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A scientific Journal published by Indonesian Sedimentologists Forum (FOSI), a commission of the Indonesian Association of Geologist (IAGI)

Berita Sedimentologi was first published in February 1996 as a newsletter for the members of the Indonesia Sedimentologists Forum (Forum Sedimentologiwan Indonesia or FOSI) only. In its first year, Berita Sedimentologi was published in Indonesian language, then from 1997 onward this publication uses English as the language of communication.

Frequency of publication is 3 issues per year, usually published in April, August and December of each year.

Topics cover sedimentology and stratigraphy of both siliciclastic and carbonate rocks, depositional processes, but also cover biostratigraphy, geochemistry, basin analysis, geodynamics, petroleum geology and structural geology.

From the Editor

Dear Readers,

Welcome to **Berita Sedimentologi Vol. 48 No. 1**! In this issue, we will cover topics about the geology of the Sulawesi Island, which is a unique, K-shaped island created by complex geological evolution. The Sulawesi Island consists of 4 mountainous arms that are surrounded mostly by deep sea. The present-day seabed around the island records some offshore structural elements and depositional features which form due to active tectonic and sedimentation in the region. The seabed features are imaged in detail by modern high resolution bathymetric data and are included here in two papers.

You can find a comprehensive review of the tectonic evolution of Sulawesi and morpho-bathymetric features of Southwest Celebes Sea that use the multibeam data in the first two papers. Then the next one is about kinematic analysis of Balantak Fault, which is the boundary between Banggai-Sula continental fragment and East Sulawesi Ophiolite (Central Sulawesi province). We also include a short note on abiogenic gas seepage at Tanjung Api, Tomini Bay. This short note provides an example about the presence of abiogenic gas in Indonesia and hopefully it generates more interest to its potential in Indonesia. The last 2 papers in this issue are a historical article about geological investigations in Sulawesi before 1930 and an analysis of post-earthquake groundwater potential in the Mamuju Regency, West Sulawesi.

The next issue of Berita Sedimentologi will be about Moluccas and Halmahera Islands. We plan to publish this issue in September 2022 therefore we invite potential authors to send manuscripts to us. Please visit our journal website for more information about submission guidelines. Manuscripts are accepted until mid/late August.

See you in the next issue.

Minarwan
Editor-in-Chief

Cover Photograph:

Outcrop of ultramafic rocks, Pulau Dua (Dua Island), Central Sulawesi Province. This ultramafic rock outcrop is part of the East Sulawesi Ophiolite (photo by courtesy of A.M. Surya Nugraha).

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About FOSI

The forum was founded in 1995 as the Indonesian Sedimentologists Forum (FOSI). This organization is a communication and discussion forum for geologists, especially for those dealing with sedimentology and sedimentary geology in Indonesia.

The forum was accepted as the sedimentological commission of the Indonesian Association of Geologists (IAGI) in 1996. About 300 members were registered in 1999, including industrial and academic fellows, as well as students.

FOSI has close international relations with the Society of Sedimentary Geology (SEPM) and the International Association of Sedimentologists (IAS).

Fellowship is open to those holding a recognized degree in geology or a cognate subject and non-graduates who have at least two years relevant experience.

FOSI has organized three international conferences in 1999, 2001 and the most recently in 2018.

Most of FOSI administrative work will be handled by the editorial team. IAGI office in Jakarta will help if necessary.

The official website of FOSI is:
http://www.iagi.or.id/fosi/

FOSI Membership

Any person who has a background in geoscience and/or is engaged in the practising or teaching of geoscience or its related business may apply for general membership. As the organization has just been restarted, we use **LinkedIn** **(www.linkedin.com)** as the main data base platform. We realize that it is not the ideal solution, and we may look for other alternative in the near future. Having said that, for the current situation, LinkedIn is fit for purpose. International members and students are welcome to join the organization.

ABOUT THIS GROUP

FOSI was established in 1995 and became a commission of IAGI (Ikatan Ahli Geologi Indonesia/Indonesian Geologists Association) few years later. The association is aimed as a discussion forum for Sedimentologists in Indonesia, to share experience and knowledge amongst the members. Through the network with international organizations, such as SEPM and IAS, FOSI tries to put Indonesian sedimentary geology into broader perspective.

FOSI Group Member as of June 2022:

1,001 members

Including Yudistira Effendi and 213 other connections

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Enigmatic Sulawesi: The Tectonic Collage

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ABSTRACT

Sulawesi has a complex tectonic history that is affected by major plate re-organisations during the Cenozoic resulting in an extension-dominated setting in an overall setting of convergence of the Indo-Australian, Pacific and Philippine Sea, and Eurasian plates. It is a complex collage of disparate tectonic terranes brought into juxtaposition by a variety of tectonic processes which have occurred at very fast rates. The island is subject to a variety of geohazards related to earthquake and volcanic activity.

Keywords: Sulawesi, tectonic, evolution

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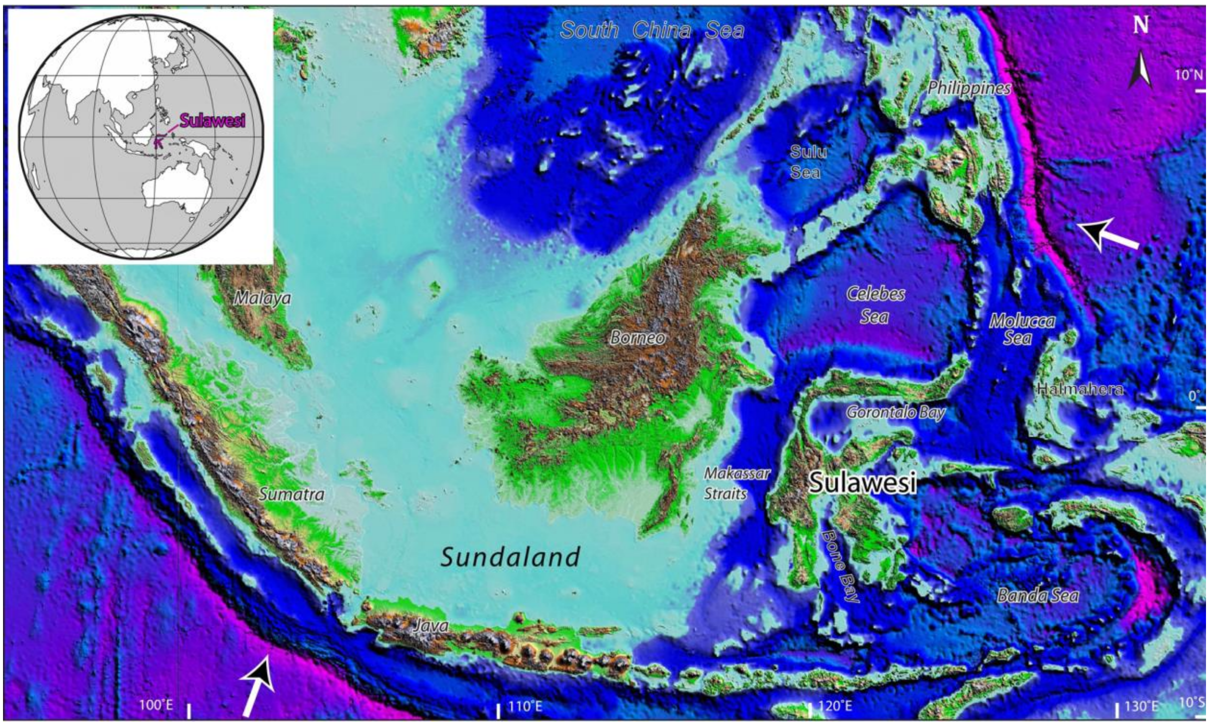

Figure 1: *Sulawesi Locality Map; major plate motions relative to Sundaland indicated (modified after Hennig et al., 2017).*

INTRODUCTION

Located between Borneo in the west and the Moluccas in the east, the K-shaped island of Sulawesi (Figure 1) is the largest island in Wallacea (Hall, 2012a), the series of islands stretching between the Eurasian and Australian continental plates. Sulawesi, comprising four long, narrow mountainous arms separated by deep bays, is the spiritual heartland of Wallacea as it was here that Alfred Russell Wallace first recognised the spectacular divide between Asian and Australo-Pacific biogeography and set up the resultant "Wallace Line" to the west of Sulawesi in the Makassar Strait.

Rapid geographic changes have occurred throughout Wallacea over the last 100 million years. The biogeographical complexity reflects significant changes in vertical and horizontal distribution of land and sea which in turn reflects the complex geological history, largely driven by subduction and strike-slip fault movements.

Sulawesi has a remarkable biodiversity, a gloriously rich endemic fauna, and complex geology that has attracted natural scientists since the 19th century (Nugraha and Hall, 2018). Plate tectonic hypotheses and tectonic reconstructions for many years interpreted the region in terms of multiple collisions but there have been significant changes in our understanding of Sulawesi's geology in recent years, in particular the importance of Neogene extension as have the timing and speed of change

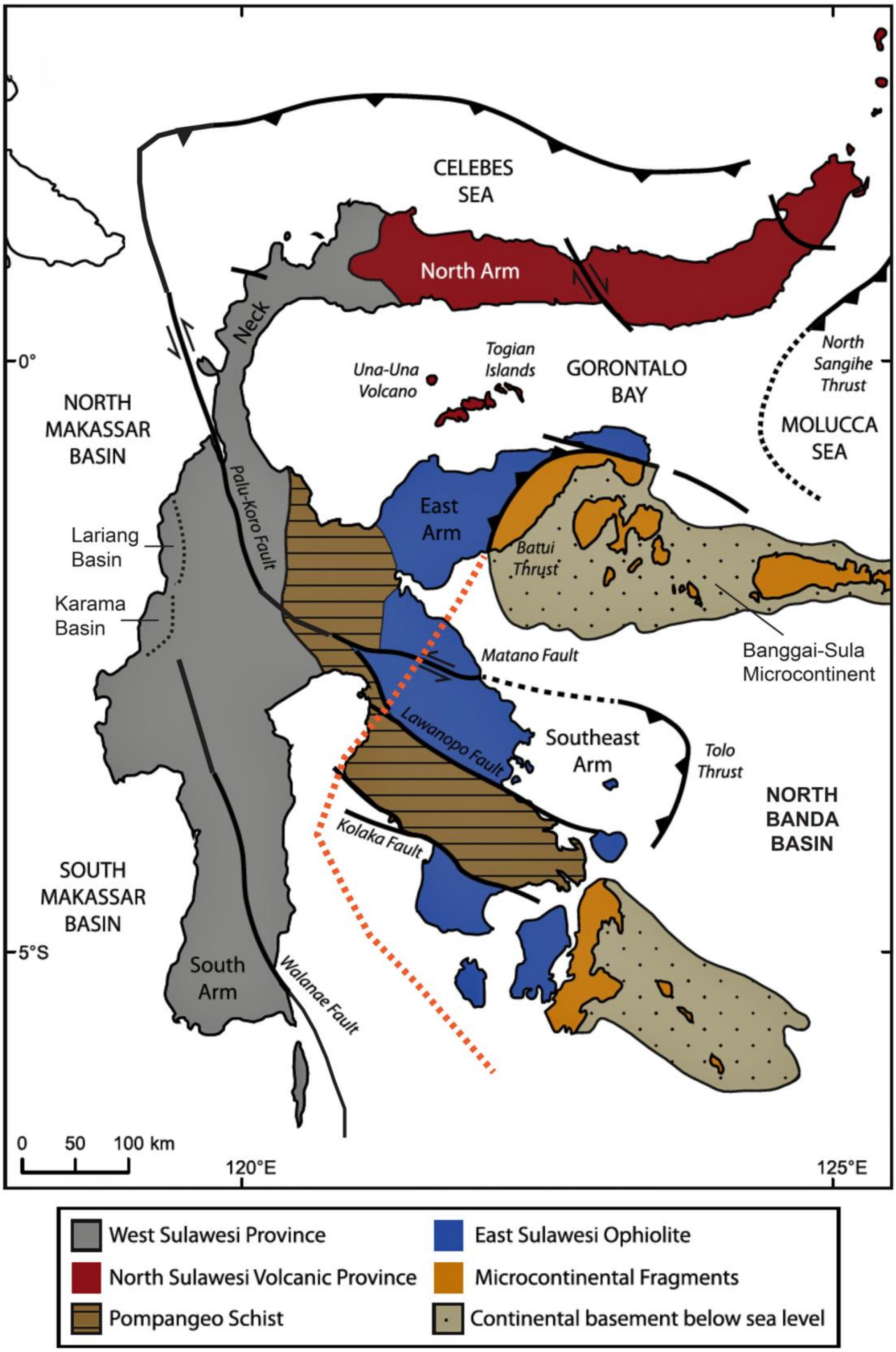

Figure 2: *Major geological units and faults of Sulawesi (modified after White et al., 2014). Orange dotted line indicates limit of "Australian" continental crust (after Hall et al., 2017).*

which led to the formation of the island's high mountains and deep basins (Nugraha and Hall, 2018).

In this paper, we provide a comprehensive summary of the geology of offshore and onshore Sulawesi utilising, where possible, modern high-resolution bathymetry to demonstrate recent and ongoing tectonics.

REGIONAL GEOLOGY

Sulawesi lies within Eastern Indonesia in a highly complex and dynamic plate tectonic setting located at the meeting of three major tectonic plates – the oceanic/continental Indo-Australian, predominantly continental Eurasian and oceanic Pacific/Philippine Sea plates. As a result of plate interactions, a complex system of subduction, back-arc-thrusting, extension, and major transform zones have generated a composite assemblage of small marginal ocean basins and microcontinental blocks bounded by subduction zones, extensional margins, and major transcurrent faults (Hall, 1996). The region is extremely susceptible to seismic activity, and volcanic arcs line compressional tectonic boundaries.

On the eastern margin of Sundaland, Sulawesi consists of an intricate mosaic of Gondwana-derived fragments, obducted oceanic crust, high pressure metamorphic belts, island arc and continental margin igneous suites, and a variety of sedimentary sequences which were assembled during Late Mesozoic to Late Cenozoic times (Figures 2 & 3). Broadly, Sulawesi consists of two terranes; a western magmatic belt, paired with an eastern terrane comprising ophiolite, blueschist, and continental fragments (Sula and Buton microcontinents), the latter derived from the Australian continental plate. Tertiary collision between these microcontinents and Western Sulawesi has inactivated west-directed subduction south of the northern tip of Sulawesi, and has led to arc reversal, with renewed subduction from the North Sulawesi Trench (Soeria-Atmadja et al., 1999; White et al., 2017). From a magmatic perspective, Sulawesi can be sub-divided into four litho-tectonic provinces, namely: (a) the Western and North Sulawesi Plutonic-Volcanic Arc, located in the South Arm and West Sulawesi through the Neck and the North Arm; (b) the Central Sulawesi Metamorphic Belt, (c) the East Sulawesi Ophiolite Belt in the East Arm, and; (d) the Banggai-Sula and Tukang-Besi continental fragments in the Southeast Arm (Figure 2; Soeria-Atmadja et al., 1999; Maulana et al., 2020).

