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Geological interpretation based on satelite imagery: Updating geological maps of Indonesia to 1:50,000 map scale

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Abstract: Indonesia is an archipelago comprising over 13,700 islands and a total territory of more than seven million km^{2}. Geologically, the earth's crust in this region displays several special features as a result of the collision of three mega plates, Eurasia, Indiaustralia and Pacific. Inter-related features such as island arcs, volcanic belts, seismic zones, gravity anomaly zones, and deep sea trenches resulted from the collision process.

Knowledge of the regional geology of the entire Indonesian region was greatly advanced by the completion of systematic geological mapping at the scale of 1: 100,000 of Jawa and Madura Islands and at the scale of 1:250,000 on the other islands. A great quantity of data concerning various aspects of geology and geophysics, collected during more than 50 years, has accumulated.

The need for geological information at a larger scale, however, is now increasing. This demand is related to national development programs as well as to Indonesia's industrial growth. Exploration for energy, mineral and ground water resources, the generation of information for land-use planning and geological hazard mitigation will all benefit from the availability of geological maps at the scale of 1:50,000. Therefore, since 2010 the Geological Agency, Ministry of Energy and Mineral Resources of Republic of Indonesia, has initiated new geological mapping project starting with geological interpretation based on data from satellite imagery combined with existing field data.

The methodology for geological interpretation is based on visual interpretation of remote sensing data of morpho-structural aspects of the imagery combined with field data existing in a GIS environment. Interpretation keys were determined in order to provide guidelines on how to recognize certain geological objects on satellite imagery. Preparation of data including the creation of shaded relief of the digital surface model (DSM) and intensity layer of orthorectified images (ORRI), contour generation, color composite of optical images, drainage pattern generation and fusion of passive and active remotely-sensed images.

Keywords: geological map, remote sensing, Indonesia

BACKGROUND

Indonesia is the largest archipelagic country in the world, which has five major islands and about 300 smaller island groups. Altogether there are more than 13,700 islands. The archipelago is situated at a junction between two oceans, the Pacific and Indian oceans, and bridges two continents, the Asian and Australian continents. Indonesia has a total area of 9.8 million km^2, of which more than 7.9 million km^2 is ocean.

From the point of view of earth science, Indonesia has various unique geological phenomena due to its location at the triple junction of three mega-plates: Eurasia, Indiaustralia and Pacific (Figure 1). The involvement of these three mega-plates interaction with each other, has resulted in the formation of double island arcs, K-shaped islands, active volcanic belts, active seismic zones, deep sea trenches and the negative gravity anomalies. Morphologically this condition has resulted in a distinct and varied relief with high mountain belts, deep valleys, and high cliffs. Moreover, due to this complex geological history, Indonesia also has a huge amount of geological resources including oil and gas, coal, gold, diamonds, iron, nickel and other mineral resources such as clay and gem stones. However, the potency of geo-hazards such as earthquakes, landslides, volcanic activity, floods and tsunami are also a major concern.

The knowledge of the regional geology of the entire Indonesian region has been greatly advanced following the completion of systematic geological mapping in 1995. Much data concerning all aspects of geology and geophysics has been acquired during more than 50 years of geological mapping. From the compiled geological data, it is possible to perceive the distribution of various kinds of rock units ranging in age from Palaeozoic, through Mesozoic to Cenozoic. The rock units consist of sedimentary, carbonate, and volcanic rocks which are subdivided into broad groups based on their ages, respectively; Quaternary, Tertiary, and Pre-Tertiary ages. In addition, based on the rock lithology and origin, some rocks are grouped into plutonic, ophiolite, metamorphic and mélange rocks (Figure 2).

DEVELOPMENT OF GEOLOGICAL INFORMATION

The Center for Geological Survey, one of the units of the Geological Agency of the Ministry of Energy and Mineral Resources, continues its activities in mapping and research on various aspects of geology and geophysics in the entire Indonesian region, which originally was initiated

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in 1850 by previous research institutions. The results of the research, investigation and mapping have become national assets represented by all the the geological and geophysical data which are collected in the Geological Museum and Library within the Center for Geological Survey of the Geological Agency that was established in 1979.

The above activities in mapping and research of many aspects of geology and geophysics were diversified and reinvigorated with the commencement of the Indonesian Five Year Development Plan in 1969. Systematic mapping which initially was only applied to geology and geophysics, were later been applied to construct other thematic maps, such as seismotectonics, geomorphology, and Quaternary geology. The research in aspects of geology and geophysics also includes topics such as paleontology, sedimentology, petrology, geochemistry, gravity, paleo-magnetics, radiometric dating, rock physics, and structural geology.

