences in a narrow NNW-SSE striking zone approximately 6 km long. There are 1.5 Mt sulphide ore with 15% Pb, 5% Zn, 5 oz/ton Ag and oxide ore with 10% Pb, 36.7% Zn, 3 oz/ton in Bawsaing deposit (Goossens, 1978; Zaw et al., 1984, 1999; Htun et al., 2017a, b). Cavity filling vein-type in Yadanatheingi mine occurs along a shear zone about 10 m thick which cuts across the sediments of the Chaung Magyi Series in NW-SE direction which possible ore reserve is 72 000 tonnes with 3.3% Pb, 1.2% Zn, 360 ppm Ag (Htun et al., 2017a). Other deposits such as the Phaungdaw mine are found in vein fissures and stockworks in veins and skarn type near the contact between granitic rock and marble. The secondary Zinc carbonate deposit at Lonchein mine is about 203270 tonnes with smithsonite ore, 41.54% Zn and hydrozincite ore, 55.25% Zn (Than Htun et al., 2017a) in Plateau Limestone of Devonian–Permian age of Southern Shan State and Naungmain of Northern Shan State. The location of zinc occurrences in Myanmar are shown in (Fig. 9).

Tin-Tungsten: Tin-tungsten occurrence is well defined in the Tanintharyi Region, southwestern Kayah State, western marginal zone and poorly defined in the Southeastern part of Shan Plateau. In these regions, the primary tin and tungsten deposit occur in pegmatite and quartz veins which are associated with S-type granitic rocks and also intruded into the sedimentary rocks. More than 400 tin–tungsten worksites and mines are recorded in Myanmar both in primary and placer deposits such as Mawchi mine (Myint et al., 2017) (Fig. 10). The possible ore reserve of Mawchi mines is about 31 Mt ore @ an average of 0.3% mixed Sn + WO_3 (Aung Zaw Myint et al., 2017; Than Htun et al., 2017b). Tin-tungsten mineralization occurs along the granitic belt in the SE Asia peninsula distributed over more than 1200 Km in Myanmar with more prominent tungsten toward the north, passing through the Tanintharyi Region, Kayin, Mon, Kayah &