Intrusive rocks, varying in composition from granitic to gabbroic cover almost 20% of the island, with the largest concentrations occurring in western Sulawesi. These rocks and sometimes associated with gold and copper mineralization (e.g., Perello, 1994; Bergman et al., 1996; Elburg et al., 2003; Maulana et al., 2020).

“Basement” Rocks and Magmatism

The question of the age and origin of the “basement” rocks of Sulawesi remains the single most unresolved question in Sulawesi geology.

Much dating has been carried out recently and many previous assumptions have proved to be erroneous; many supposed Mesozoic or Palaeozoic rocks have been shown to be Neogene in age (Figure 4). Suffice to say, we are not aware of a single modern date which has been older than that previously assumed.

The rocks of Southeast Sulawesi include blueschists, intervening peridotites and other metamorphic rocks (including parts of the Sula Spur microcontinent). This apparently simple configuration of continent, accretionary complex, ophiolite, and continent has been interpreted to be mainly the result of convergence and accretion.

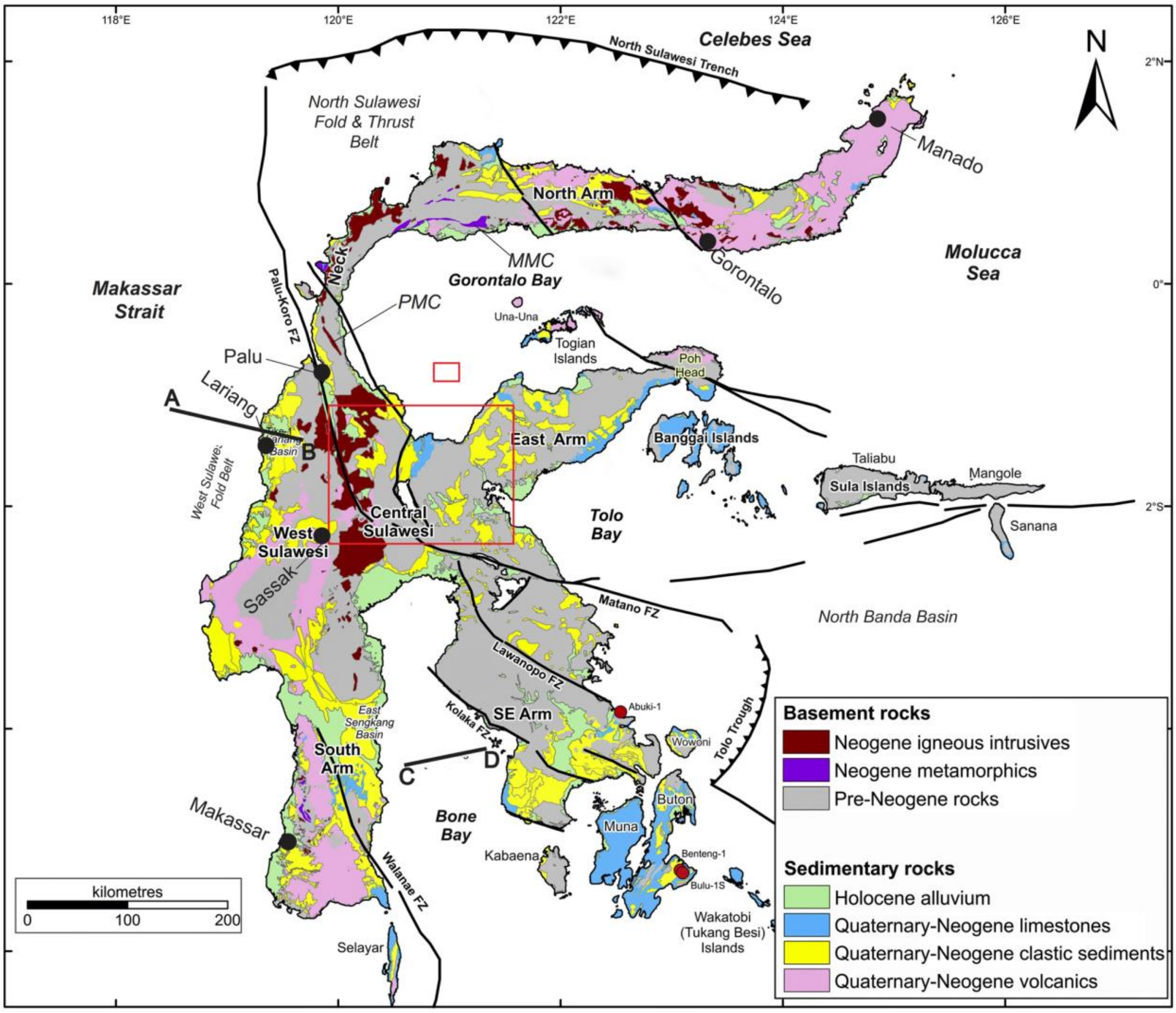

Figure 3: *Simplified geological map of Sulawesi with major structures and litho-tectonic units indicated (modified after Nugraha and Hall, 2018). Positions of Palu Metamorphic Complex (PMC) and Malino Metamorphic Complex (MMC) indicated. Line A-B indicates approximate position of the geoseismic section shown on Figure 6 and line C-D the seismic line on Figure 11. Small red rectangle in Gorontalo Bay marks position of Figure 10A; larger red rectangle in central Sulawesi marks position of Figure 10B.*

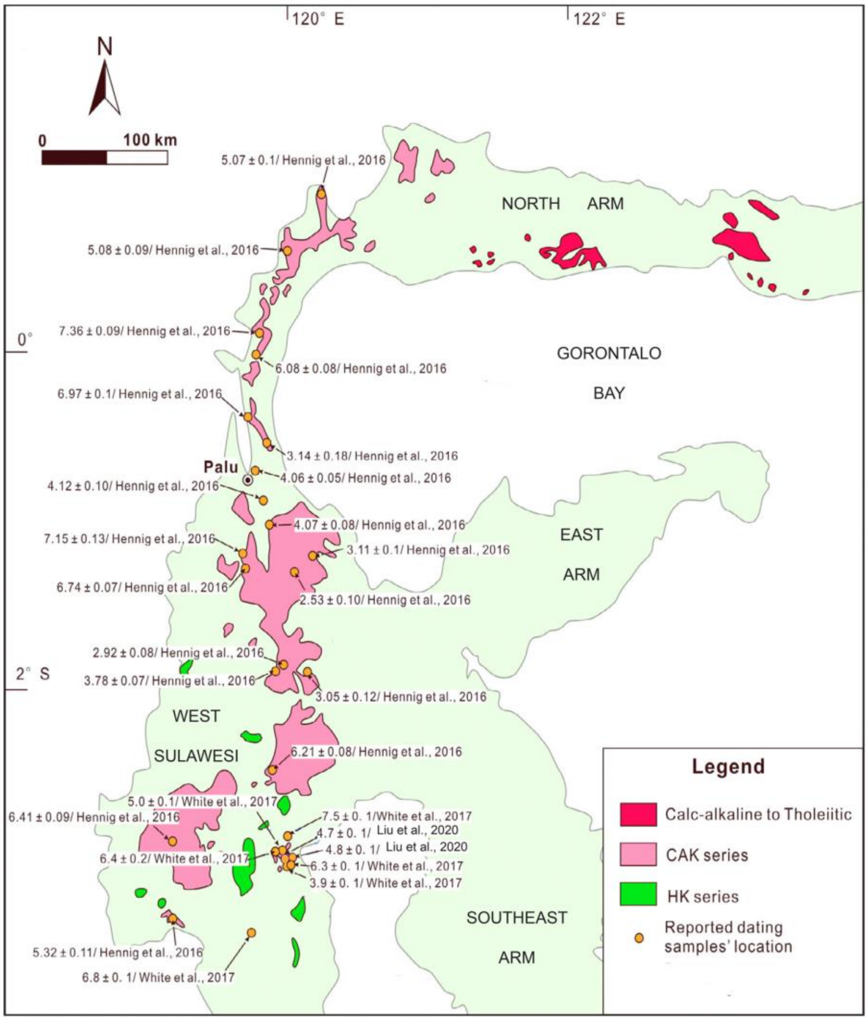

Figure 4: *Map showing distribution of late Miocene-Pliocene granitoids with dates (after Liu et al., 2020, incorporating dating reported by Hennig et al., 2016 and White et al., 2017); CAK = felsic high-K calc-alkaline suite, HK = mafic potassic to ultrapotassic suite.*

Metamorphic complexes in West and Central Sulawesi were emplaced or formed as consequence of mid-Cretaceous accretion of Australian continental fragments to Sundaland. During the Early Eocene western Sulawesi rifted away from Borneo forming the Makassar Strait at the same time as oceanic spreading in the Celebes Sea. From the Middle Eocene to Late Oligocene the North Arm Volcanic Arc formed as consequence of north-directed subduction of the Indian Ocean beneath the North Arm. In the Early Miocene, the East Sulawesi Ophiolite was emplaced by northwest - directed obduction during collision of the Sula Spur with the North Arm. The Central Sulawesi Meta-morphic Belt includes meta-morphic rocks associated with the ophiolite, the Sundaland margin and the Banggai–Sula Block. Regional extension, from Sulawesi eastwards, commenced in the Middle Miocene, associated with rollback of sub-duction into the Banda embayment. There was wide-spread magmatic activity in the Western Sulawesi Igneous Province, probably mainly extension-related, from the Middle Miocene producing high-K calc-alkaline acidic igneous rocks. Subduction of the Celebes Sea under the North Arm is interpreted to have started around 5 Ma, but the subduction is quite complicated with both southward and eastwards subduction and associated volcanism across the entire length of the North Arm. Subduction rollback of the North Sulawesi subduction zone initiated a new phase of extension in northern

Sulawesi which has been active until the present-day.

In West Sulawesi, there is no geological/geophysical evidence for oceanic subduction in the Late Miocene, with the magmatic flare-up occurring ~8 m.y. after the collision of the Tukang Besi-Buton microcontinent in the Middle Miocene and ~2 m.y. before the docking of the Banggai-Sula microcontinent in the Early Pliocene (Hall, 2002; Metcalfe, 2010).

Magmatic zircons in West Sulawesi yielded weighted mean ages of ca. 7.2–6.1 Ma. the preponderance of Late Miocene magmatism, showing a noticeable climax of magmatism (flare-up) at ~7–6 Ma that forms a continuous magmatic belt throughout West Sulawesi. The geochemistry indicates significant involvement of continental crustal materials in petrogenesis, in accordance with the common presence of Precambrian to Mesozoic zircons in the Late Miocene igneous rocks. This magmatic flare-up in West Sulawesi and coeval regional extension in eastern Indonesia are attributed to a resumed episode of slab rollback of the Banda slab into the Banda Embayment (Zhang et al., 2020).

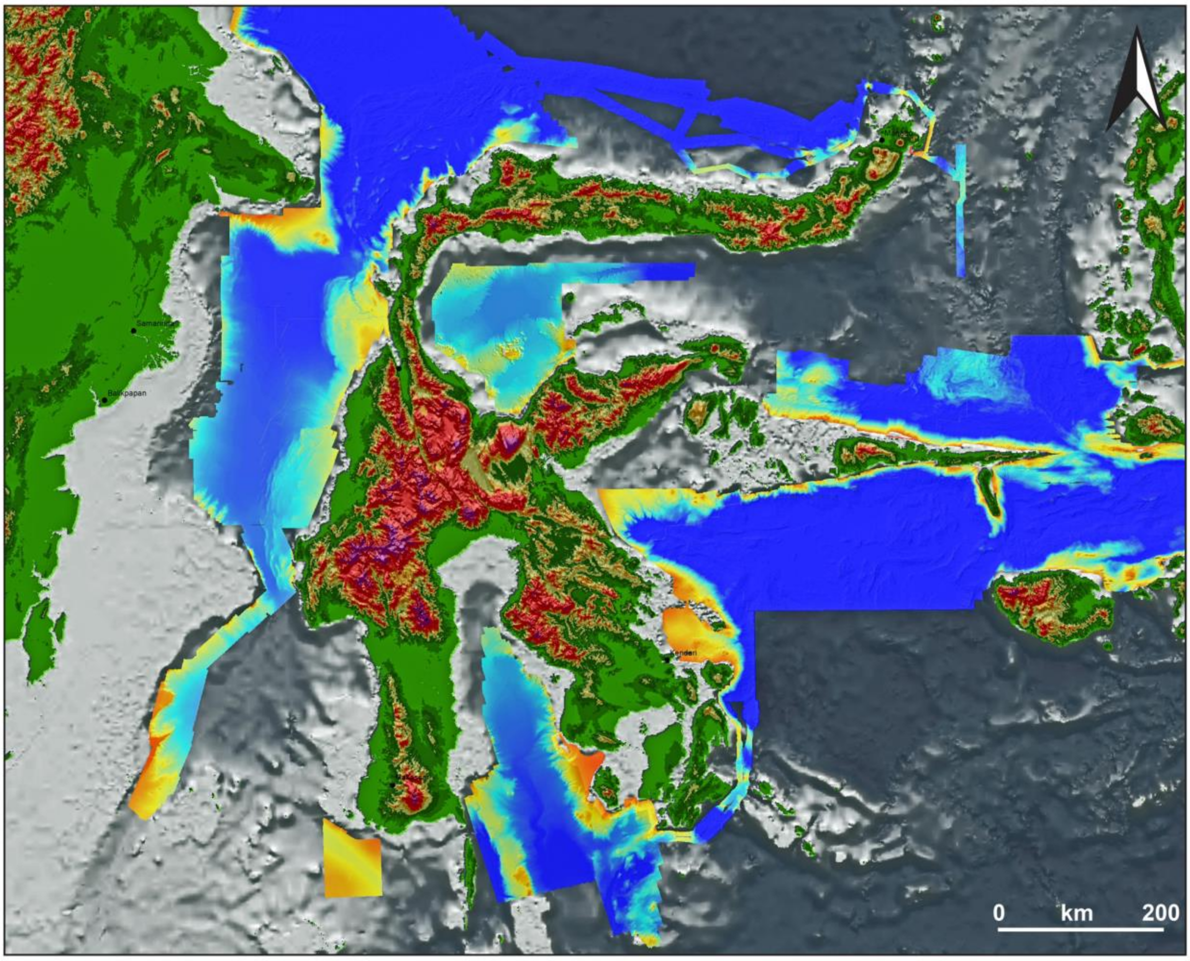

Figure 5: *Composite image of Sulawesi topography and bathymetry; compiled from available data.*

STRUCTURAL ELEMENTS

Sulawesi comprises numerous disparate geological units brought into (temporary) juxtaposition by tectonic movements. Figure 5 is a composite image of Sulawesi and its offshore areas utilising SRTM topographic and available high resolution bathymetric data. These data give a total topographic visualization of Sulawesi and provide a wonderful insight into neotectonics and offshore sedimentary features. Clearly evident on the figure are the emerging West Sulawesi Fold Belt on the eastern side of the Makassar Strait, strong linear features such as the Palu-Koro fault and other faults though central and southern Sulawesi, the deep extensional basins of Gorontalo Bay, Bone Bay and the North Banda Basin.