Indonesia has now succeeded in the completion of systematic geological mapping at the scale of 1:100,000 in Jawa and Madura Island and 1:250,000 in the islands outside Jawa and Madura together with the 1:1,000,000 map of the entire Indonesian region. Based on these systematic maps, geological and thematic maps at the scale of 1:5,000,000 have been compiled.

The need of geological information in Indonesia at a larger scale is now increasing. This demand is related to national development programs as well to Indonesia's industrial growth. Exploration for energy, mineral and ground water resources, information required to aid land use planning and geological hazard avoidance and mitigation are all issues that argue for the development of geological maps at the scale of at least 1:50,000. In order to answer this demand, the Geological Agency as an Institution that is responsible for geological survey, has been conducting geological mapping program, which is planned to last from year 2010 until 2025. This program was initiated employing geological interpretation based on satellite imagery combined with field data collected during from previous work. Later on, validation will be conducted with ground truth in addition to stratigraphic study and the collection of new field data.

Table 1: The extent of geologic units on land (1,925,814 km^2), calculated using grid by Handoko (Sukamto, 2000).

No.	GEOLOGICAL UNIT	EXTENT (± km^2)
1	Quaternary sediments	570,798
2	Quaternary carbonates	15,811
3	Quaternary volcanics	140,860
4	Tertiary sediments	474,513
5	Tertiary carbonates	119,877
6	Tertiary volcanics	118,349
7	Tertiary-Cretaceous Sediments	98,229
8	Mesozoic sediments	99,901
9	Mesozoic carbonates	18,344
10	Mesozoic volcanics	21,204
11	Paleozoic rocks	45,783
12	Metamorphic rocks	82,247
13	Plutonic rocks	66,442
14	Melange rocks	31,115
15	Ophiolitic rocks	36,970

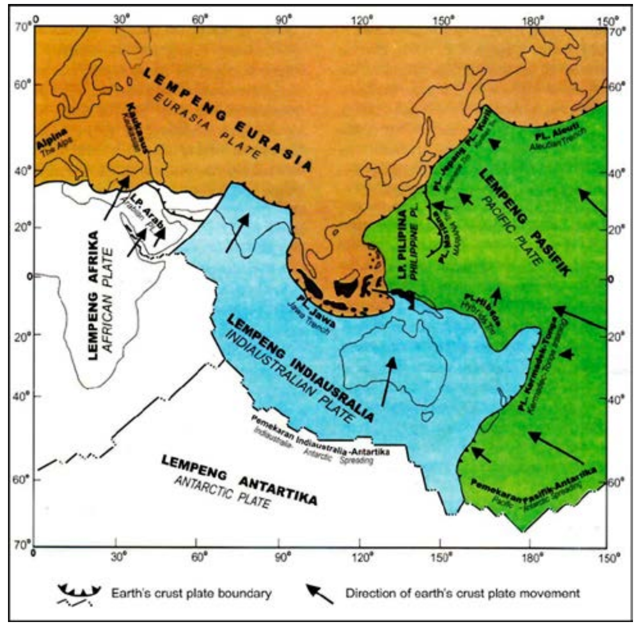

Figure 1: Indonesian archipelago location at the triple junction of three mega plates, Eurasia, Indiaustralia and Pacific, modified from Le Pichon (1968).

CURRENT KNOWLEDGE ON THE GEOLOGY OF INDONESIA

The large quantity of geological and geophysical data which are stored in the Geological Agency, Ministry of Energy and Mineral Resources, is a national asset that should be utilized by the broad geoscience communities, domestic as well as international. Investigation, research and mapping of the geology and geophysics during eight periods of Indonesia's Five-Year Development plans (1960-1999) contributed very considerable and available data resources. Systematic geological maps at a scale of 1:100,000 for Jawa and Madura, 1:250,000 for islands outside Jawa and Madura, and scale 1:1,000,000 for the entire Indonesian region are now available. The Geological Map of Indonesia at a scale of 1:5,000,000 has also been published (GRDC, 1992).

The simplified geological map of Figure 2 shows the distribution of the geologic units on land which covers an area of 1,952,814 km^2. The extent of each geologic unit is measured on the basis of the distribution of the unit which appears on the Geological Map of Indonesia at scale 1:5,000,000 (GRDC, 1992). The extent of each geologic unit of Quaternary, Tertiary, Mesozoic and Paleozoic age is shown in Table 1; including geologic units based on their rock association: metamorphic rocks, plutonic rocks, mélange rocks and ophiolitic rocks. This summary information about the geological units, based on the geological eras, is introduced here to give an insight into the potential for mineral and energy resources as well for geohazards that possibly may occur within each geological unit.