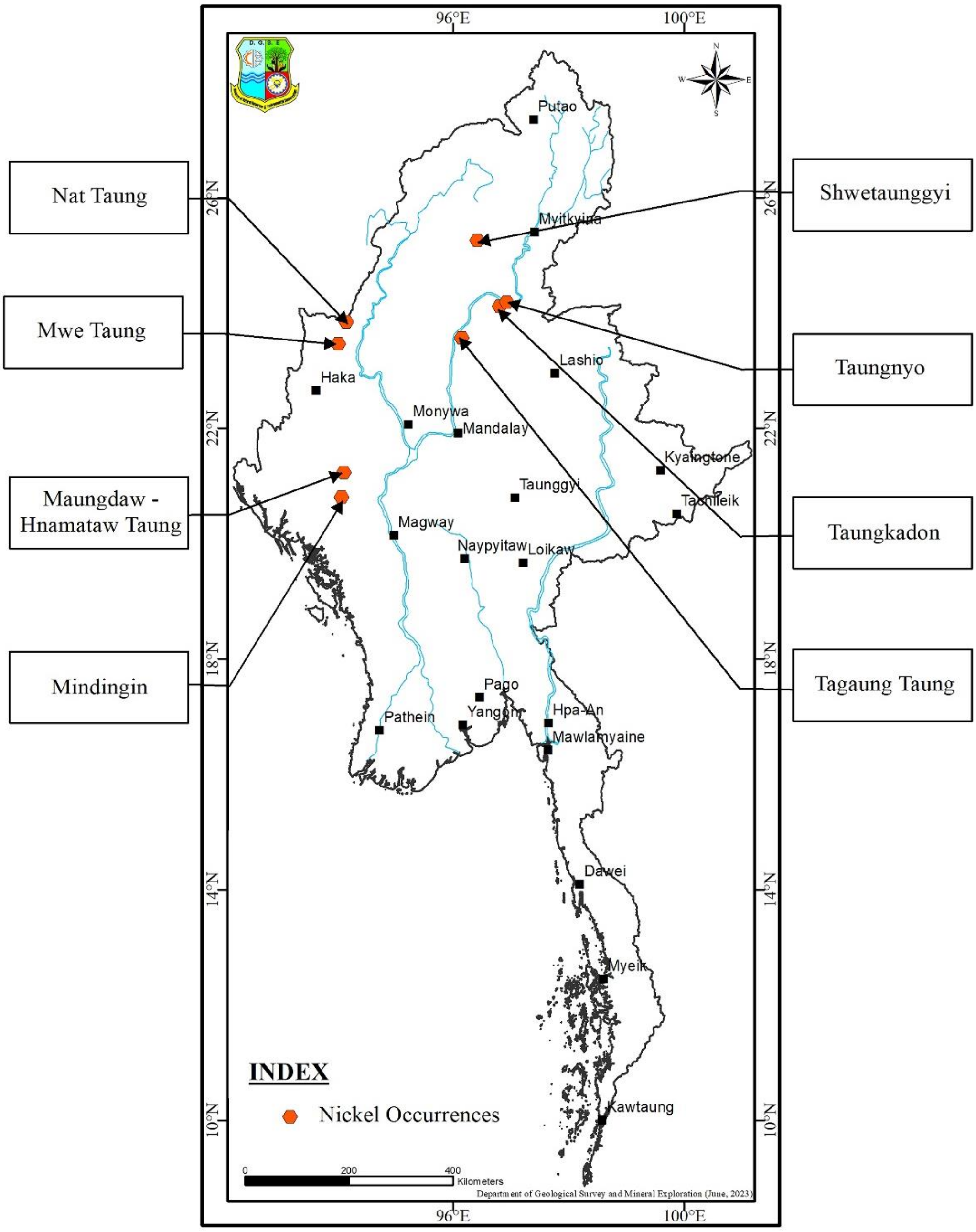


Fig. 7: The location of nickel occurrences in Myanmar.