Several major structures may affect more than one litho-tectonic unit (Hamilton,1979; Silver et al., 1983; Parkinson et al., 1998). Included within these are a number of structures interpreted as strike-slip features, mostly with an inferred sinistral motion, while other major structures have usually been interpreted as compressional features; in the last decade large detached extensional faults have been recognised near the coast in central Sulawesi.

West Sulawesi (including South Arm)

West Sulawesi consists of a metamorphic basement overlain by Late Cretaceous turbidites that were deposited in a forearc setting (Figure 2). These are in turn covered by volcanic-sedimentary successions that were deposited during the early Middle Eocene to earliest Miocene (van Leeuwen and Muhardjo, 2005). It forms the (rifted) continental margin of eastern Sundaland with basement complexes of Gondwanan origin occurring in West Sulawesi and the South Arm. The microcontinental fragments rifted from Australia in the Jurassic and accreted to Sundaland in the Cretaceous and developed in a continental margin setting on the eastern margin of Sundaland during the Late Cretaceous and Paleogene. (e.g., Parkinson et al., 1998; Hall et al., 2009; Hall, 2012a).

In the Lariang/Karama region, 3,500 m of Eocene to Oligocene mixed terrestrial and marginal marine sedimentary rocks are unconformably overlain by early to late Miocene shallow marine carbonate and mudstones in turn overlain by early Pliocene shelf sediments and the Plio-Pleistocene syn-orogenic Pasangkayu Formation (“Celebes Molasse”) (Calvert and Hall, 2007). Oil seeps have been known for over 100 years: the abundance of terrestrial biomarkers and the presence of saturated oleane biomarkers suggest a source deposited in a deltaic or nearshore environment (Sutadiwiria et al., 2018) It is likely that the source rocks are syn-tectonic Eocene coals or carbonaceous mudstones.

Serpentinized ultramafic rocks occur in two separate basement complexes in the South Arm, the Bantimala and Barru Blocks. Both are derived from a supra-subduction zone environment and were obducted during the closure of small back-arc basins. The ultramafic suites from these two blocks are juxtaposed with metamorphic assemblages, which were later intruded by younger volcanics

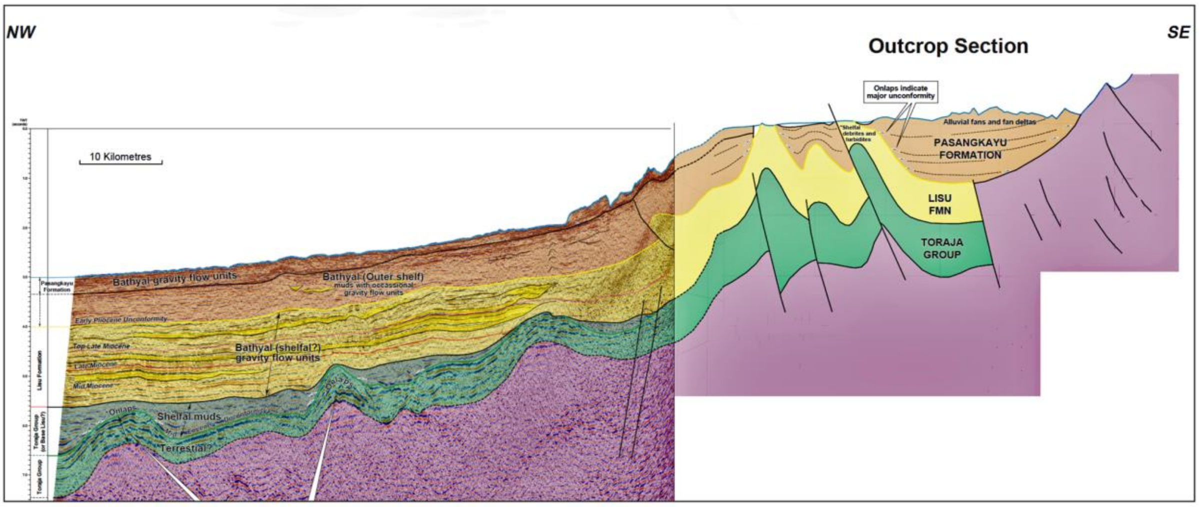

Figure 6: *Onshore and offshore geological seismic section West Sulawesi Fold Belt (modified after Isis, 2005); location of section shown on Figure 2 as line A-B.*

(Maulana et al., 2015; Jaya et al., 2017). Detrital zircon age distributions of the basement rocks in the South Arm display predominant Mesozoic (Cretaceous and Triassic) and Palaeozoic populations with a small population of Proterozoic ages supporting the hypothesis that the West Sulawesi block originated from the region of the Bird's Head, namely the Inner Banda block (Jaya et al., 2017).

South Sulawesi has an almost complete stratigraphic succession (Figure 3) spanning the late Cretaceous to the present day, with carbonate and igneous lithologies spanning much of the Tertiary (Wilson, 1999). It is dominated by a west-verging Late Miocene to Pliocene collisional orogen in the north and a later (Late Pliocene) major NNW-SSE trending sinistral strike-slip fault system which has produced a pull-apart basin (Walanae Depression) with elevated rift shoulders along its margins (Western and Eastern Divide ranges) (Guritno et al., 1996; Wilson and Moss, 1999).

Two disparate terranes in the South Arm are juxtaposed across the sinistral Walanae fault zone which extends into Bone Bay. In the west, Paleogene arkosic sandstone, siltstone, claystone, marl and conglomerate, intercalated with layers or lenses of coal and limestone are overlain by a thick succession of shallow marine carbonate which continued until the middle Miocene, on high blocks, surrounded by deep marine sedimentation (Tonasa Carbonate Platform; Coffield et al., 1993; Wilson and Bosence, 1996; Wilson and Moss, 1999). The main factors affecting carbonate depositional environments and facies distributions were differential subsidence, controlling water depths and accommodation space, types of carbonate producers and active faulting (Wilson, 1999). East of the fault zone, lithologies are quite distinct from those to the west and the oldest lithologies are of Eocene age (Maulana et al., 2015).

Cenozoic magmatism occurs throughout West Sulawesi, whose petro-genesis, sources, and tectonic settings have been relatively well constrained by extensive geological, petrologic, geochemical, and isotopic investigations (Polvé et al., 1997; Elburg et al., 2003; Maulana et al., 2015, 2016; Jaya et al., 2017). A notable feature of the Late Cenozoic igneous rocks is that they have an almost exclusively potassic to ultra-potassic composition. They can be subdivided into a shoshonitic to ultra-potassic (HK) series and a high-K calc-alkaline (CAK) series and are interpreted to have formed in a post-subduction (extensional) tectonic setting (Elburg et al., 2003).

The most significant Cu–Au mineralization is at Sassak which occurs in a quartz syenite intrusion of shoshonitic affinity; K–Ar dates of nearby related rocks range from 10.6 to 11.9 Ma (Priadi et al., 1994). The Sassak Cu–Au porphyry is located within the Walanae fault zone (Soeria-Atmadja et al., 1999).

West Sulawesi Fold Belt

The West Sulawesi Fold Belt (WSFB; Figures 3, 6 & 7), first mentioned by Coffield et al. (1993) was described in some detail in the offshore area adjacent to the Lariang-Karama region of western Sulawesi by Fraser et al. (2003). The Lariang-Karama region covers the central and southern onshore parts of the WSFB and was described by Calvert and Hall (2003). The WSFB lies immediately west of the Palu-Koro Fault, a major crustal lineament initially set up by spreading within the Celebes Sea during the Eocene, and part of the greater Sorong fault system.

Figure 6 is a composite seismic and geological section through both the offshore and onshore sectors of the WSFB and shows the basement involved tectonics onshore near the basin margin and the intensity of the deformation decreasing towards distal parts of the fold belt where deformation appears to be ongoing.

The offshore WSFB (Figure 7) is not a single fold belt and is divided into three structural provinces based on seafloor characteristics, subsurface deformation, and in particular the character and position of the deformation front: the Southern Structural Province (SSP) a west-verging thinned-skinned fold-and-thrust belt

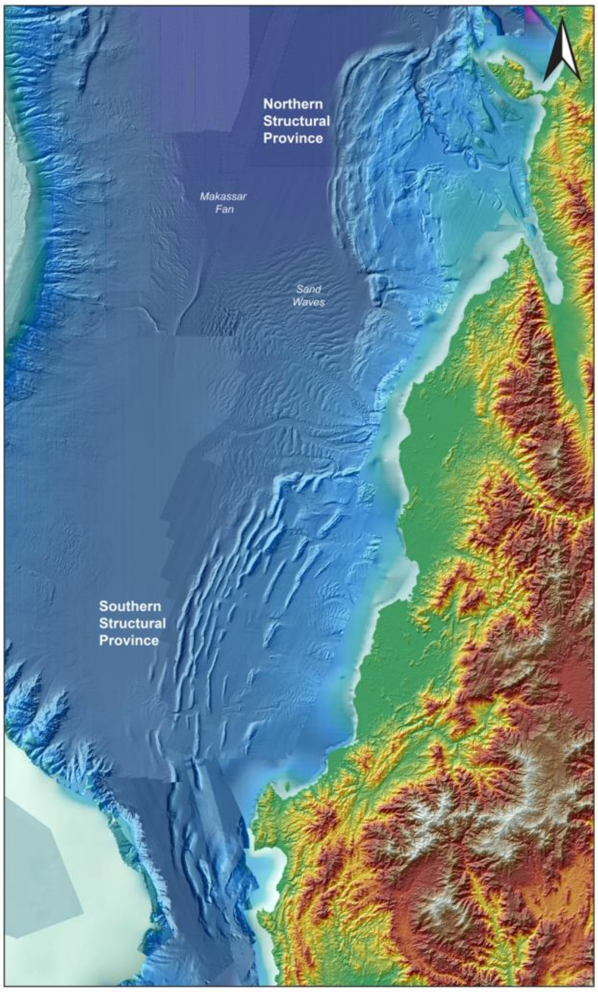

Figure 7: *Composite bathymetric and SRTM image of West Sulawesi Fold Belt.*

with thrust faults detaching on different decollement layers; Central Structural Province (CSP) with less deformation; and the Northern Structural Province (NSP) strongly deformed where folding, thrusting, and detachment layers are difficult to interpret (Puspita et al., 2005). It is considered there is similar contraction in all three areas, but compression in the CSP did not ramp up into a Tertiary detachment as it did in SSP and NSP and all the offshore compression was taken up by basement-involved thrusting onshore (Figure 6).

The age of folding is well-constrained onshore where continental alluvial plain and marine deposits of the Plio-Pleistocene Pasangkayu Formation ("Celebes Molasse") formed in response to uplift of the hinterland. Continuing deformation is recorded on offshore seismic sections and syn-depositional folding of younger parts of the Pasangkayu Formation (Calvert and Hall, 2003; Fraser et al., 2003). A spectacular canyon, no longer active, eroded into the WSFB by the paleo-Palu depositional system (Baillie et al., 2008) is shown as Figure 8.

The Neck and North Arm

The section describes the land portion of Sulawesi north of the western part of the Palu-Koro Fault system and comprises the Sulawesi Neck and the North Arm (Figures 2 & 3).

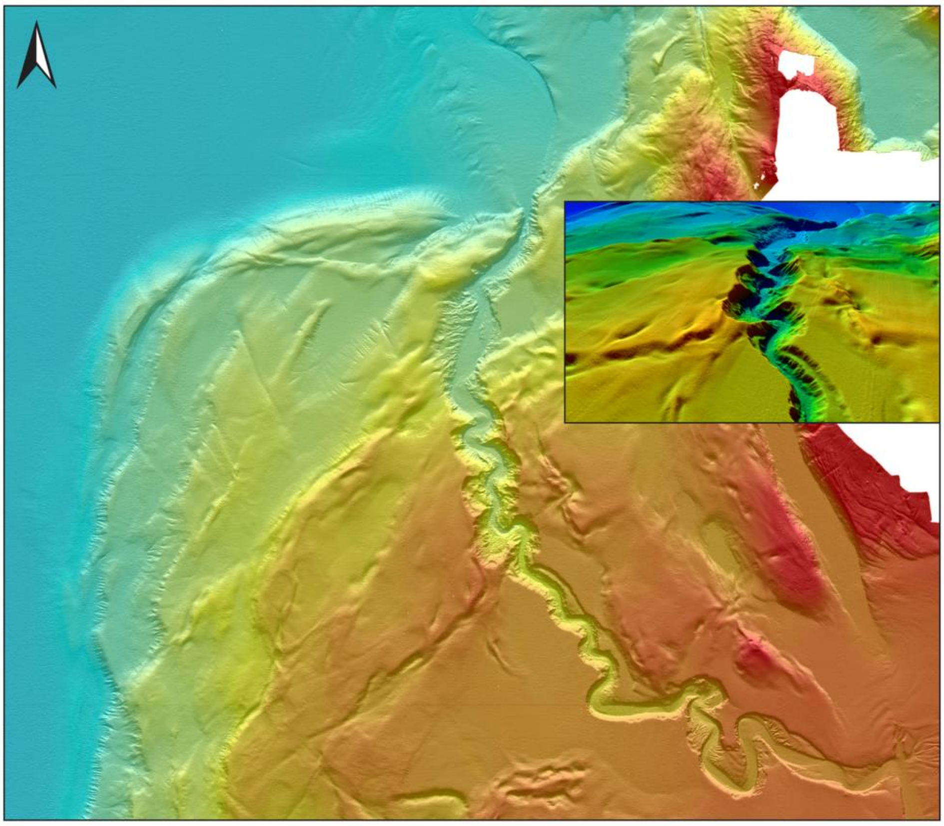

Figure 8: *Bathymetric image of northern sector of West Sulawesi Fold Belt showing prominent Palu Canyon shown as oblique view inset (after Baillie et al., 2008).*

The North Arm is varied and complex with volcano-plutonic, sedimentary and metamorphic suites present in an intra-oceanic arc of tholeiitic to calc-alkaline composition built on Eocene oceanic crust Two distinct geochemical provinces are present (Elburg et al., 2003; van Leeuwen and Muhardjo, 2005). Porphyry Cu-Au and Mo mineralisation is associated with magmatic processes in the North Arm: a lower crustal source for Mo and Au-rich porphyry systems independent of the nature of the crust and derived from mantle sources has been suggested (Soeria-Atmadja et al., 1999).

Geochemical and isotopic data indicate that the North Arm was part of an arc system between 51 and 18 Ma, with eruption and intrusion of subduction-related magmas of continental affinity in the western part of the area and of oceanic affinity in the east (Elburg et al., 2003). High-K magmatism in the west started around 14 Ma, and its isotopic signature can only be explained by a source with a long and varied geochemical history, probably located within the Australian subcontinental lithospheric mantle.