The distribution of these various geological units may be used in evaluating the veracity of the opinion that Indonesia remains well endowed with mineral and energy resources. Peat deposits, for example, have been estimated to be over

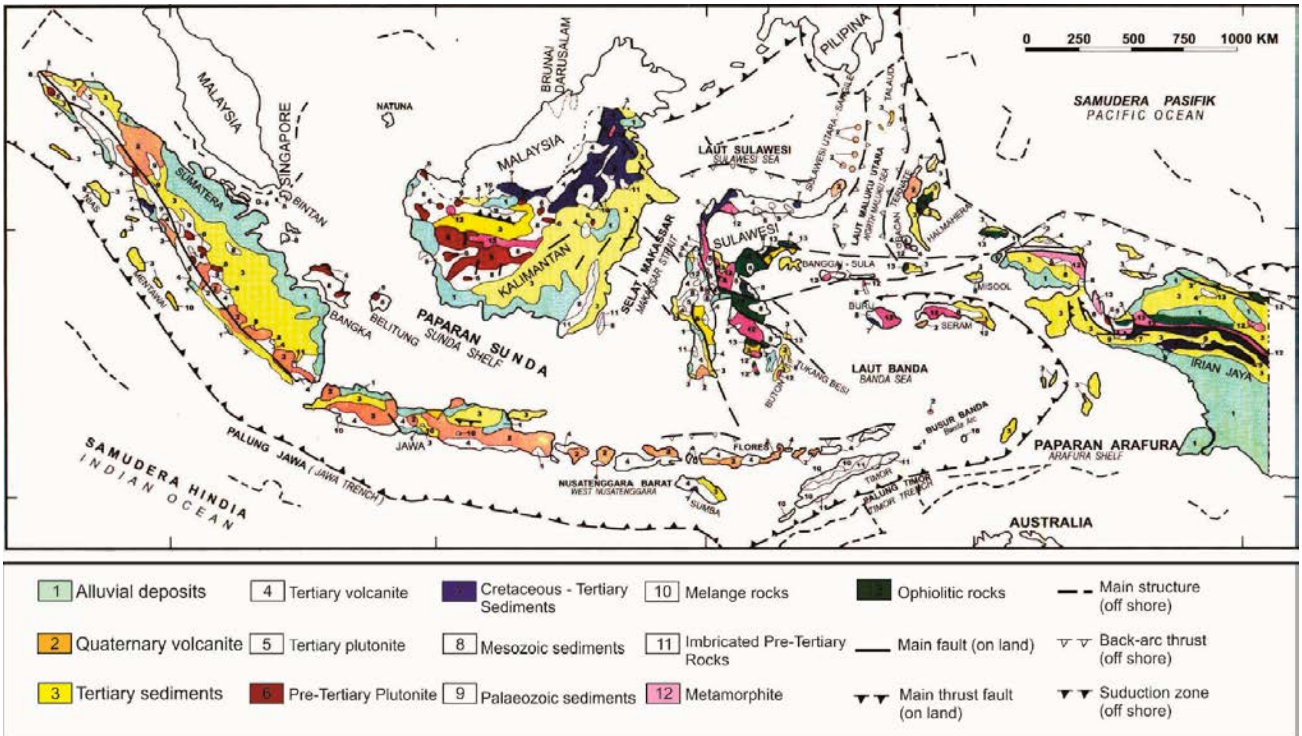

Figure 2: The geology of Indonesia simplified from the Geological Map of Indonesia, 1:5,000,000 compiled by Geological Agency (GRDC, 1992).

2 m thick over a total area of 88,015 km^2 in Sumatera, Kalimantan and Papua (Soedradjat *et al*., 1991) in areas ($\pm$570,798 km^2) underlain by Quaternary sedimentary rocks.

Coal which originally was estimated to have a reserve of $\pm$ 32.1 billion tons (Soedradjat *et al*., 1991), later rising to an estimated $\pm$36.34 billion tons (Suhala & Yoesoef, 1995), is found in Tertiary sedimentary rocks, which have an areal extent of $\pm$474,513 km^2. Tertiary sedimentary rocks can also be used to re-evaluate sedimentary basins that may contain hydrocarbon reserves. Quaternary, Tertiary and Mesozoic carbonate rocks as potential raw material for Portland cement and other industries are of very great extent ($\pm$154,032 km^2). Limestone layers may attain thickness of hundreds of meters, so that when the average thickness is estimated at only 100 m, the limestone would have a reserve of at least 39.28 trillion tons (specific weight 2.55). This figure is much higher than the previous estimated reserve of limestone which was only $\pm$ 20 billion tons (Soedradjat *et al*., 1991).