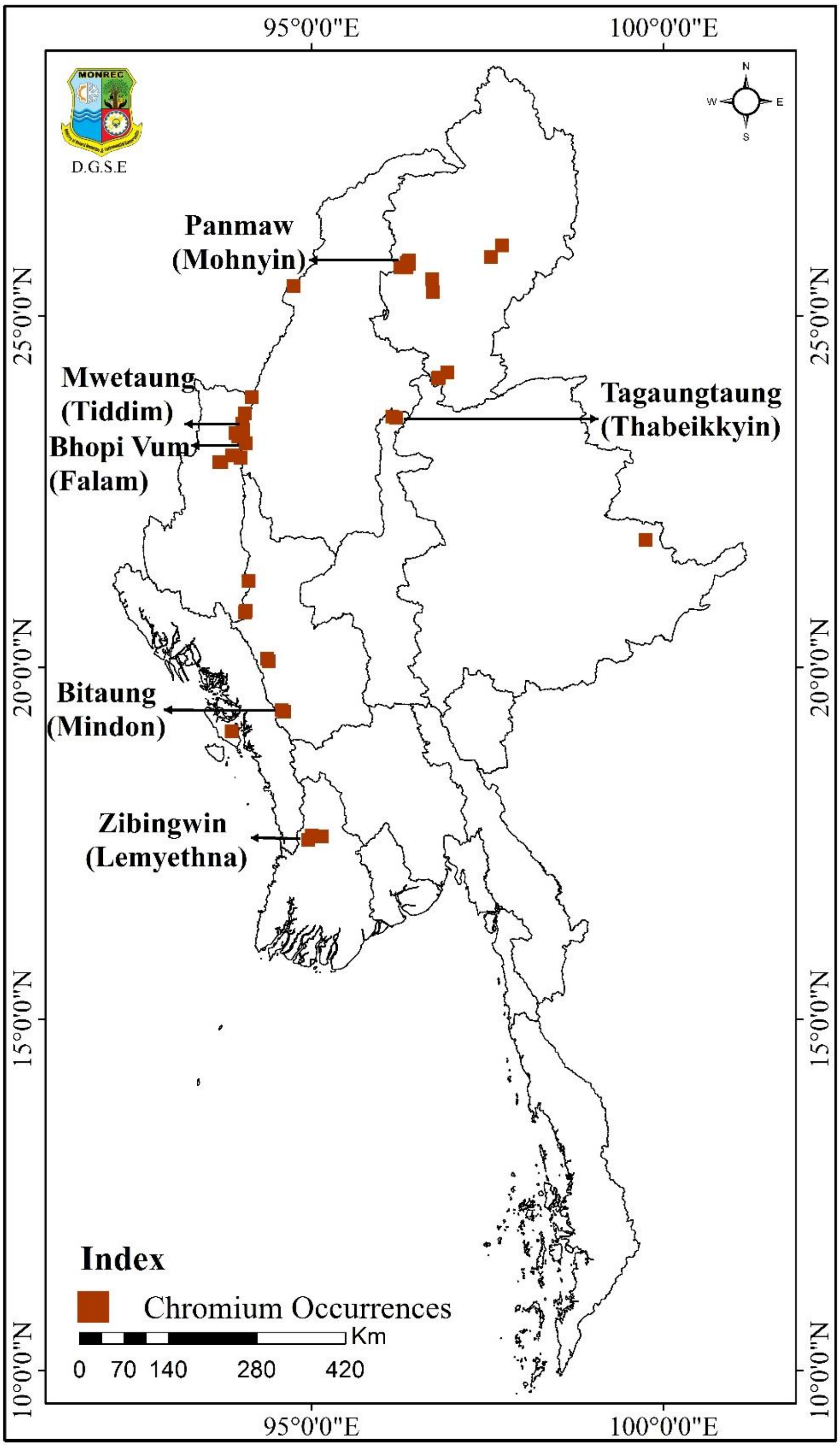


Fig. 8: The location of chromium occurrences in Myanmar.