Volcanic activity in the region is a consequence of dual subduction of the Molucca Sea, west beneath North Sulawesi and east beneath Halmahera. Paleocene to Pliocene magmatism shows a progression from an Older Series with calc-alkaline /tholeiitic signatures (51–17 Ma) to a Younger Series of mafic-intermediate high-K magmas (14–5 Ma) and felsic K-rich calc-alkaline magmas (9–2 Ma). The isotopic and geochemical compositions of the Older Series samples indicate that the more westerly samples have been generated in a continental arc setting and the more easterly samples in an oceanic arc (Elburg et al., 2003).

The North Sulawesi subduction zone has been active since about 8 Ma (Hall, 2011), located to the north of an earlier Tertiary volcanic arc (Hall, 2012b). Age dating of calc-alkaline rocks associated with subduction from the north took place 2.35 Ma (Pliocene) age (Perello, 1994). Ten active volcanoes overlie the subduction zone which underlies North Sulawesi and the Sangihe Islands. The Tondano caldera, immediately south of Manado (Figure 2), is a 15x30 km NE-SW elongate caldera formed by large volume explosive eruptions and caldera collapse. It contains small inactive post-caldera volcanoes and an active geothermal system and is ringed by weakly welded and intensely dissected ignimbrite deposits (Kushendratno et al., 2012).

Low-temperature thermochronology on apatite from granitoid rocks in the Neck reveals rapid exhumation rates of 0.75–0.9 mm/yr that indicate removal of around 2 km of upper crust since the Middle Pliocene (Hennig et al., 2014). Two significant metamorphic complexes are present in the Neck and North Arm and provide information on the high speed at which tectonic processes, including magmatism, exhumation, and reworking into a sediment, must have occurred (Hennig et al., 2017).

The Palu Metamorphic Complex (Figure 3; van Leeuwen et al., 2016) represents a medium-P metamorphic belt, ranging from chlorite to staurolite grade metamorphism, which is exposed immediately adjacent to the Palu Fault.

Its lithologies are dominated by biotite gneiss and schist, with subordinate amphibolite, granulite, migmatite, peridotite, calc-silicate rocks and meta-granitoids. The metamorphic rocks are strongly deformed, and some were partially melted to form migmatites. Metamorphic rocks of the PMC have yielded Early to Late Pliocene cooling ages. Intruded S-type granites have similar Pliocene ages. Both show very fast cooling rates, indicating rapid exhumation of the complex (Hennig et al., 2017).

The Malino Metamorphic Complex (Figure 3; MMC) is in the western part of the North Arm and consists predominantly of quartzo-feldspathic schist and gneiss, with intercalations of quartzite, graphite schist, marl and amphibolite. Greenschists form a discontinuous selvage around the complex. The MMC is interpreted as a metamorphic core complex which underwent lithospheric extension during the Early–Middle Miocene. Exhumation took place during a second phase of extensional uplift was accommodated by brittle faulting from the Late Miocene-Pliocene onwards. Preliminary zircon dating and isotope analysis indicate that their igneous and sedimentary protoliths were old continental crust, probably of Australian derivation. Reconnaissance dating indicates that the MMC rocks were metamorphosed in the mid-Miocene (23–11 Ma) (Advokaat et al., 2017).

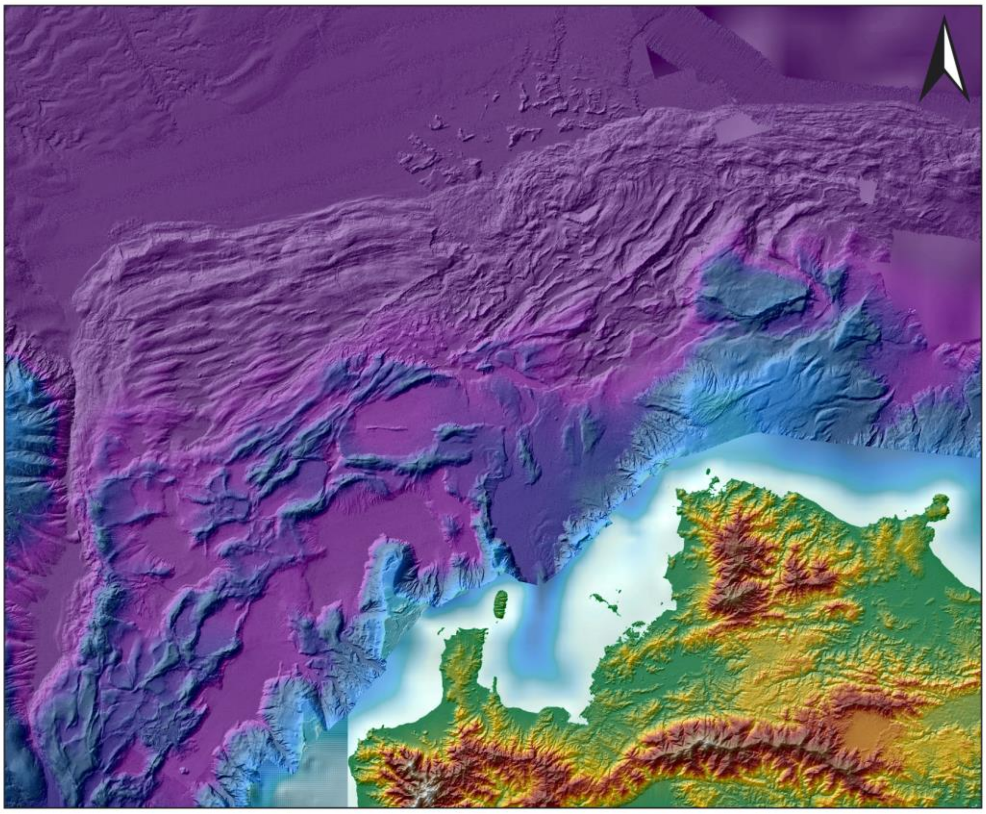

Figure 9: *Bathymetric image of north-western sector of North Sulawesi Fold & Thrust Belt; prominent N-S lineament on western edge of mage is the Palu Fault.*

North Sulawesi Fold & Thrust Belt

The North Sulawesi Fold & Thrust Belt (NSFTB) occurs offshore of the North Arm in the southern part of the Celebes Sea (Figure 3). It is bound to the north by the North Sulawesi Trench. Deformation is related to Palu-Koro fault zone movements and subduction of the Celebes Sea beneath the North Arm.

Seismic evidence in the northern Makassar Strait shows the presence of major flower structures between the present day Mangkalihat Peninsula and Sulawesi representing periods of transpression developed along the Palu-Koro fault system “structural freeways” (Fraser et al., 2003).

Seafloor bathymetry (Figure 9) shows the characteristic fold-and-thrust belt geometries as well as several ovoid basins immediately north of the North Arm which appear to be extensional (or perhaps transtensional), related to the rollback of the southward subducting Celebes Sea since the Pliocene (Advokaat et al., 2017, Tiranda and Hall, in prep). The continuation of the Palu-Koro fault system forms a prominent lineament against the Mangkalihat Peninsula, there is no evidence of faults crossing from Sulawesi into Borneo.

Deformation in the NSFTB is interpreted to have occurred from the latest Miocene or Pliocene to present with subduction of Celebes Sea at the North Sulawesi Trench and movement on the Palu-Koro Fault (Tiranda and Hall, in prep).

Gorontalo Bay

Gorontalo Bay (Figure 2; also known as the Gulf of Tomini) is a deep, inter-arm sea, bounded by the mountainous North Arm on the north, central Sulawesi and the East Arm on the south and bounded by to the west by the narrow Sulawesi Neck. It is surrounded by mountains up to 2–3 km high formed by metamorphic complexes and granitoid intrusions that can be traced from the Central North Arm to the Neck and further south into mid Central Sulawesi (Hennig et al., 2014). A thick depositional succession within the bay exceeds ten kilometres in thickness (Jablonski et al., 2007).

Pholbud et al. (2012) recognised a three-part stratigraphy: basement is proposed to be Sundaland continental crust, below a major unconformity interpreted to be either Mid Eocene or Early Miocene in age; above the unconformity is a sequence up to 6 sec TWT divided into a lower part interpreted as quartz-rich marine sediments, with little volcanic debris, derived from granites and continental basement of western Sulawesi and an upper shallow-water carbonate succession. At the top of the succession and imaged beautifully on bathymetric data (Figure 10A, for location see Figure 3) are submerged reefs and pinnacle reefs which mark rapid subsidence which began at about 5 Ma and are partly buried by Pliocene–Recent deep-water deposits in the basin centre. Initiation of subsidence has been related to rollback-driven extension from the North Sulawesi Trench (Cottam et al., 2011; Hall, 2011, 2012a; Hennig et al., 2014).

Rapid subsidence began at about 5 Ma and rates of subsidence eventually exceeded rates of carbonate production, killing all the reefs except for rare pinnacles and close to the present

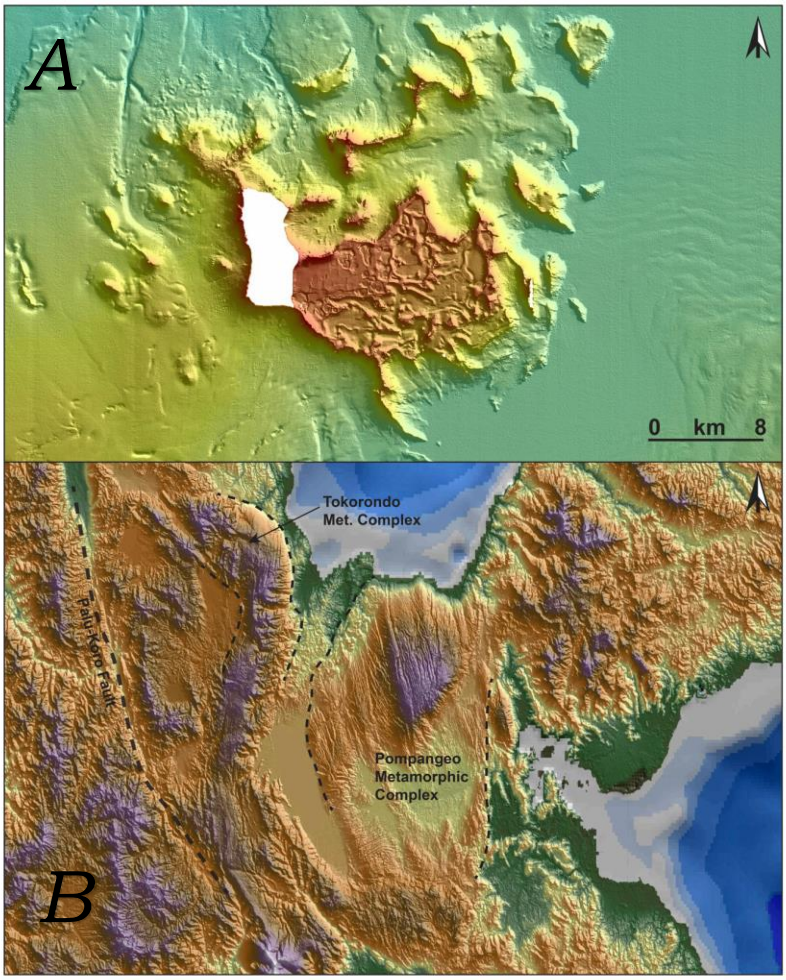

Figure 10: *Evidence of extension in and around Gorontalo Bay. (A) Bathymetric image of prominent submerged carbonate complex, Gorontalo Bay. Base of the complex around 1300m water depth, central part of the complex 600–800m, pinnacle tops 400–500m. (B) SRTM image of northern Central Sulawesi showing metamorphic complexes.*

coastlines, and exceeding rates of clastic supply, so that they are now between 1800m and 2000m deep in their deepest parts.

Una-Una (Figures 2 & 3) is an isolated active calc-alkaline shoshonitic volcano (Sendjaja et al., 2018). Broom-Fendley et al. (2011) have proposed that Una-Una and the nearby Tongian Islands (~2 Ma) are the product of young extension of Gorontalo Bay due to slab roll-back.

East Arm

Central Sulawesi comprises metamorphic rocks of the former accretionary margin of Sundaland (Parkinson, 1998), which are over-thrusted by a complete, but dismembered, ophiolite exposed in the East Arm (Parkinson, 1998; Kadarusman et al., 2004). The ophiolite belt extends from central Sulawesi to the east and southeast arms, including Buton and Muna Islands.

The East Sulawesi Ophiolite (ESO), one of the three largest ophiolites in the world, is a tectonically dismembered full suite of ophiolite lithologies and comprises, from base to top, residual mantle peridotite and mafic–ultramafic cumulate through layered to isotropic gabbro, to sheeted dolerites and basaltic volcanic rocks of normal mid-oceanic-ridge basalt (MORB) composition (Parkinson, 1998; Kadarusman et al., 2004). Trace element data on the lavas and dolerites, and particularly their depletion in Nb compared to neighbouring incompatible elements, suggest a subduction zone environment for their origin (Monnier et al., 1995).

It is intercalated with Cretaceous or Mesozoic pelagic sedimentary rocks

Metamorphic ages (28–32Ma; Parkinson, 1998) from rocks overthrust by the East Sulawesi Ophiolite suggest emplacement of this ophiolite sequence occurred during or after the middle to late Oligocene. The geochemical variations and disparities for both peridotite and basalt and the non-cogenetic relationship between crust and mantle sections in several locations suggest that the ESO may have been formed at one tectonic setting and was later overprinted by magmatism in different environments through its birth to emplacement. A possible Cretaceous origin of an oceanic plateau has been suggested (Kadarusman et al., 2004).

The Central Sulawesi metamorphic belt is confined to the central part of the eastern arm of the island and is considered to have resulted from collision between fragments of Gondwana origin and the active Asian margin in the Late Oligocene or Early Miocene. It consists of sheared metamorphic rocks including the Pompangeo schist complex and a melange complex (Parkinson, 1998), as well as an ophiolite terrane (Lamasi Complex) (Polve et al., 1997). This region has been interpreted to represent an accretionary complex that was formed during Cretaceous and Paleogene times, as a suture between the western and eastern parts of Sulawesi (Hamilton, 1979; Parkinson et al., 1998).

Obduction did not involve westward thrusting of a piece of Australia on the Eurasian margin but was more likely emplaced by north-to-south obduction of the margin of the Eurasian plate, represented by the Celebes Sea, over the basement of eastern Sulawesi, probably of Australian origin (Monnier et al., 1995)

Southeast Arm

The Banggai-Sula islands lie offshore to the east of the East Arm, whilst Tukang-Besi, Buton and the surrounding islands are located to the southeast of the tip of the Southeast Arm (Figure 3). On the Banggai-Sula islands Permo-Triassic slate, schist, and gneiss are intruded by Permo-Triassic granitoids. These metamorphic and igneous rocks, which comprise the basement complex, are microcontinental fragments of Australian origin were previously considered to be separate fragments sliced from New Guinea and carried west along the Sorong Fault system (Hamilton, 1979; Garrard et al., 1988). They are now interpreted as part of the Sula Spur that collided with the North Arm in the Early Miocene and subsequently fragmented (Spakman & Hall, 2010; Hall, 2011).