Various kinds of geological units of which the extent has been measured above may provide information for the further exploration of various kinds of metallic minerals, industrial minerals, coal and peat, petroleum and natural gas. More intensive prospecting is still needed to explore possible potential resources and this requires the detail provided by geological maps at a larger scale of 1:50,000. Such information on regional geology, which covers the entire Indonesian region is an asset that can be used in further investigation needed for mineral and energy resource evaluation, geohazards and land use planning decisions within a fully self supporting civil society.

RAPID MAPPING

In order to accelerate planning and to support national development, the Geological Agency as the institution responsible for national geological survey and mapping, proposed a rapid mapping programme to cover Indonesia's entire land territory from 2010 until 2025. This programme started with geological mapping based on interpretation of remotely-sensed data combined with existing data in a GIS environment. The programme is categorized as "rapid mapping" because the final target is to complete more than 3700 updated map sheets at the scale of 1:50,000 by 2015. Thereafter, the programme will be continued by a field campaign as a method of verification until 2025. Geological interpretation on the basis of remotely-sensed data combined with the large quantity of geological and geophysical data, which are stored in the Geological Agency can provide a fast and effective way to produce geological maps at the 1:50,000 scale. Combination of an optical dataset (e.g. Landsat ETM, ALOS DAICHI and ASTER) and synthetic aperture radar (e.g. IFSAR, Radarsat-2 and TerraSAR-X) should produce data of outstanding quality for analysing and extracting surface geological phenomena for geological interpretation maps.

The earths surface is composed of various lithological units which are reflected in morphological complexity because of the exogenous and endogenous geological processes involved. Morphological features and resultant landforms can be analyzed through field campaigns and also from remotely-sensed data. Interpretation of geological features from remotely-sensed data is aimed to collect geological information for further applications. There are some advantages of using such data as, for example, many remote areas and small islands can be examined quickly and without problems related to accessibility and difficult terrain. Such a rapid mapping program can therefore reduce both time and cost of obtaining detailed initial geological information. However, the program will still need validation in the form of a limited field campaign and the use of specific computer aided tools.

GEOLOGICAL AND TECHNICAL CHALLENGES

Development of geological information at larger scales (1:50,000) is a critical issue for the Geological Agency as the institution responsible for systematic national geological survey and mapping in Indonesia. However, resolving this issue involves many practical challenges for the researchers including the huge area of the Indonesian territory, its archipelagic setting, the complexity of its geology and the large number of remote areas involved. As mentioned above, rapidly acquired, remote sensed data can partly resolve some of these challenges.

The quality of the results of image interpretation depends on a number of factors: the interpreter, the image data used, and the guidelines provided. Professional experience, including experience of image interpretation determines the skills of an image-interpreter. A background in geological interpretation is essential in order for the interpreter to extract image features related to geological phenomena. Furthermore, local knowledge, derived from field visits, is required to help in the interpretation. Finally the quality of interpretation guidelines are a large influence, for example standards for the development of Indonesian geologic maps have an important role in ensuring the replicability of work.

Geological interpretation in a tropical terrain is often particularly challenging due to the dense vegetation cover in heterogeneous rain forest and the thickness of weathered soil that renders spectral information for the rock units beneath difficult to recognize. The technical challenge in geological interpretation was how to make the visual interpretation of remotely-sensed data of morpho-structural aspects combine with field data existing in a GIS environment. Interpretation keys needed to be established such as tone/hue, texture, shape, size, pattern, site and association which provide guidelines on how to recognize certain geological objects on satellite imagery. Other aspects used in geological interpretation were landforms, relief, drainage pattern, vegetation and land use.

The aim was to define and delineate the lithology of geological units and recognise geological structures that could be used to analyze and interpret sub-surface conditions and geological relationships. Geological sections relatively crossing or perpendicular to the main geometry of geological structures were made and represented at the surface by contours. Distributions of lithology in the subsurface were interpreted from trends and steepness of slopes as seen on the data images.

Updating geological maps to a larger scale in part focuses on further subdividing the existing mapped geological units by introducing new classes or categories of units. Lineaments, scarps and land offsets are assigned to geological structures which are categorized as faults, joints, calderas, and bedding traces.

CRITERIA DATA NEEDED

The use of remote sensing data for geological application has been applied by the Geological Bureau in Indonesia since the beginning of 1960. In the beginning, the remotely-sensed images were aerial photographs, which were analyzed with stereoscopes to extract information about the surface geology. Advanced technologies have led to the use of better remotely sensed data leading to higher accuracy, precision and detailed graphic and temporal resolution.