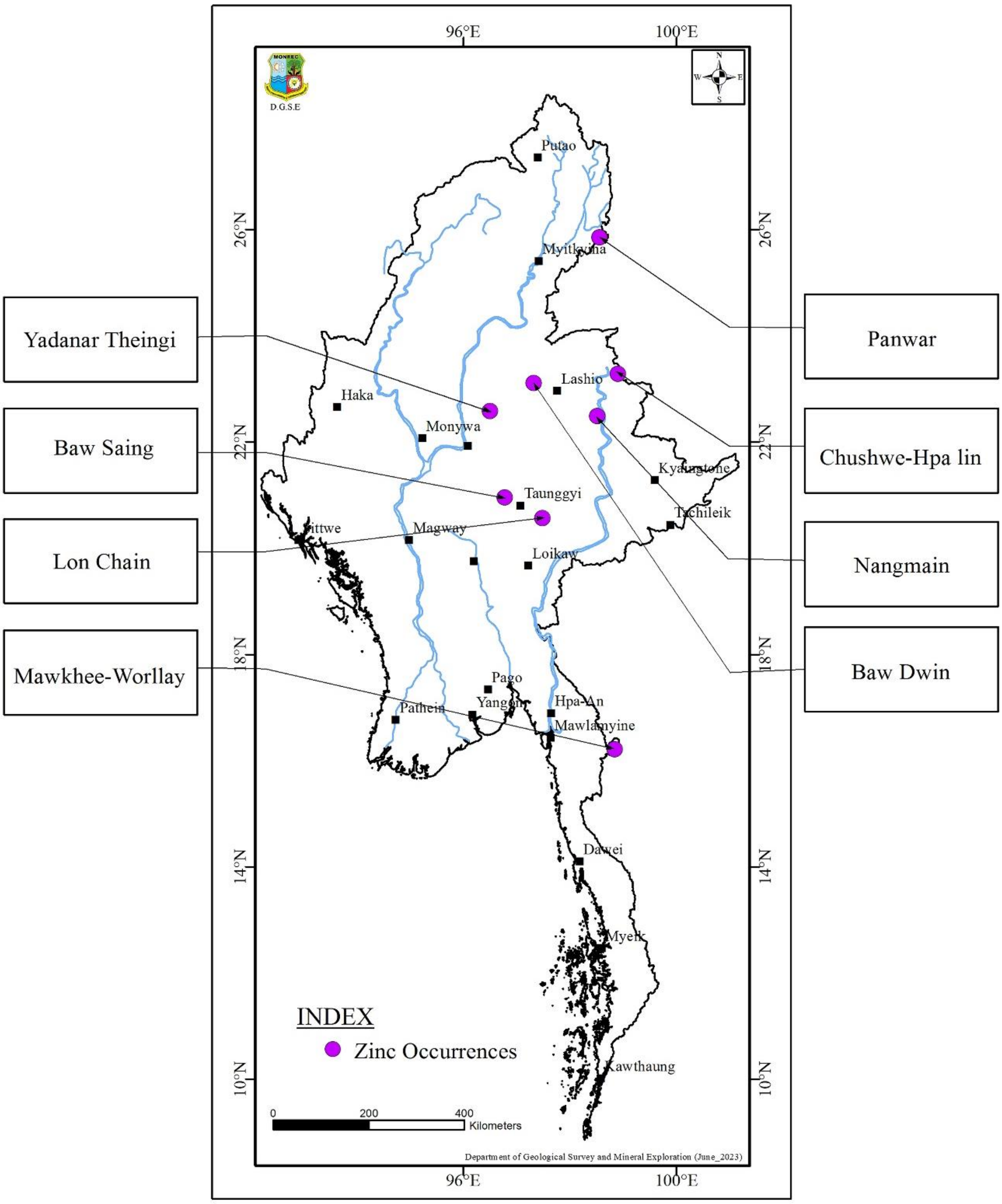


Fig. 9: The location of zinc occurrences in Myanmar.

Shan States, and East of Pyinmana and widespread also at Mong Hsat and Mongton of Eastern Shan State (Mitchell, 2018). Tin-tungsten ores occur in close association with granitoid, and related rocks emplaced during the Late Mesozoic-Tertiary (Htun et al., 2017b). The country rocks of these intrusive masses consist of the clastic metasedimentary rocks of the Mergui Group, Taungnyo Group, Mawchi Group of the Carboniferous to lower Permian age. Other Tin-tungsten deposit such as Hermyingyi mine have a reserve of about 0.7 Mt @ an average of 0.4% mixed Sn + WO_3 (Htun et al., 2017b), Yadanabon mine is estimated about 43 tonnes of concentrates @ an average of 0.79% mixed Sn +WO_3 (Gardiner et al., 2016; Htun et al., 2017b), Kanbauk mine is about 6.7 Mt@ 0.37% Sn, 0.18 WO_3 (Bender, 1983; Htun et al., 2017b) and Heinda mine is estimated about 12464 tonnes concentrates @ 0.68% Sn (Htun et al., 2017b).

Antimony: The antimony mineralization occurs in parts of Shan, Kayah, Mon States and Mandalay Region. Antimony ores are generally found in veins or lenses and pockets of epithermal origin in clastic sediments of Carboniferous and Paleozoic carbonate rocks (Fig. 11). The majority of antimony mineralization occurs in clastic sediments in Mergui Group and in the abundant carbonates of Ordovician, Silurian and Permian ages. The best-known antimony deposit is at Thabyu, Kayin State, near Myanmar-Thailand Border (Kyaw, 2017). Thabyu deposit is stratabound in the Mergui Group and the possible ore reserve is about 0.013 Mt @ an average 37% Sb. Another antimony deposit occurs in the Lebyin area as stratabound in NgaYant Chaung turbidites (older than Carboniferous?) with 0.112 Mt @1.64–34.5% Sb ore reserve (Kyaw, 2017).

Iron and Manganese: Iron and Manganese are poorly defined in metasedimentary and volcanic rocks in the Eastern Shan State. Iron mineralization is found in the northeastern part especially in Kathing Taung area in HpaKant Township, Kan Taw Yan areas in Waing Maw Township, Taung Nyo Taung area in Shwe Gu Township, Kachin State and grades ranging from Fe 37.52 to 69.88 % as residual deposits (D.G.S.E., 1998), while occurring magnetite at Mong Yawng area in eastern Shan State up to Fe 62.96% (D.G.S.E., 2015 a, b), and others occurrences found at Kanmaw Island area about 21.2 Mt @ 36.4% Fe at lateritic iron in Kyunsu Township, Thanintharyi Region (D.G.S.E., 2005) and Kyartwinyay deposit, Pyin Oo Lwin about 3.5 Mt @ 54% Fe (D.G.S.E., 1980). The residual Pangpet (Fe–U–Cu) deposit (under construction mill) is also found in the Southern Shan State which possible ore reserve is about limonite ore: 70 Mt @ 43% Fe; hematite ore: 10 Mt @ 56% Fe with 1.5% Cu, 0.2% UO_3 (Bender, 1983).