The Mesozoic and Tertiary successions of Buton and Tukang-Besi are similar to those on Banggai-Sula and considered to have Australian affinities (Pigram & Panggabean, 1984; Garrard et al., 1988).

To the east of the Southeast Arm, large gravitational collapse structures in the the Tolo Trough are interpreted to be caused by the regional exhumation of Sulawesi (Rudyawan and Hall, 2012; Titu-Eki and Hall, 2020). Abundant normal faults in the area are due to extension related to subduction rollback in the Banda Sea (Spakman and Hall, 2010; Titu-Eki and Hall, 2020)

Bone Bay

Bone Bay (or Gulf) is located between the South and SE Arms of Sulawesi and is the site of a thick undeformed synrift Neogene section with carbonate buildups on both basin flanks and deeper marine sediments in axial parts. The main basin trends N-S and is divided into several sub-basins and highs. Based on modern 2D seismic and multibeam bathy-metry we suggest that the basin is largely transtensional in origin: some seismic sections show classic half-graben geometry (Figure 11) others show a "bath-tub" section with steep sides to both the west and east.

A prominent channel system is present in the centre of the basin with the main channel having a width of up to 3 km (Figure 11). The channelling is only present above a marked probable Early Pliocene unconformity. This event records major uplift of Sulawesi and subsi-dence of Bone Gulf with resultant major influx of clastic sedi-ments from the north, development of a southward - flowing canyon system, and back-stepping and drowning of carbonates at the basin margins (Camplin and Hall, 2014).

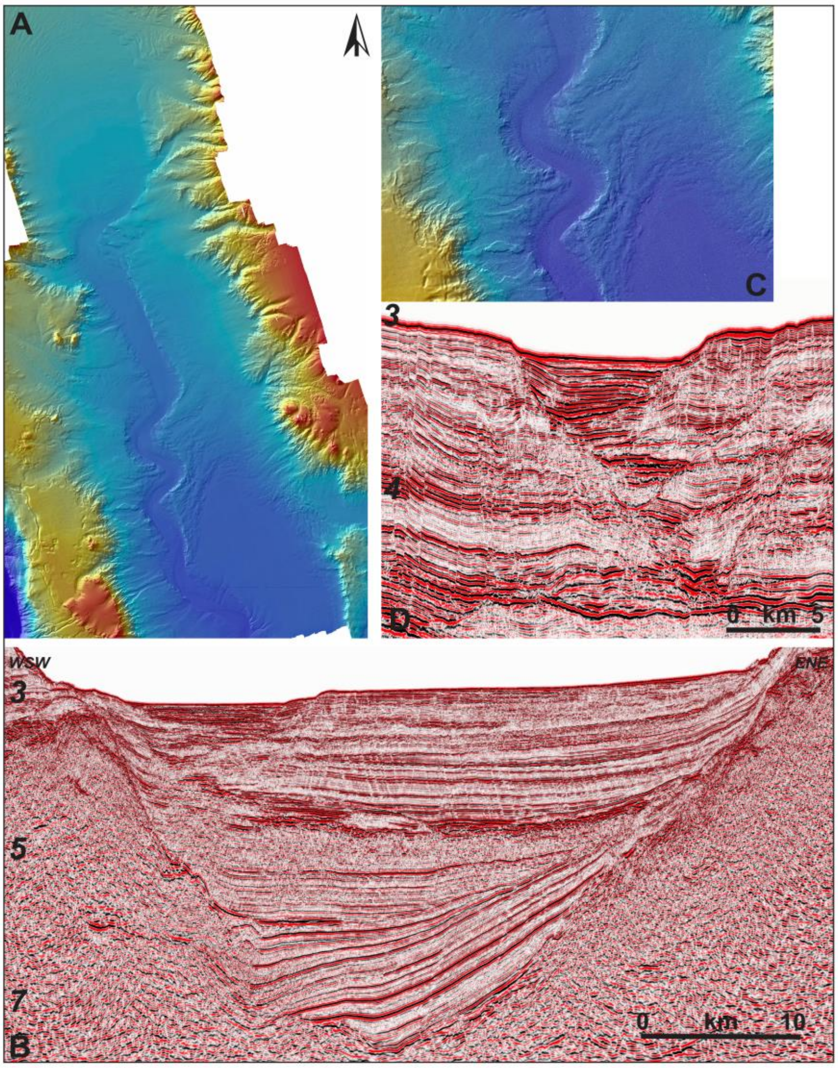

Figure 11: *Bone Bay bathymetric and seismic images. (A) bathymetry image of Bone Bay. (B) seismic image of basin infill, location of line shown as line C-D on Figure 2 (C) detailed bathymetric image of main channel. (D) Seismic image showing channel development of main channel.*

It is suggested that the prominent channel is formed by density flows initiated by large volumes of water fed into the gulf by annual rains (Baillie et al., 2008). The climate of Sulawesi is tropical with two seasons: "dry" from March to September, and "rainy" from October to February. The city of Makassar, located to the west of Bone Bay on the South Arm average rainfall around 1,000–1,500mm per year;

orographic rain is significantly higher in higher areas.

SYNTHESIS AND TECTONIC EVOLUTION

While the broad details of its geology have long been known, the tectonic evolution of Sulawesi is very complex, remains controversial, and not fully understood.

Until the last decade, there had been consensus that Sulawesi was largely the product of contractional and strike-slip tectonics and consequent rotation. For example, Katili (1978) regarded Sulawesi as the result of early Pliocene collision of Sulawesi and the Australian-New Guinea plate, transforming Sulawesi into an island with its convex side turned towards the continent, at the same time causing obduction of ophiolite in the eastern east of the island. Similarly, Silver et al., (1983) postulated that Sulawesi had been shaped and deformed because of collision with the Sula platform and that the collision had resulted in rotation of the North Arm and the development of the North Sulawesi Trench.

In a landmark paper, Pigram and Panggabean (1984) recognised detached continental fragments of Australian origin in Eastern Indonesia, including parts of Sulawesi, and proposed a model of tectonic transport by seafloor spreading – colloquially known as the “salami slicer” model. It became generally accepted that collisions in Sulawesi had been driven by terrane from the east.

That model began to be questioned in the past 15 years or so as the result of the huge amount of new information becoming available from GPS measurements, SRTM, satellite and bathymetric imagery, advanced radiometric dating, seismic imaging carried out by the petroleum exploration industry, seismic tomography, and importantly, the field-based work of Professor Robert Hall and his students at Royal Holloway, University of London.

Figure 12 is a series of tectonic reconstructions (after Hall, 2012b) is used to illustrate the tectonic development of the Indian Ocean–Indonesia region at selected time intervals since 120 Ma (that is, Early Cretaceous).

There are two main periods of activity, (a) a Mesozoic and Paleogene period of formation of the main tectonic “blocks” which would eventually comprise Sulawesi, and (b) Neogene moving and interaction of the blocks to build Sulawesi.

Rotation

Internal rotation of fragments within Sulawesi is thought to have been achieved via a linked system of strike-slip and thrust faults (Hamilton, 1979; Silver et al., 1983). This rotation is related to the accretion of microcontinental fragments onto eastern Sulawesi and to the subduction of oceanic crust of the Celebes Sea southwards down the North Sulawesi Trench (Hamilton, 1979; Silver et al., 1983; Parkinson, 1998). To accommo-

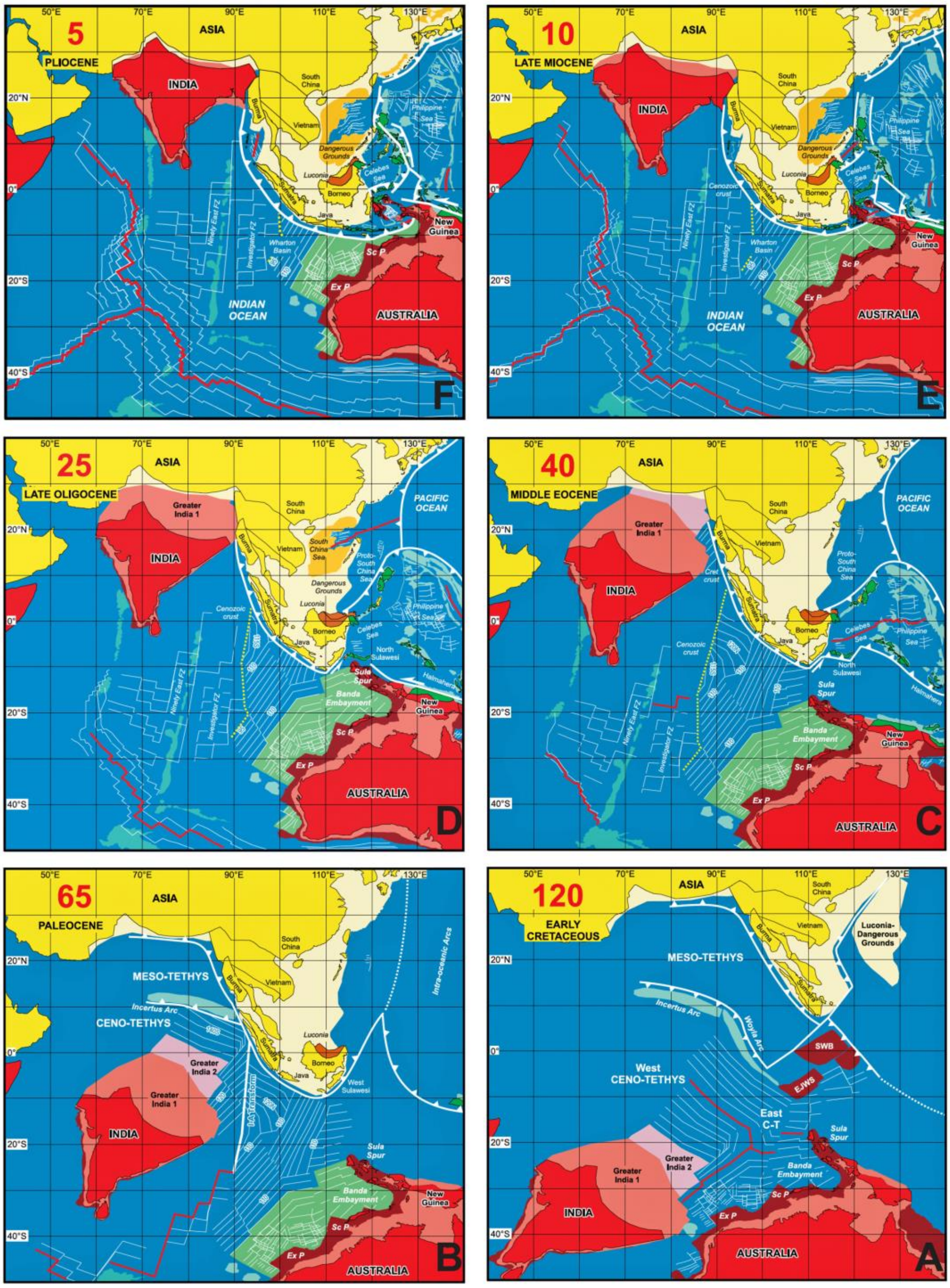

Figure 12: *Montage of tectonic reconstructions of Indian Ocean - Indonesian region at selected times (after Hall, 2012b). (A) 120 Ma: East Java–West Sulawesi (EJWS) and Southwest Borneo (SWB) have moved away from Australia and closing on Sundaland margin. (B) 65 Ma: EJWS and SWB part of Sundaland; brief episode of NW-directed subduction marked by volcanic activity in West Sulawesi. (C) 45 Ma: Celebes Sea spreading in a back-arc setting; Ceno-Tethys subducted northwards from Sumatra to Halmahera. (D) 25 Ma: Sula Spur about to contact the North Arm volcanic arc. (E) 10 Ma: Subduction rollback of the Celebes Sea caused spreading of the Sulu Sea in a back-arc setting; rollback into Banda Embayment caused extension of the Sula Spur to form the North Banda Sea. (F) 5 Ma: Molucca Sea subduction was almost complete, Halmahera and Sangihe arcs about to collide; Sulawesi amalgamation almost complete.*

date this movement, linkage of a splaying fault system across Sulawesi has been suggested (Hamilton, 1979; Silver et al., 1983; Parkinson, 1998). Socquet et al. (2006) showed that ongoing deformation of Sulawesi is largely confined to the region north of the Paul-Koro and Lawanopo fault systems (Figure 2) and can be reasonably described by a small number of rapidly rotating crustal blocks (Figure 13). Relative to the Sunda Plate, the southwestern part of Sulawesi rotates anticlockwise at 1.4°/Myr. The north-eastern part of Sulawesi comprises three blocks rotates clockwise at 2.5–3°/Myr. South of the Palu-Koro fault system, GPS observations showed that the relative motion between Sundaland and Sulawesi is small (<2 mm yr−1), but north of the fault system accommodation rates varied from 11 to 42 mm/year (Socquet et al., 2006). The authors noted that Sulawesi provides a primary example of how collision can be accommodated by crustal block rotation instead of mountain building.

Wrench Faulting

The sinistral wrench systems are the western extremity of one of the most important and longest structural elements in the Western Pacific and Southeast Asia. The eastern end is the Sorong fault system (SFS), the southern boundary of both the Molucca Sea and the Philippine Sea plates with the Australian Plate (Hall and Wilson, 2000). The SFS, initiated no later than the early Miocene and still active, the result of oblique convergence of Australia and the Philippine Sea plates, has been responsible for translating continental fragments from the northern margin of the Australian Plate (i.e., the Bird's Head of New Guinea) into the outer edge of Sundaland (Pigram and Panggabean, 1984; Hutchison, 1996). There is no evidence that the Sorong fault system extends into Sulawesi beyond the Sula islands; instead, there is a highly extended continental margin north of the North Banda Basin which is underlain by Middle Miocene–Pliocene (12.5–7.3 Ma) oceanic crust (Rudyawan and Hall, 2012).

During the Pliocene, prior extensional settings in the Makassar Strait became compressional as the Sulu Spur collided with the south-eastern corner of Sundaland. This collision not only helped assemble Sulawesi into its current (ephemeral) K-shape but also formed the WSFB, progressively obscuring the original Eocene rift system in the Makassar Strait (Fraser et al., 2003).

The WSFB is the direct result of transpression and collision, resulting from movements on the Paul-Koro fault system. Walsperdorf and Vigney (1998) reported five years of GPS measurements across the Palu-Koro fault showing left lateral strike-slip of 3.4 cm/yr with a small normal component of 0.4 cm/yr.

Wrench faulting is important in the Bone Bay area and has produced multiple depocentres and structural highs (Camplin and Hall, 2014). We believe a sinistral strike-slip fault system extends in a general north-northwesterly direction from Bone Bay through the South Arm and is responsible for the formation of the thick, transtensional depocentre in Bone Bay.