Some quality aspects regarding the remotely sensed data that are used during identification of geological features in the Indonesian archipelago are:

1. Technology must take account of the tropical climatic condition in Indonesia.
2. Sensors for data acquisition must cover optical and altitude information.
3. Up-to-date data acquisition and collection are of main concern.
4. Datasets are expected to be processed with the latest technologies in order to achieve a high quality standard of radiometric correction, geometric correction, enhancement, filtering, fusion, and classification.
5. Digital technology will ensure that data is easy to collect, process, duplicate, interpret, analyze, and store.

Several products that can meet acceptable quality standards in geological mapping applications and have been used by The Geological Agency are:

1. LANDSAT 7 ETM+; optical satellite observation with orbital height of 705 km, temporal resolution 18 days, swath 185 x 185 km, 7 bands with 30 x 30 m spatial resolutions and 120 m thermal band resolution. Cloud sensitive but having good spectral information for surface geological survey.
2. ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer; 16 bands of optical earth satellite observation with three sub system of 15 m spatial resolution in visible near infra red (VNIR), 30 m in short wave infra red (SWIR), 90 m spatial resolution in thermal infra red (TIR). This sensor can run oblique scanning to create three dimensional images or create a digital elevation model (DEM).
3. SRTM – Shuttle Radar Topography Mission; radar technology with 90 m and 30 m spatial resolutions. Sensors used are C-band and X-band with capabilities of three dimensional representation, cloud penetration, and active sensor which could operate in day and night.
4. IFSAR – Interferometry Synthetic Aperture Radar; an airborne radar technology with single-pass mode of acquisition. This sensor produce digital elevation model (DEM) and orthorectified radar image (ORRI). Using X-band technology with 3 cm of wavelength that can penetrate could, haze, dust, rain and night.

IFSAR type II, having spatial resolution of 5 m digital surface model (DSM) with 1 m vertical accuracy and 2 m of horizontal accuracy. Spatial resolution of ORRI product is 1.25 m with 2 m accuracy. IFSAR type I, having spatial resolution of 5 m DSM with 15 – 50 cm vertical accuracy and 1 m of horizontal accuracy. Spatial resolution of ORRI product is 0.625 m with 1 m accuracy.

5. Radarsat-2; Canadian satellite earth observation. Launched in December 2007. Radar technology in orbital height 798 km of sun-synchronous orbit and using C-band and multi polarization of HH, VV, HV and VH. Highest spatial resolution is 1 m in Spotlight Mode, 3 m in Ultra Fine Mode with 100 m position of accuracy.
6. TerraSar-X; German satellite earth observation. Launched in June 2007 and operated since January 2008. Radar technology using X-band and multi polarization of HH, VV, HV and VH. This sensor can operate in day and night and in all weather conditions. TerraSar-X is having 11 days of temporal resolution and 1 m of spatial resolution. There are three modes of data acquisition of TerraSar-X: Spot Light with 1 m of spatial resolution and swath 5 km x 10 km, Strip Map with 3 m of spatial resolution and swath 30 km x 50 km and finally Scan SAR with 18 m of spatial resolution and swath 100 km x 150 km.

METHODOLOGY

Geological interpretation based on remotely sensed data required datasets which contain specific information on the earth's surface. Spectral, altitude and terrain data combined with secondary data regarding morphology, lithology, location of observation, rock units, geochemistry, measurements of strikes and dips and other local attributes comprised the main information used to develop the geological maps. In order to achieve a better performance in interpretation work, it was necessary to develop all information into a database format and process in a GIS environment. Airborne and satellite images, field data, and other secondary data were prepared before geological interpretation started and finally compiled in a preliminary geological map based on remote sensing data interpretation (Figure 3).

Spatial Data Preparation

Preparation of data included the creation of shaded relief of the digital surface model (DSM) and intensity layer of orthorectified images (ORRI) taken from satellite radar images which are posted by 50 m to generate contours at a 25 m interval. Data preparation on optical images (Landsat ETM+7) included the creation of orthorectified images and color composites of R/G/B: 4/5/7 in order to highlight geological features in the areas of interest. Image fusion of active and passive satellite imagery was also undertaken in order to create datasets which have both spectral information and highly detailed terrain information. The drainage pattern provides an essential aid in morpho-structural analysis and characterization of landform-lithology in geological interpretation and was derived from the digital surface model data by using particular hydro-enforcement software.

Development of Existing Data

A great deal of data from various aspects of geology and geophysics had been accumulated over the previous fifty years. However, development of an inventory of such a great amount of data can be a problem. Data collections which are stored in the library are mostly only available in non-digital format and must be converted into digital data in the form of vector and raster layers together with data attributes.