Wan Saw–Wan Phai manganese deposit occur as stratabound deposit in the Ordovician siltstone of Sibumasu terrane in the Shan Region which possible ore reserve is about 5–7.5 Mt @ 20–75% Mn (Zaw et al., 1999). Manganese deposits also occur at Ar Ye and Wan Sa Lo near Mong Hpayak and Tachileik in Eastern Shan by association with andesitic rocks as major production of Myanmar and the grade is ranging from 25% to 68% of MnO_2 (D.G.S.E., 2009), while considering the occurrences at Ta Ping-Mong Ma by association with meta-sedimentary rocks (D.G.S.E., 2003 a, b), and also found in other areas as Pawe kyan, area by 2.8 Mt @ 27.2% Mn near Bokepyin Township (D.G.S.E., 1985), Shan Taung Oo area by 2.84% MnO_2 at Kyaukse Township (D.G.S.E., 1984) and Thinpone Taung area by 0.01 Mt @ 51.20 % Mn near Mount Popa (D.G.S.E., 1971), Konniu area by 0.019 Mt @ 7.25 to 34.4% MnO_2 near Hopone Township, Southern Shan State (D.G.S.E., 2013) (Fig. 12).

4. Discussion

Not only the types but also occurrences of critical minerals in Myanmar are diversified. For lithium resource, the two sources from different types: pegmatite and brine. There are well-defined lithium bearing minerals such as lepidolite, petalite and spodumene in pegmatite veins, but there is no well-recognized brine-type deposits in Myanmar except the Tharzi area where preliminary exploration works have not