Fission Tack and Fault Kinematics

Fault kinematic and fission-track analyses show that the Late Cenozoic central Sulawesi deformation results from three successive tectonic regimes:

1. A Late Miocene–early Pliocene WNW-trending shortening characterized by transpressional deformation along the Palu-Koro Fault. This resulted from the collision between the Sula Spur with Sulawesi and produced locally a transpressional regime because of the northward extrusion of the Central Sulawesi block limited by the Palu-Koro Fault. Soon after 25 Ma the Sula Spur began to collide with the North Sulawesi volcanic arc, and this is the first Australia–SE Asia collision. Ophiolites were thrust onto the continental crust, derived from the ocean north of the Sula Spur and probably from the North Sulawesi fore-arc (Hall, 2011).

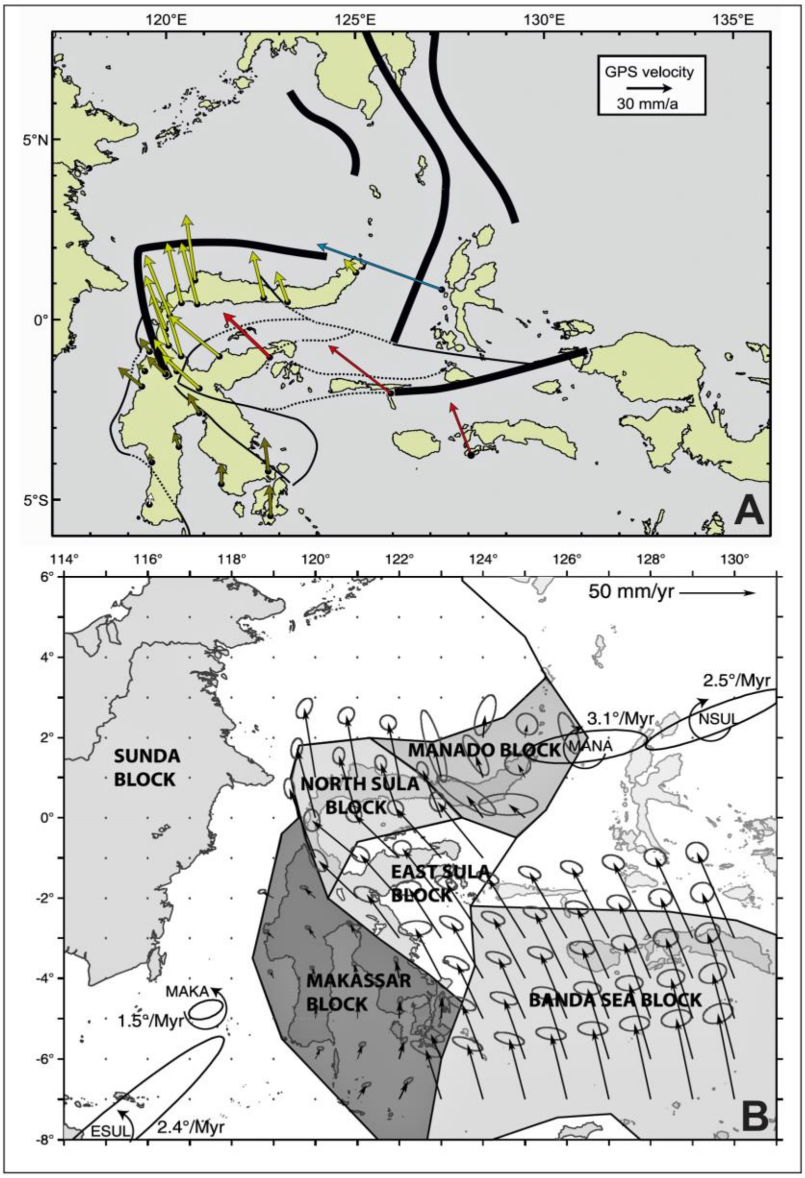

Figure 13: *Sulawesi rotation. (A) GPS velocities and interpreted blocks, East Indonesia (after Socquet et al., 2006; Hall, 2011) (B) rotational part of the inferred velocity field relative to the Sunda Plate, error ellipses indicated (after Socquet et al., 2006).*

2. A Pliocene collapse tectonic regime associated with W-trending extension. Coeval with these events regional cooling and exhumation took place.

3. A Quaternary transtensional regime resulting from the combined effects of the Central Sulawesi block northward motion, and extension related to back-arc spreading behind the North Sulawesi sub-duction zone (Bellier et al., 2006).

Neogene Extension

Through the latter part of the 20th century and the early part of the 21st, Sulawesi has generally been interpreted as the product of convergence in the Cretaceous and Cenozoic; more recent studies have indicated that extension has played a significant role in its Neogene evolution. For example, high mountains in west Central Sulawesi have been considered the product of magmatism and metamorphism related to Neogene collision; however, new dating of metamorphic and granitoid rocks has identified protoliths and sources of melts and indicates an important role for extension (Hennig et al., 2016).

Late Miocene magmatic flare-up in West Sulawesi and coeval regional extension in eastern Indonesia are attributed to a resumed episode of Banda slab rollback (Zhang et al., 2020). Neogene extensional tectonics has also been recognised in southwest Sulawesi where widespread block-faulting and the onset of potassic volcanism commenced around 14–13 Ma. It reached its peak about one million years later with the juxtaposition of the Bone Group against the Salokalupang Group along the Walanae Fault Zone. Potassic volcanism continued up to the end of the Pliocene, and locally into the Quaternary (van Leeuwen et al., 2010).

Widespread Neogene extension, driven by subduction, has also been recognised as important in the northern part of Sulawesi from central Sulawesi, though Gorontalo Bay and beyond the North Arm where extension exhumed the deep crust in onshore metamorphic core complexes at the same time as subsidence in Gorontalo Bay.

Analysis of SRTM data for central Sulawesi reveals two grooved, dome-like massifs that form the northern end of the Tokorondo Mountains in the northwest and the Pompangeo Mountains in the southeast (Figure 10B). Each massif extends from near sea level to ~2.5 km elevation. The larger, southeastern corrugated landform, centred on the Pompangeo Mountains and extending over ~2000 km^2, consists primarily of marble, phyllite, quartz-mica schist, and meta-conglomerate (Parkinson, 1998). The landforms are interpreted as the denuded footwalls of extensional detachment faults with aerially extensive, topographically smooth footwalls similar to those at other active core complexes (Spencer, 2010, 2011). The North Arm is deforming in response to gravitational potential energy contrasts. Subduction of the Celebes Sea beneath the northern arm of the island initiated at 8 Ma (Hall, 2011) with the rollback of the slab causing back-arc extension and rapid subsidence of Gorontalo Bay. Rapid uplift and exhumation metamorphics and synchronous rapid subsidence offshore in Gorontalo Bay (Pholbud et al., 2012; Pezzati et al., 2014) has been interpreted to be linked to northward rollback of the southward-subducting Celebes Sea under the North Arm during the Pliocene to present-day (Hall, 2011). GPS data show rapid northward motion of the North Arm with respect to the Celebes Sea, indicating that this process is ongoing at present day (Advokaat et al., 2017).

Greenfield et al. (2021) analysed earthquakes around Sulawesi to study the active deformation and suggested that the accretionary wedge above the subducting Celebes Sea is being deformed in response to gravitational potential energy contrasts, spreading from a region of high gravitational potential energy to a lower one. The hot and weak continental fragment is spreading out under its own weight with deformation is driven by stresses transmitted though the lithosphere, rather than tractions on the base of the lithosphere caused by circulation in the underlying mantle.

The importance of the role of extension has become more apparent in recent years and it may be that many more features previously thought to be contraction will be reassessed as due to extension or hyper extension. For example, the Seram–Kumawa shear zone is a newly recognised major Neogene structure within the Australian continental margin of the Banda embayment (Hall et al., 2017). Figure 14 shows a cartoon summary of the major structures during the Early Pliocene development of this structure, and it may be that the continental fragments were dispersed by extension rather than multiple collisions.

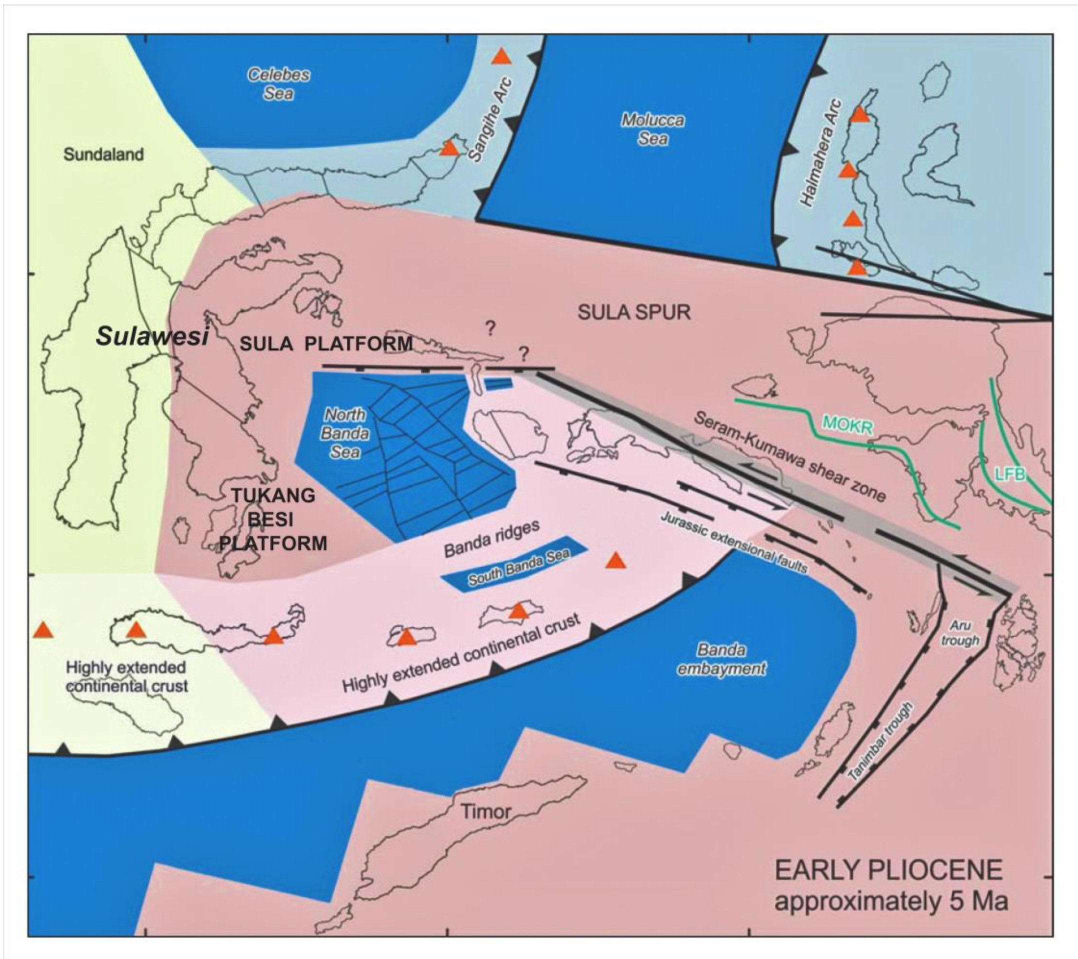

Figure 14: *Early Pliocene reconstruction of the northern and eastern Banda arc in the Early Pliocene (after Hall et al., 2017): areas shown in light pink were highly stretched by the Early Pliocene and further extended since*

CONCLUSIONS

Sulawesi comprises a series of disparate tectonic terranes, developed under a variety continental and oceanic settings, brought into juxtaposition while sedimentation continued and undergoing continuing deformation. The processes involved in that juxtaposition include strike-slip and extensional processes and occurred at very fast rates.

Early Miocene collisions in eastern Sulawesi did not cause orogeny in western Sulawesi. It was only during the Pliocene that the character of sedimentation across the whole of western, central and eastern Sulawesi changed significantly (Hall et al., 2017). The final juxtaposition of tectonic elements occurred between the Pliocene and the present day. Internal rotation and juxtaposition was achieved via a system of linked faults, the linkage and displacements along faults is still contentious (Wilson and Moss, 1999).

Neogene evolution of the northern Sulawesi involved initial westward subduction and associated magmatic activity followed by collision of the arc with the Sula microcontinent, which resulted in clockwise rotation of the north arm, back-arc thrusting, and inception of southward subduction along the North Sulawesi trench. Rapid uplift on land with contemporaneous subsidence offshore is interpreted to have resulted from extension driven by clockwise rotation of the North Arm associated with northward rollback of the North Sulawesi subduction zone.

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Morpho-bathymetric features of the Southwest Celebes Sea

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ABSTRACT

The Southwest Celebes Sea lies within the region of Celebes Sea (also known locally as Sulawesi Sea)-Makassar Strait gateway which is controlled by active tectonic of North Sulawesi Trench and Palu-Koro Fault zone. In addition, this region is the major inter-ocean route of Indonesian Throughflow (ITF). Using the high-resolution multibeam bathymetry data supplemented with 2D seismic profiles, this study describes major morpho-bathymetric features that can be observed within the Southwest Celebes Sea. There are 4 types of morpho-bathymetric features: structural features, erosional features, gravitational features, and depositional features. The dominant structural related tectonic features and gravitational features mainly occur in the North Sulawesi Fold-Thrust Belt associated with the formation of the North Sulawesi Trench and Palu-Koro Fault zone. Whereas, to the northern part, the deeper area of the Celebes Sea and the region on the west are mainly controlled by erosional and depositional features. The identification of morpho-bathymetric features provides useful information for basin analysis study and present-day or future offshore activities such as infrastructure engineering related to geohazard potential caused.

Keywords: morpho-bathymetric; seabed morphology; multibeam bathymetry; Celebes Sea; Makassar Strait; Sulawesi

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INTRODUCTION

In 2017, the high-resolution multi beam bathymetry was made available by GeoData Ventures (GDV) covering an area of approximately 65,000 km² of the Celebes Sea-Makassar Strait gateway (note: the Celebes Sea is known locally as the Sulawesi Sea). The main purpose is to depict the basin architecture in the unexplored offshore area particularly the Southwest Celebes Sea and adjacent area. The Southwest Celebes Sea (Figure 1) is divided into 3 subareas. The North Sulawesi Fold-Thrust Belt (NSFTB) is separated from the other 2 subareas in the west by the Palu-Koro Fault. The southern basin is named here as the Muara Basin whereas the shallower part to the west of Celebes Sea is named the Deepwater Tarakan Basin. These 2 sub-areas are separated by a prominent structural high called the Maratua Ridge.

Several 2D seismic acquisitions have been acquired from 2005 to 2009 by PGS which mainly covers the Muara Sub-Basin, Deepwater Tarakan Basin, and a small part of NSFTB. The newly acquired multibeam dataset would not only aid the seismic interpretation of the sub-surface but also provide information on the seabed morphology. This also provides valuable information and understanding for the assessment for many present-day offshore activities related to infrastructures engineering, regional basin architecture study, and geohazard potential.

This paper presents an interpretation of morpho-bathymetric features related to the various geological processes that occurred in the region. The description and examples of the specific features are subdivided according to the main geological processes responsible for their development. The high-resolution bathymetry in the Southwest Celebes Sea provides exceptional details of the morpho-bathymetric features related to the different geological processes.