Building a geological database system referred firstly to broad geological information in particular areas and further pursued into local specific geological information. A database inventory was collected and stored with the information content including information on regional geology, physiography, stratigraphy, geological structures, tectonic setting, and energy and mineral resources. Specific data wers stored in vector format in the following hierarchy: project (Prj_ID), map sheet number (sheet_ID), region (region_ID), location number (loc_ID), formation (Fm_ID), symbols (symbol_ID), group (group_ID), class lithology (litho_ID), environment (en_ID), era, period, epoch, fossil, remarks, storage number (sto_ID) and references.

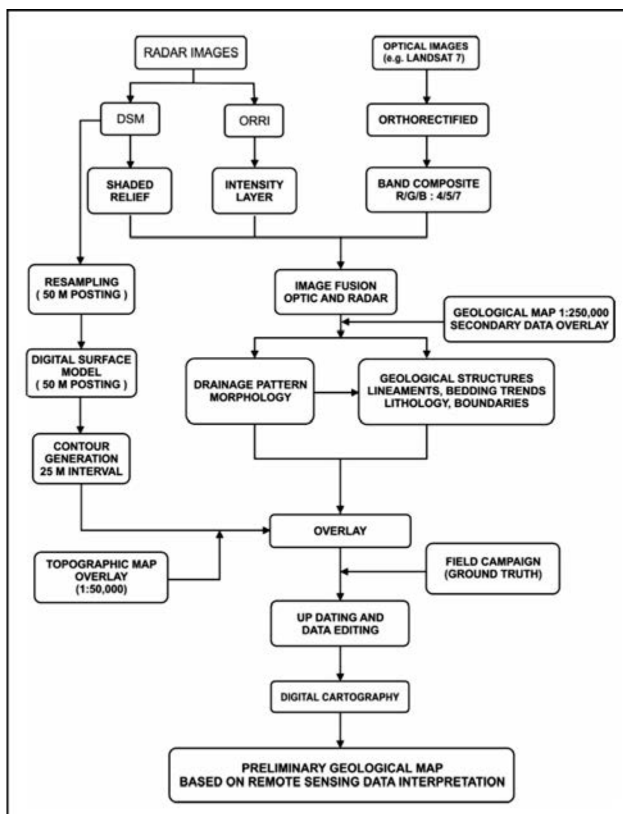

Figure 3: Flow chart in updating geological maps of Indonesia to 1:50,000 map scale.

Development of the data base into a GIS environment was necessary in order to support the geological interpretation work and ensure that geological interpretation met a good quality standard and used valid and precise information.

Geological Interpretation

Geological interpretation based on satellite images was done by visual interpretation with computer aided software. Specific computer software was used with capabilities of digital image processing, modeling, three dimensional visualization, hydro enforcement, and other visual enhancement techniques. Overlays of various datasets including field data in the form of vector data from previous projects were combined to analyze and develop a preliminary geological map. The interpretation was conducted by overlaying information layers from vector and raster data to extract new detailed geological information.

The method of interpretation was to describe morphological features in a particular area, define the landform genetics, and group into geo-morphological classes. Key elements are shape, pattern, relief, drainage, vegetation and dimension of a particular morphology. Furthermore, other geological features were analyzed on the imagery to differentiate and delineate lithologic units or rock units. Optical satellite images can help to determine relatively younger and older formations or rock units. Combination with high resolution radar images may help to recognize sediments, intrusions, alluvial deposits, metamorphic rocks, and volcanic deposits.

Validation and Ground Truth

Ground truth and stratigraphic surveys were undertaken for some area of interest which are believed to be key area in order to validate the geological interpretation results. For this purpose a limited number of objects or areas are selected and visited in the field. The data collected in the field is referred to as ground truth.

Geological interpretation results are inevitably subjective results, therefore it is necessary to validate and cross check the relationships of several 'interpreted' formations or rock units in the field. Field identification was also undertaken to collect new authentic data as well as for data validation in order to prove the interpretation results and to check the correlation of rock units or formations in a particular area.

Ground truth investigations were also conducted by visiting areas in which there was ambiguity in the interpretation of results. Furthermore, a more systematic survey was also undertaken by carrying out stratigraphic studies regarding rock formations that have already been interpreted. Survey lines were prepared in order to make new geologic cross sections of the interpretation maps at 1:50,000 scale. The data records that were collected during field survey contain information of station number, date, scale, formation, lithology, thickness, texture, sedimentary structures, composition, fossils, color, strike/dip, sample number, remarks and other descriptive information as thought necessary. All data records were compiled and added as a new information layer in geological interpretation map in order to develop a preliminary geological map at 1:50,000 map scale.