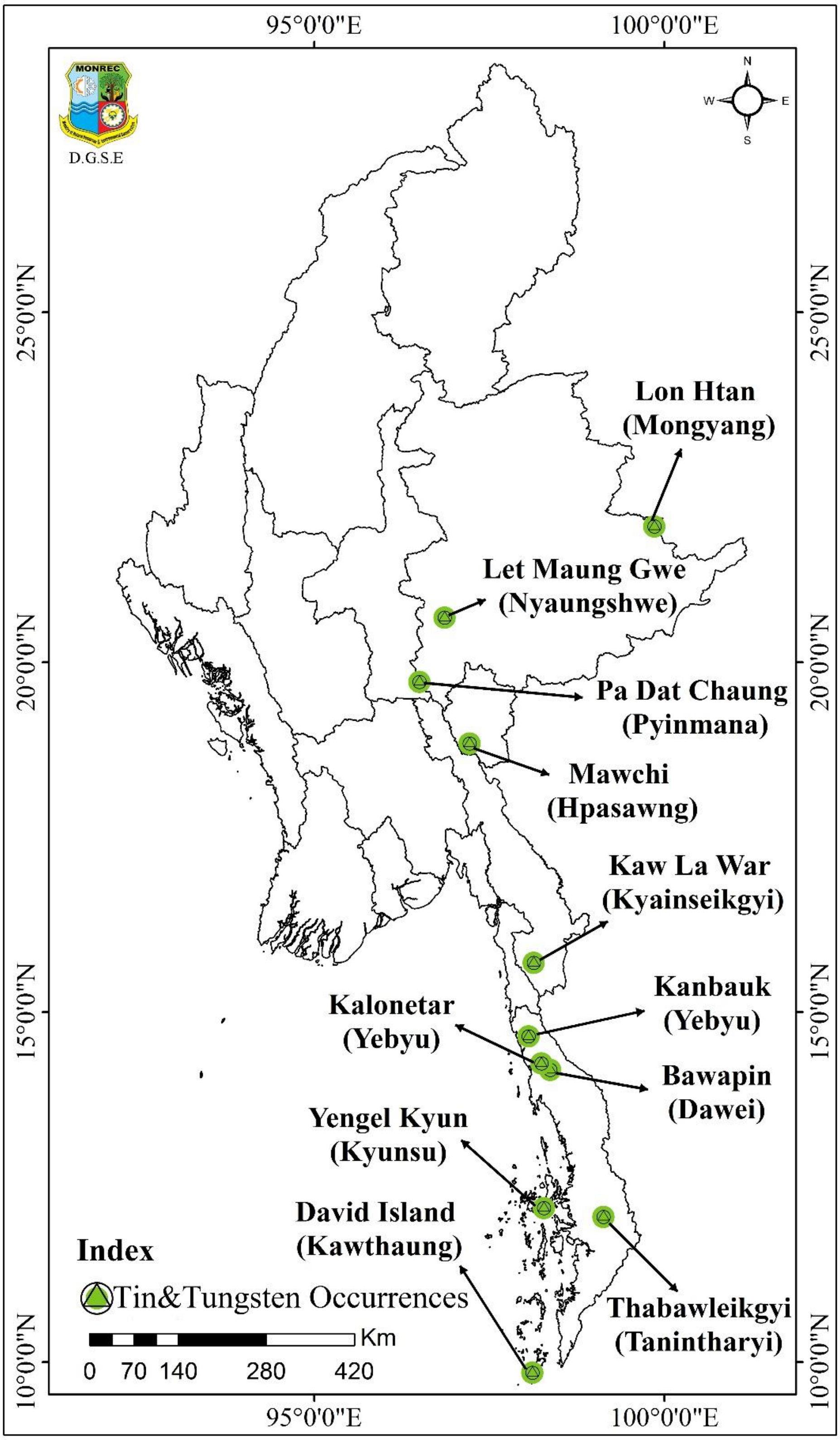


Fig. 10: The location of tin-tungsten occurrences in Myanmar.