REGIONAL GEOLOGY & OCEANOGRAPHIC SETTING

Situated in the boundary of the Sunda margin and Celebes Sea Plate, the Celebes Sea has a complex deformation history, especially during the Pliocene-present day (Figure 1). This event formed the North Sulawesi Trench as a result of the southward subduction of the Celebes Sea and the formation of the Palu-Koro Fault. Important changes that happened during the past 45 Ma, including spreading of the Celebes Sea, associated with separation of West Sulawesi from Borneo (Hall, 2002, 2012), subsidence throughout the Oligocene-Early Miocene (25-20 Ma), and counter-clockwise rotation of Borneo followed by inversion during 20-10 Ma (Hall, 2002, 2012). A Pliocene tectonic event is critical to the formation of the North Sulawesi Trench and Palu-Koro Fault (Hall, 2002, 2012).

Early Pliocene (5 Ma) to the present, Celebes Sea Slab rollback (Hall, 2012; Rudyawan, 2016) caused a change of trend of the North Sulawesi Trench from a relatively NE-SW trending thrust to an ENE-WSW trending thrust (Advokaat, 2015). The Palu-Koro Fault formed during the Pliocene (5 Ma) based on the non-coaxial strain in the Palu metamorphic rocks (Watkinson, 2011). Furthermore, the northward rollback of the south-dipping Celebes Sea slab may have been linked to the Palu-Koro strike-slip fault as a subduction-transform edge propagator (STEP) fault (Govers and Wortel, 2005). The region of Southwest Celebes Sea effectively resulted from several complex tectonic phases from the Middle Eocene until the present day.

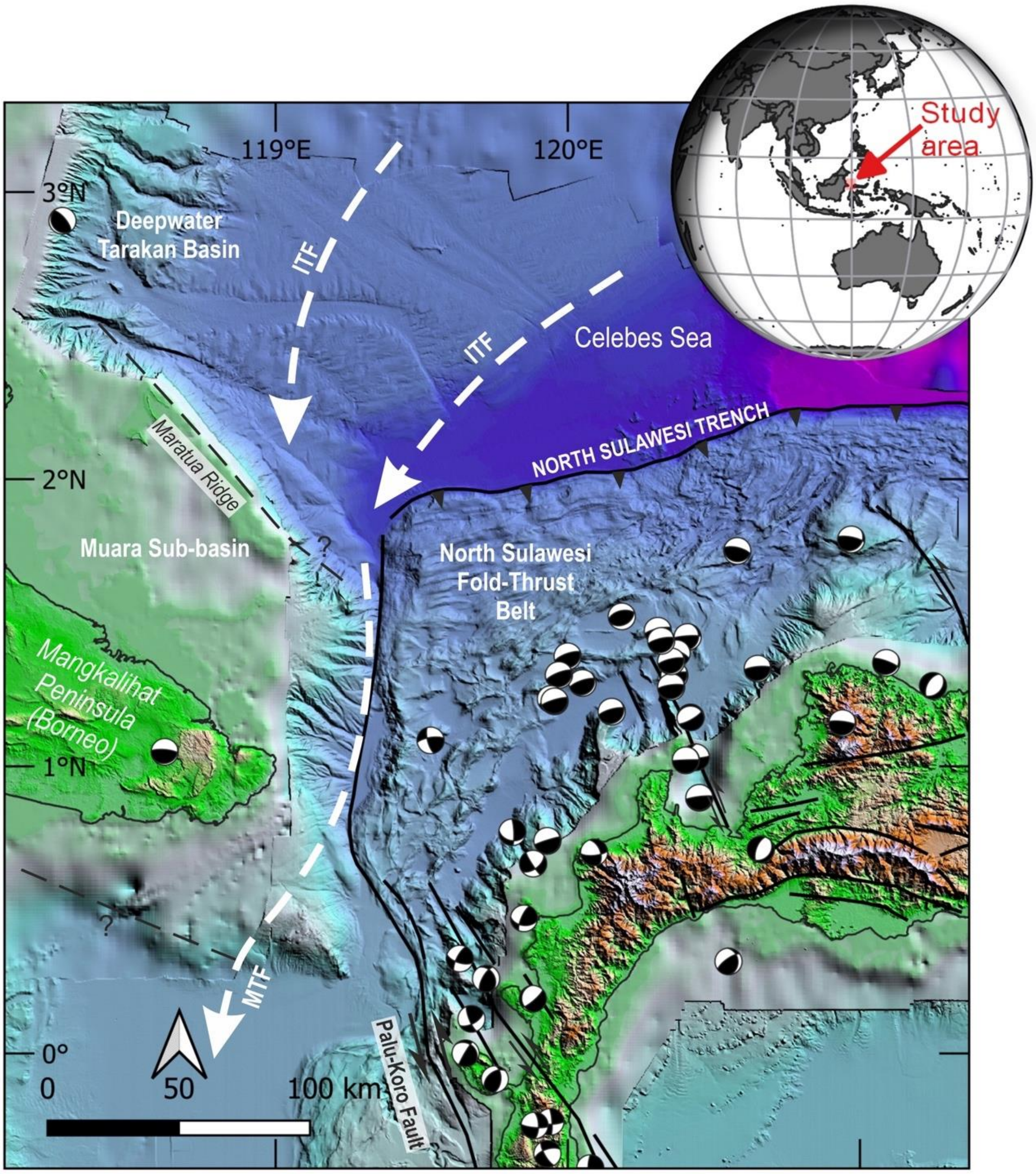

Figure 1. *ASTER DEM, bathymetry, and gravity image of study area showing topography, regions, basin or sub-basin, active seismicity, oceanography setting, and major tectonic provinces of the study area (Cloke et al., 1999; Camp et al., 2009; Advokaat, 2015; Hall, 2019; Tiranda and Hall, 2021, Preprint). Earthquake events are from 1976-to 2021 with focal depth <30 km from CMT focal mechanism based on Ekström et al. (2012). ITF and MTF's current orientation is from Gordon et al. (1999), Mayer and Damm (2012), Susanto et al. (2012), and Brackenridge et al. (2020).*

In terms of the oceanographic setting, the region of Southwest Celebes Sea has been identified as one of the major inter-ocean routes of Indonesian Through flow (ITF), with the Celebes Sea-Makassar Strait gateway is expected to transport high water mass (Wajsowicz, 1993, 1996; Gordon et al., 1999; Susanto et al., 2012) (Figure 1). The inter-ocean routes are part of the Pacific water inflow path, with the Makassar Strait as the primary inflow route known as the Makassar Strait Throughflow (MTF) (Mayer and Damm, 2012; Brackenridge et al., 2020). Based on the flow simulation conducted by Mayer and Damm (2012), the current enters the Makassar Strait from the north via the Celebes Sea as a surface current, deepens below the surface layer to become a strong and confined subsurface jet. The simulation results indicate high flow transport within the

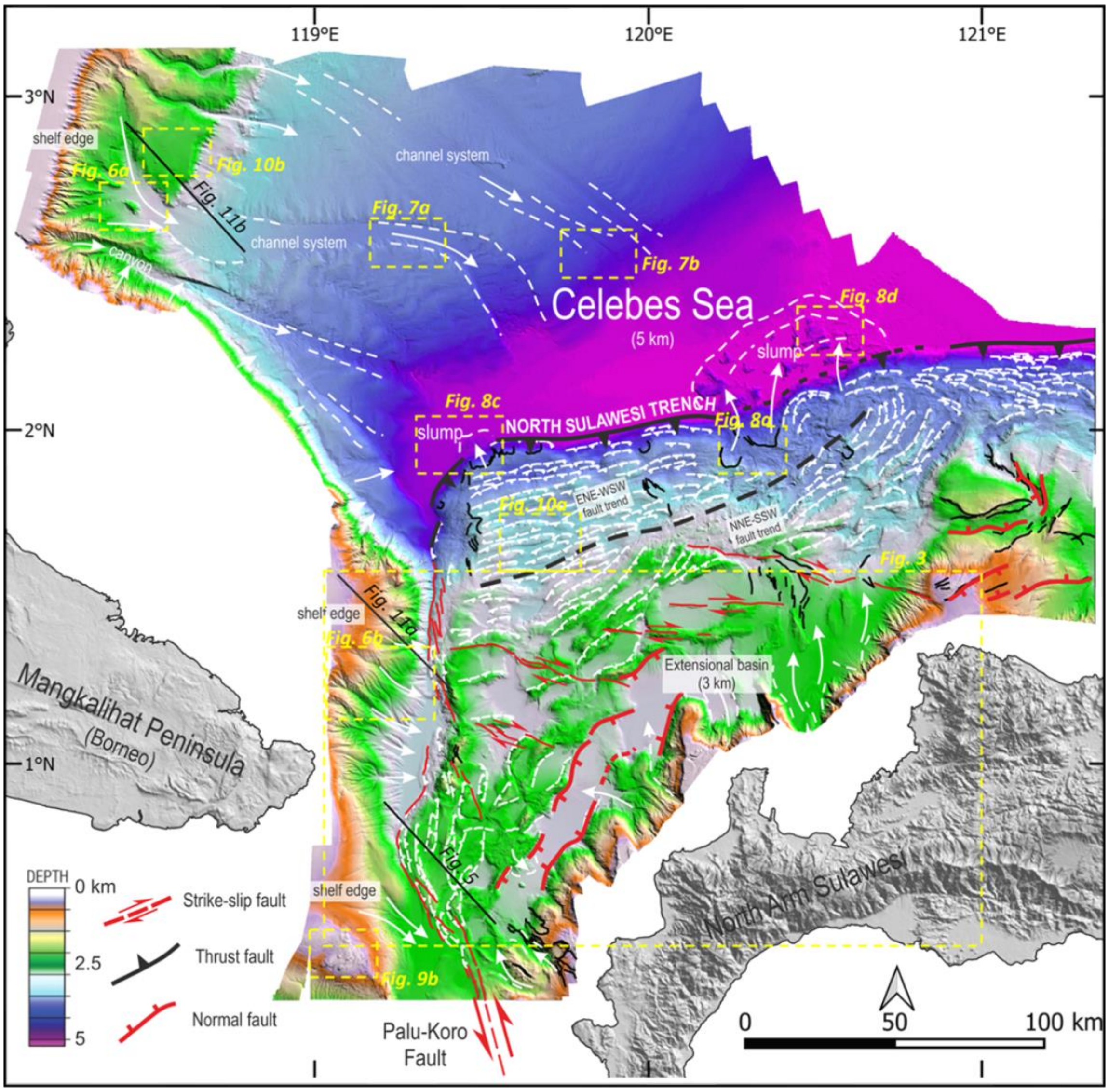

Figure 2. *Combined DEM from SRTM map with a shaded-relief map of multibeam bathymetry showing morpho-bathymetric interpretation with specific examples described in this paper. Illumination direction from NE.*

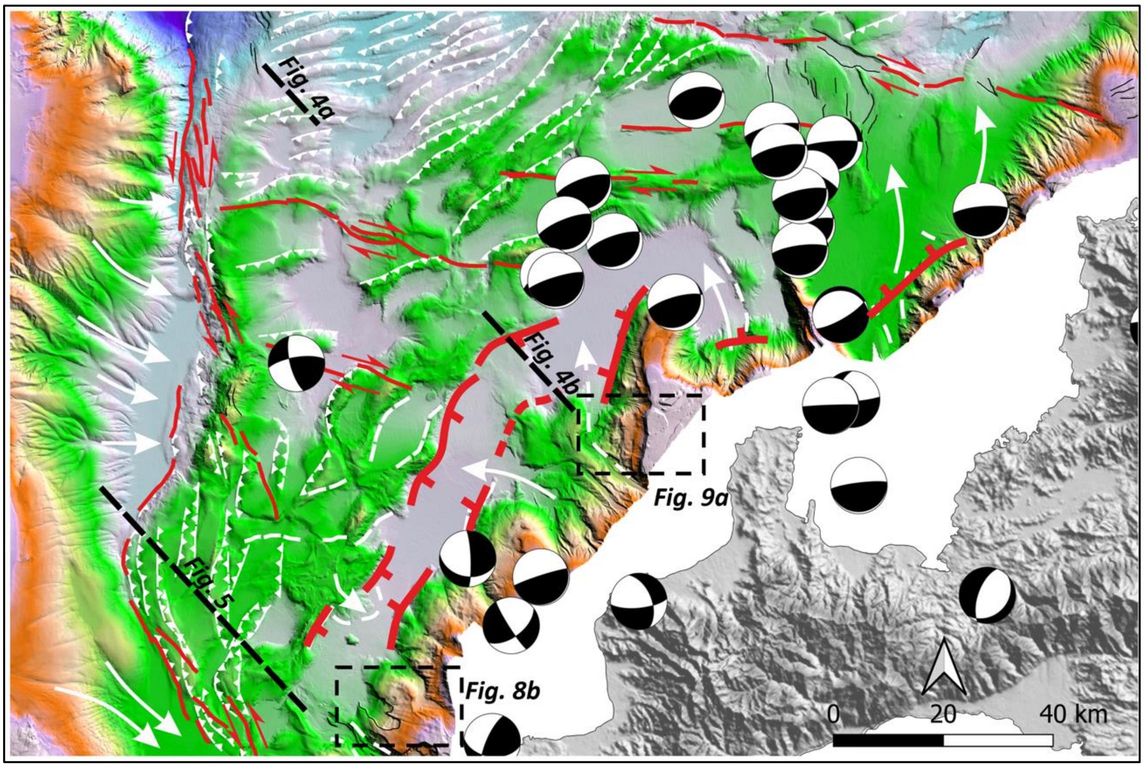

Figure 3. *Morpho-bathymetric interpretation of the NSFTB highlighting the complex structural features associated with the formation of NSFTB and the Palu-Koro Fault. Detailed structural features are shown in Figure 4, Figure 5, Figure 8, and Figure 9. Illumination direction from NE.*

range of about 50-300 m which contributes about 65-70% to the MTF and about 30% to the entire volume transport of the ITF (Mayer and Damm, 2012). This water mass flow in the region making it one of the most important factors of the oceanographic dynamics in the Indonesia region, especially in the Celebes Sea-Makassar Strait gateway.

DATASET AND METHODOLOGY

The dataset used in this study includes the high-resolution multibeam bathymetry (kindly provided by GeoData Ventures) covering an area of approximately 65,000 km², mainly within the Celebes Sea, and it was supplemented by 2D seismic reflection data from PGS. The multibeam bathymetry or Multibeam Echo-sounder Systems (MBES) has a resolution of 25-15 m and has been processed to a shaded-relief map by mimicking the effect generated by illumination at a low angle using Geographic Information System (GIS) software ArcMap 10.3.1 and ER Mapper. The morpho-bathymetric features then were analyzed and interpreted using QGIS 3.16.13 software.

Additional information was compiled from public data services (e.g. global CMT catalog) and from published literature where data coverage was unavailable. Historical earthquake data from 1976 to 2021, with focal depth < 30 km from CMT focal mechanism based on Ekström et al.