Digital Layout

Geological interpretations based on remote sensing data were prepared in a digital map format at 1:50,000 scale. The information includes boundaries of rock units, geological structures, satellite/airborne imagery a as base map (both optical and radar data), the geological map at 1:250,000 scale as reference data, topographic map, and legend containing geological symbols (Figure 6).

UPDATING GEOLOGICAL MAP AT 1:50,000 MAP SCALE

The project has so far been conducted for two years starting from 2010. Until now it has produced geologic interpretation maps for at least 1700 map sheets. The areas covered areas are Sulawesi, Kalimantan, Bali, Nusa Tenggara and Papua Island. Preparation of the maps in digital layouts was done in 1:50,000 scale. The maps are represented as geological maps based on interpretation of remote sensing data (Figure 4).

In the year 2010 geological interpretation was done for Sulawesi, Bali, and Nusa Tenggara Island with the completion of more than 750 map sheets. The following

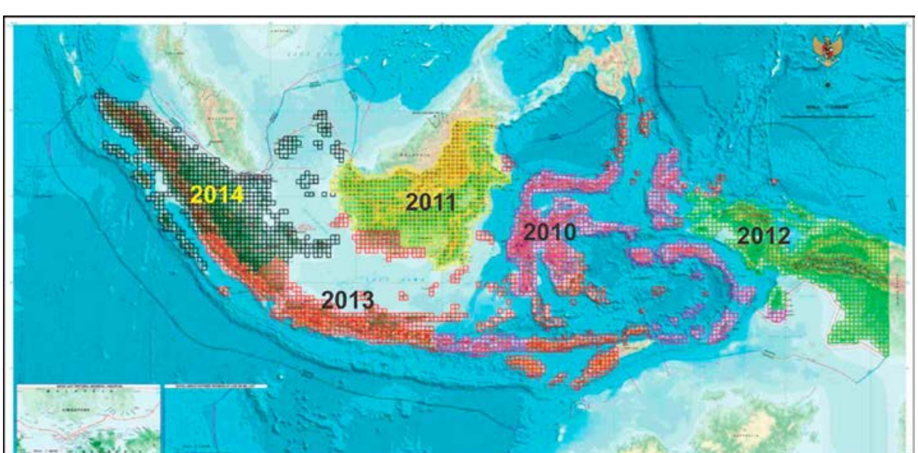

Figure 4: Planning for development of geological mapping based on remote sensing data interpretation (Sidarto, 2010).

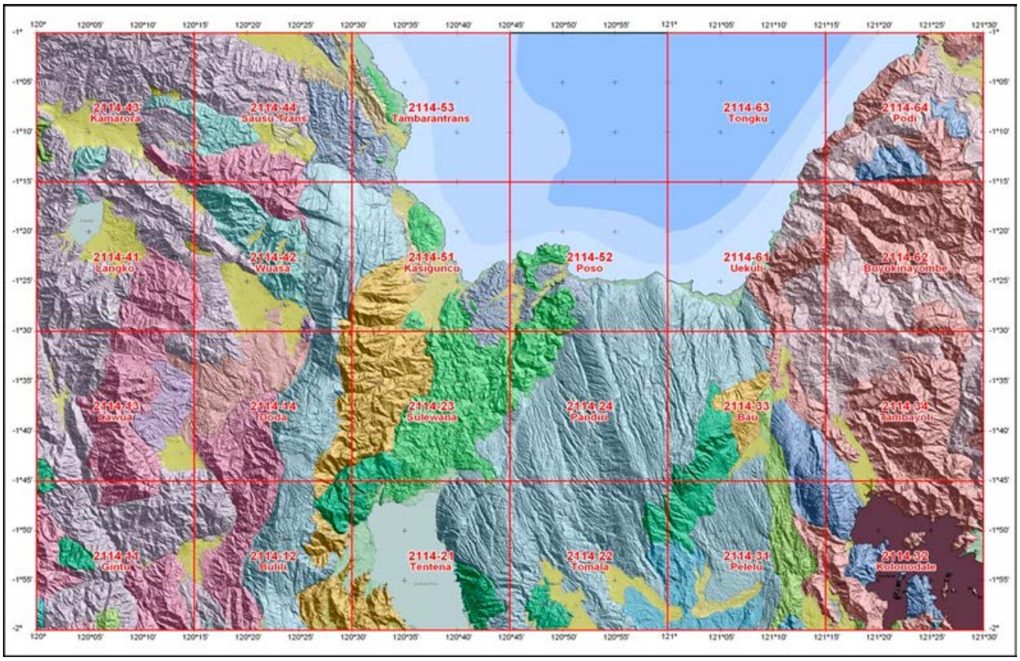

Figure 5: Updating regional geological map of 1:250,000 map scale into detailed 1:50,000 map scale.