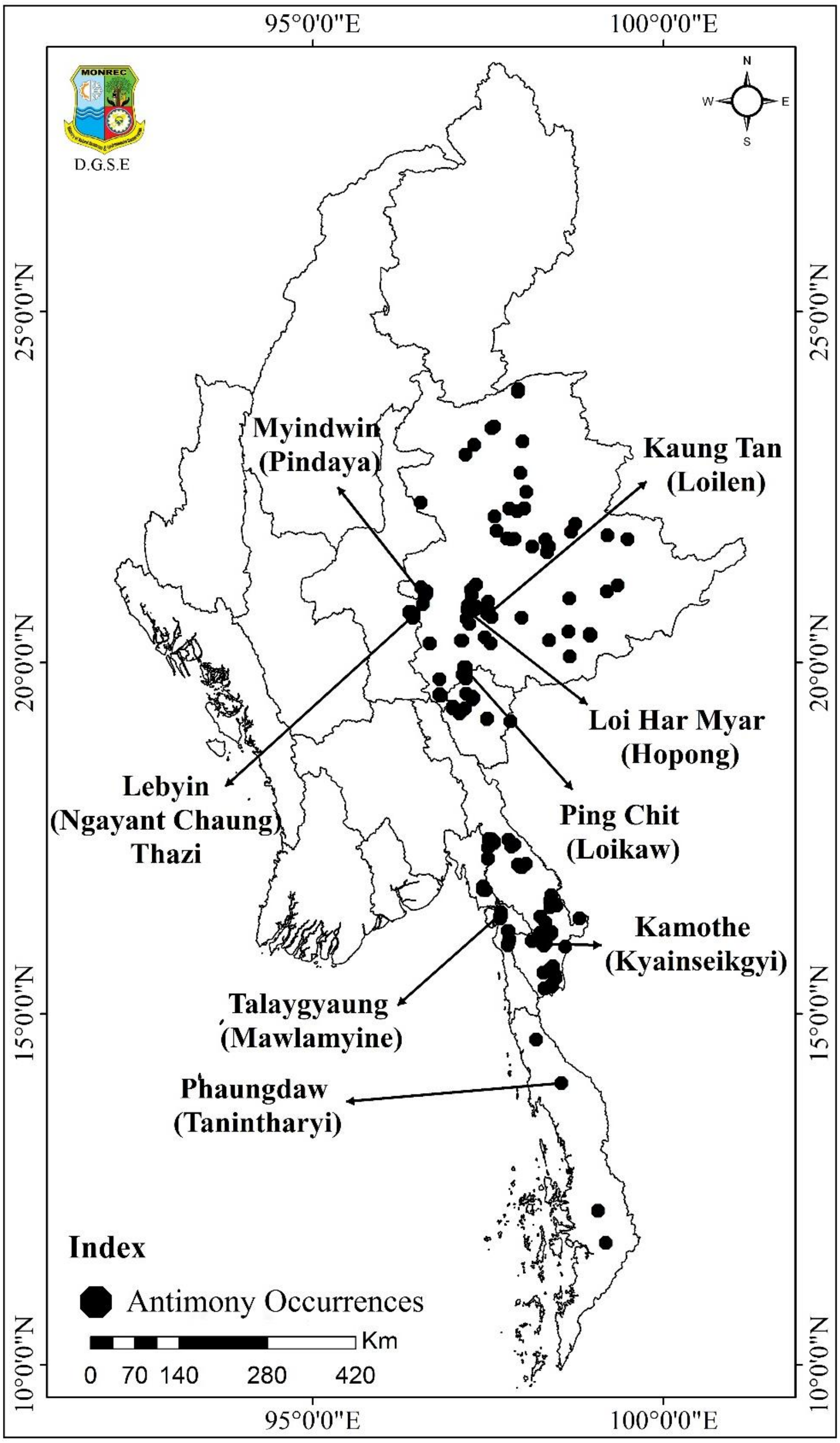


Fig. 11: The location of antimony occurrences in Myanmar.