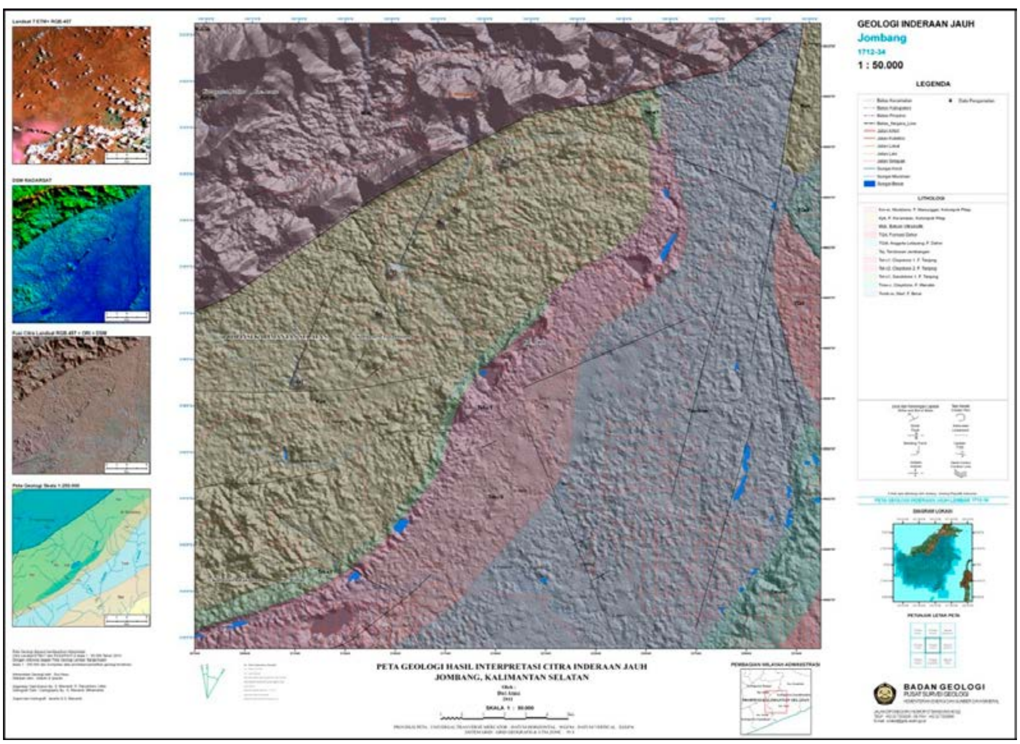

Figure 6: Layout of geological map based on remote sensing data interpretation at 1:50,000 map scale.

year (2011) geological interpretation was done for the island of Kalimantan with the completion of more than 800 map sheets. By mid 2012 the completed geological interpretations have produced more than 200 map sheets which cover Papua Island.

Creation of the larger map scale (1:50,000) divides a sheet of the regional geological map at 1:250,000 scale into 24 sheets of the new geological maps (Figure 5). There are several improvements in the updated geological map of Indonesia regarding detailed information on boundaries of rock units. As compared to the previous geological maps (1:250,000 map scale) rock formations can be divided into several lithological units or rock types. For example, in the new geological interpretation map a sedimentary formation may be subdivided into sandstone, clay and conglomerate/ coarse sandstone. Formations of volcanic rocks may be divided into several classes as lava flows, volcanic breccias, tuffs and lahars. In addition, it may be possible to gain more information on the source of eruption.

Other improvements in geological interpretation at 1:50,000 map scale are the recognition of geological lineaments which appear as minor structures in the imagery but could not be found in the field. These were successfully mapped as faults, anticlines and synclines and categorized as new geological information in the interpreted maps. This can be used to describe and to explain the detailed tectonic setting in local areas.

CONCLUSION

The methodology for updating existing geological maps to 1;50000 scale has depended on geological interpretation that is based on visual interpretation on remote sensing data, which means that all the interpretation results still need to be validated in the real world. It is therefore necessary to mount a field campaign to cross check the relationships between classes of interpreted rock units and define them based on new and authentic data.

The quality of the result of an image interpretation depends on a number of factors: the interpreter, the image data used, and the guidelines provided. The professional experience and the experience of image interpretation determine the skills of an image-interpreter. Therefore, it is important to define interpretation keys, which provide guidelines on how to recognize certain geological features on satellite imagery and to establish standardization for development of Indonesian geologic maps, thus ensuring the reproducability of the work.

These new geological interpretation maps are not standard geological maps; they are preliminary maps providing guidelines for conducting detailed geological mapping and selecting the priority areas throughout Indonesia in order to accelerate the needs of geological information for national development purposes.

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