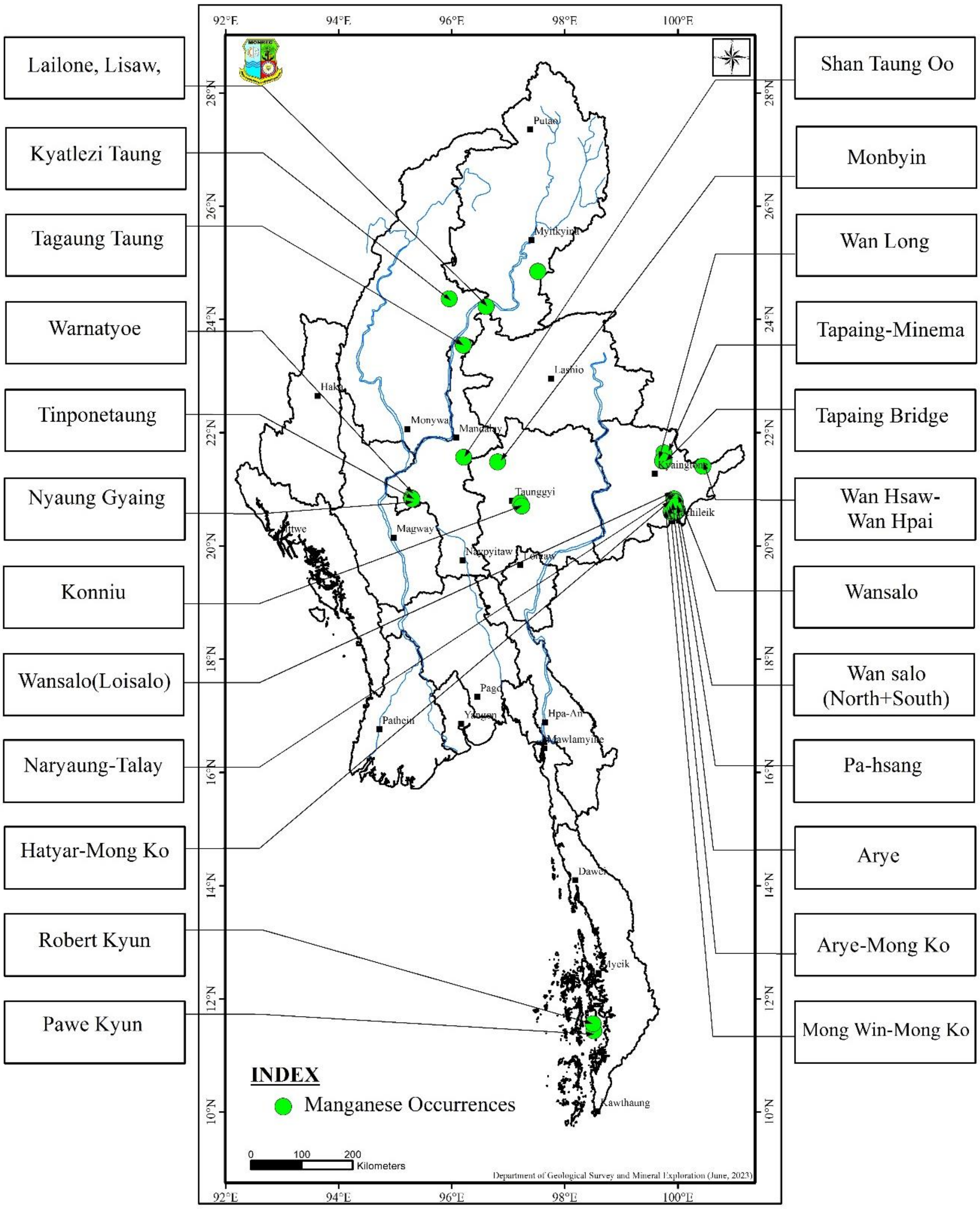


Fig. 12: The location of manganese occurrences in Myanmar.

yet been done. REEs occurrences and types of deposits in Myanmar can be classified as 1. LREE-bearing minerals such as monazite and xenotime in placer deposits**,** especially in tin potential areas, Tanintharyi Region, Southern Myanmar and 2. HREE in weathered granite of Mogok Metamorphic Belt-MMB especially in the Chipwi area, Kachin State, Myanmar. The primary source of Platinum Group Minerals in Myanmar is not well identified but a rare amount of these minerals is found as placer deposits in Indawgyi area, Kachin State and their primary source may probably be related to basic igneous rocks such as gabbroic rocks. The only source of copper in Myanmar is in the central volcanic belt. The oxide ore of nickel and chromite are found in association with ultrabasic rocks of the ophiolite suite of the western fold belt of Myanmar. In the Northern Shan state of Myanmar, the Bawdwin mine has been the main resource of base mineralization as a lead-zinc-silver deposit by VMS Style while the Bawsaing mine is recognized as lead-zinc-silver MVT style in Paleozoic carbonate rocks. The potential resources of this base metal mineralization may occur in Paleozoic carbonate sediments in the Sibumasu terrane of the eastern part of Myanmar, especially in the Northern and Southern Shan States. The deposits and potential of tin-tungsten are defined as both primary and very limited secondary deposit types associated with S-type (or) ilmenite series granite in the eastern and southern parts of Myanmar which may probably be related to the granitic rocks emplaced during the Tertiary, and the country rocks of these consist of the clastic metasedimentary rocks of Carboniferous-Permian age. The iron ore deposits of Northern Shan State are mostly residual type, at Pang Pet, Southern Shan State, the iron ore deposit is represented by primary hematite mineralization bounded in two regional fault systems in the Permian limestone seem hydrothermal source. The iron occurrence at Kathaing Taung, near the Phakhant jadeite mine area, and the Shwegu area in Kachin state are related to the ultramafic rocks. The majority of antimony mineralization occurs in the late Paleozoic carbonates (Triassic-Permian in age), and is generally found in veins or lenses, or both, the best-known antimony deposit as a stratabound type is at Thabyu area, Kayin State, near Thailand border while several antimony occurrences are found in the late Paleozoic clastic sediments at Kayah State and Mandalay Regions.

5. Conclusion

Myanmar is now focusing on the exploration of critical minerals, especially lithium and rare earth elements (REEs), and some potential area, along Mogok Metamorphic Belt in Yamethin-Thazi-Pyawbwe-Myitthar east is under preliminary exploration. Although Myanmar has some potential areas for critical minerals, detailed research works are still needed. In this study, we have described occurrences of critical minerals and elements including the potential areas of critical minerals in Myanmar which are awaiting detailed research.

Acknowledgments

The authors wish to express gratitude to Coordinating Committee for Geoscience Programmes in East and Southeast Asia-CCOP allowing us to present this title to the Thematic session. We wish to extend gratitude to D.G.S.E members, for their valuable advice, help and supporting work for this research. We also wish to express our sincere thanks to the Ministry of Natural Resources and Environmental Conservation, Myanmar for allowing us to present this manuscript.

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Thai Geoscience Journal
Vol. 4 No. 5
January 2023
ISSN 2730-2695

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Published by
Department of Mineral Resources
Geological Society of Thailand
Coordinating Committee for Geoscience Programmes in East And Southeast Asia (CCOP)

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Thai Geoscience Journal website at http://www.dmr.go.th/