(2012), were used to delineate shallow structures that possibly have surface expression. Information of the ITF (Indonesia Throughflow) and MTF (Makassar Strait Throughflow) current flow were gathered from Gordon et al. (1999); Mayer and Damm (2012); Susanto et al. (2012).

RESULTS AND DISCUSSION

Regional bathymetry

The seabed morphology within the study area has been controlled and shaped by tectonic and marine sedimentary features (Figure 2). This part presents the results of the description and interpretation of multibeam bathymetry data, including the structural interpretation and sedimentary features interpretation, followed by a description of the main features and exceptional examples of minor features that can be observed within the study area. The examples presented are sub-divided according to different geological features responsible for their development. Locations of the detailed figures in this paper (Figure 3 to Figure 11) are shown in Figure 2.

The water depth of the study area ranges from 0.5-5 km (Figure 2). Shallower areas are mainly close to the coastline of Borneo and the North Arm of Sulawesi. The study area is divided into two regions based on the multibeam bathymetry area coverage which are the Celebes Sea and the NSFTB (Figure 1). They are fault-bounded and separated by the Palu-Koro Fault and North Sulawesi Trench.

The Celebes Sea region includes the area of the Deepwater Tarakan Basin or Tarakan Deep Basin (Tiranda and Hall, 2021, Preprint) with a small portion of the Muara Basin. In the Celebes Sea region (Figure 2), shallower water is mainly located on

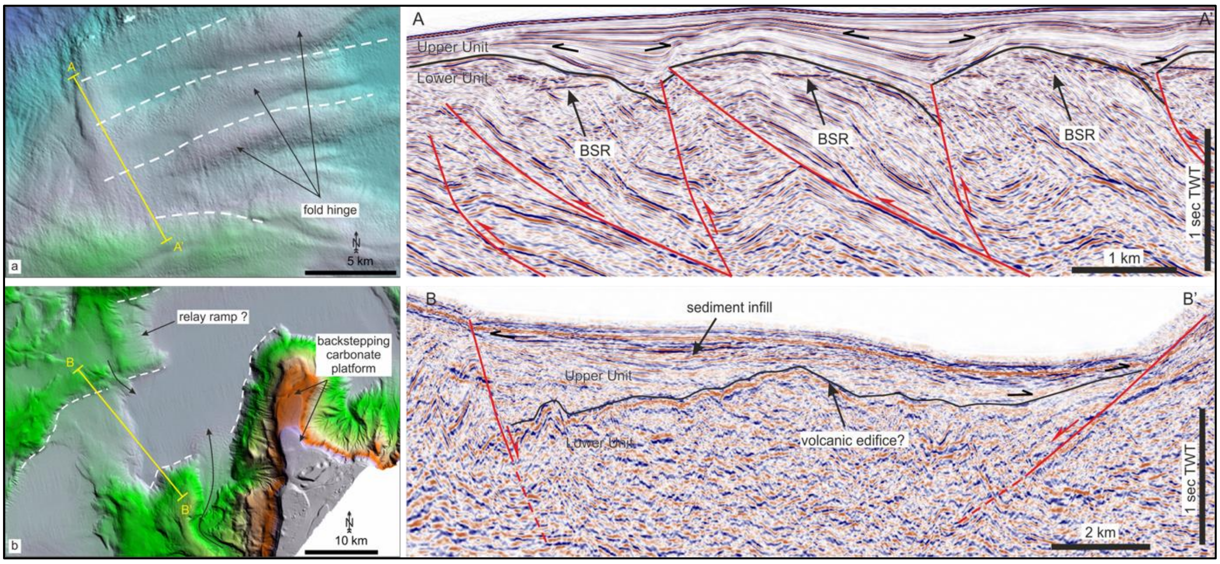

Figure 4. *Example of structural features as observed in the study area particularly the NSFTB. Illumination direction from NE. (a) Seabed morphology of the fold-thrust belt. (b) Extensional basin in the southern-most part of the NSFTB. The location is shown in Figure 2 and Figure 3.*

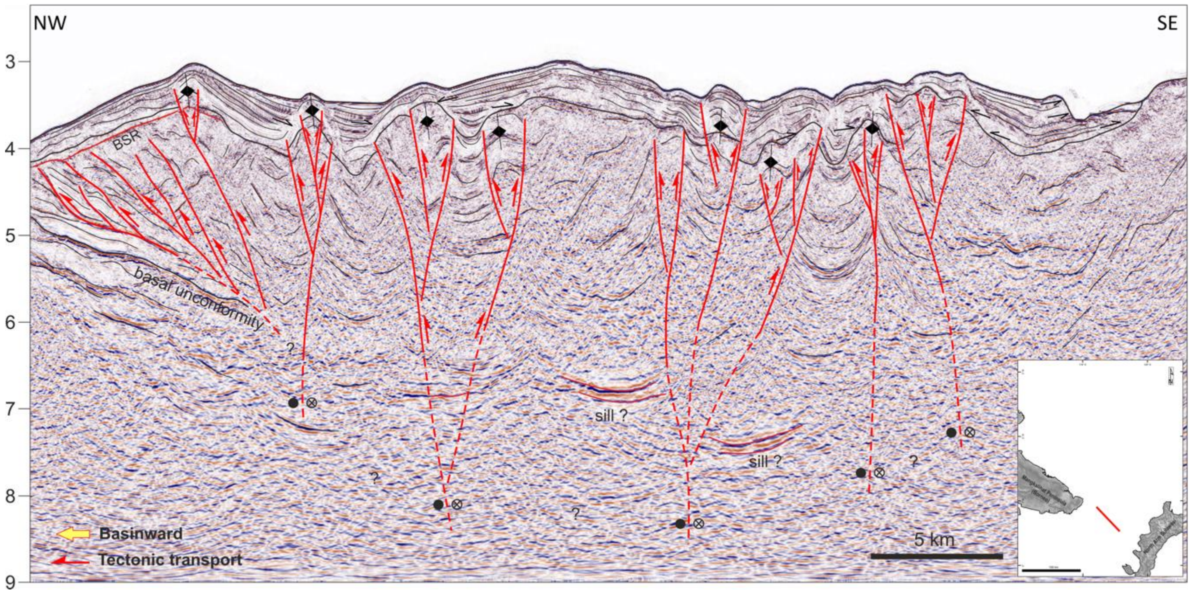

Figure 5. *The interpreted seismic section in the Celebes Sea-Makassar Strait gateway exhibits restraining stepover structure related to the Palu-Koro Fault system. The surface expression from bathymetry data shows typical rhomboidal shape geometry (Figure 3).*

the shelf margin of Borneo, where the average water depth is about 1000 m and the shallowest depths are about 500-600 m. The deeper waters are found in the eastern part of the Celebes Sea region which the main depocenter is approximately 5 km deep. A transition from shelf margin to the deeper part of the area in the east is marked by a submarine slope from the present-day shelf edge along the Borneo margin.

Within the NSFTB (Figure 2), the average water depth is approximately 2-3 km. This area is characterized by ENE-WSW and NE-SW lineaments in the northern part. NE-SW lineaments also dominate the southern part of this area with minor WNW-ESE lineaments. The westernmost part of this area was controlled by broadly N-S and NNW-SSE lineaments which might be strands of the Palu-Koro Fault. Several isolated mini-basins were developed within this area particularly in the south, associated with NE-SW trending lineaments.

Structural features

Various structural styles are observed within the study area, particularly in the NSFTB (Figure 3). For example, in the northern part of it adjacent to the North Sulawesi Trench, the fold-thrust belts are observed in seismic profiles (Figure 4). Unfortunately, the earthquake focal mechanism does not represent surface features as can be observed from bathymetry and seismic profile. The seismicity events are mainly associated with the subduction of the Celebes Sea Slab (Hall, 2019). Surface expressions mainly have shallow-rooted structures whilst the seismicity is much deeper around 25-30 km. Although at some parts, the faults are inherent to the seismicity zone below the subsurface (0-12 km depth), especially near the coastline of the North Arm of Sulawesi.

Several extensional faults seen on seismic lines are also observed in the southern-most part of the NSFTB (Figure 3 and Figure 4b). N-S trending thrust faults are observed along with the Palu-Koro Fault system which may extend and join at the edge of the North Sulawesi Trench (Figure 2). The N-S trend thrust fault observed along the northern offshore segment of the Palu-Koro Fault, is an east-dipping fault with a minor west-dipping back thrust system. In addition, from the multibeam bathymetry image, a rhomboidal-shaped structure is observed in this segment (Figure 3) and interpreted to have been formed by the left-lateral strike-slip fault forming restraining stepover structure (Figure 5).

Despite the complexity, there are a few features at the seabed that reveal the subsurface structural geology. For example, the fold-thrust belt structure in the NSFTB (Figure 4a). This fold-thrust belt is divided into two structural provinces based on the lineament trend which are the ENE-WSW trend and NNE-SSW trend (Figure 2). Moreover, the evolution of structural trends in the fold-thrust belt region may correspond to the development of extensional basins in this area associated with the subduction roll-back during Pliocene as proposed by Tiranda and Hall (2021, Preprint). There are few extensional faults developed onshore as reported by Advokaat (2015) and also supported by the seismic event onshore which is possibly associated with the development of the extensional basin offshore.

Erosional features

The region of the Celebes Sea includes well-developed canyons trending NW-

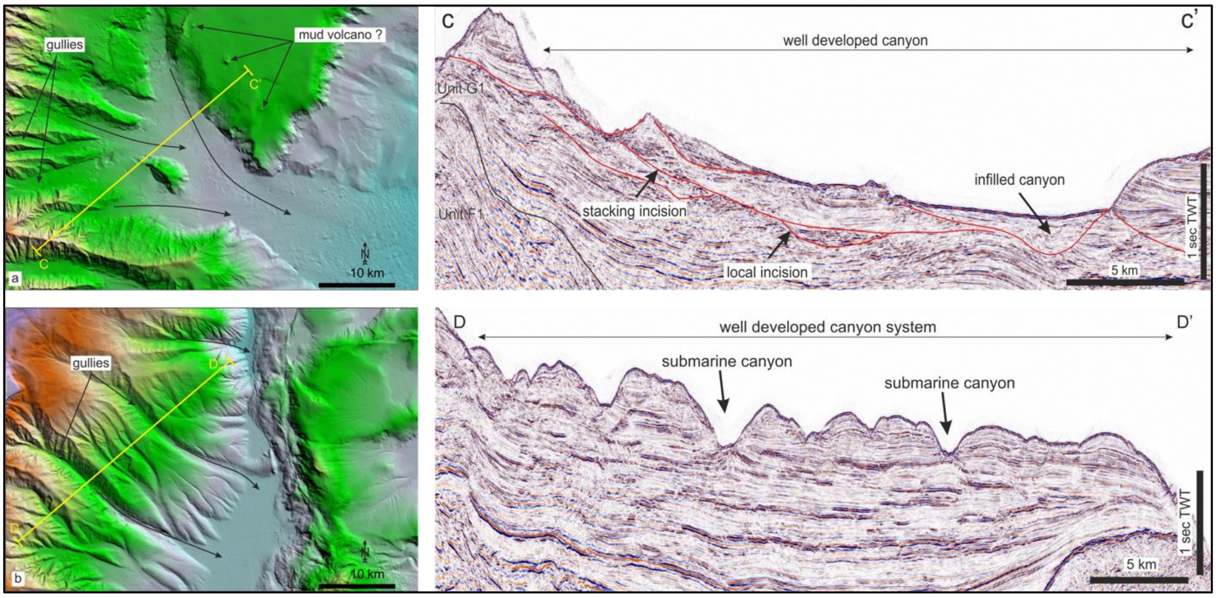

Figure 6. *Example of the erosional features showing canyon system/gullies based on multibeam bathymetry and seismic profiles. Illumination direction from NE. (a) Gullies in the Deepwater Tarakan Basin. (b) Gullies in the eastern edge of the Muara Sub-basin. The location is shown in Figure 3.*

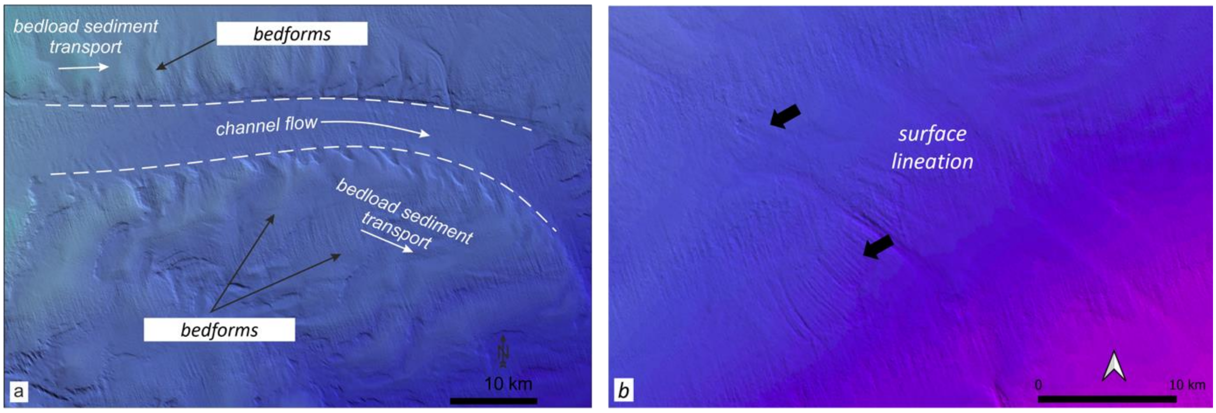

Figure 7. *Erosional features on the Celebes Sea seabed surface. Illumination direction from NE. (a) Bedforms with NE-SW trend of the crest. (b) Surface lineation indicates SE flow direction.*

SE with minor E-W and NE-SW trends (Figure 2). Present-day sedimentary deposits were transported through this canyon to the basin in the Celebes Sea and small basins close to the Palu-Koro Fault on the eastern edge of Borneo (Figure 6b). Several seismic lines also indicate vertical stacking channel systems that developed through time and were cut off by present-day submarine channel systems (Figure 6a). These features recorded in the subsurface might relate to the paleochannel system flowing broadly from west to east from the eastern part of Borneo.

Strong currents are indicated in the Celebes Sea canyon system that transported sediment to the depocenter. There are several types of erosional features produced by the bottom current observed in the Celebes Sea which is subdivided based on Stow et al. (2009) classification. Bottom currents produced bedform features characterized by asymmetrical (with an approximate size between 60 and 200 m high), bifurcating, and sinuous shapes which tend to be clustered in small areas with a coherent NE-SW trend of wave crests (Figure 7a). The asymmetrical wave shapes appear to indicate bottom traction towards the SE to the Celebes Sea. The surface lineations also indicate bottom current with SE direction formed in the much lower velocity with dominant fine-grained sediments (Figure 7b).

Gravitational features

In contrast, submarine canyons system in the NSFTB are less-developed compared to the Celebes Sea. The main sedimentary features in this area are dominated by subaqueous mass-flow features such as landslides and their secondary products like slump deposits (Figure 8). These features indicate an unstable slope which might be triggered by active tectonic activity within the area. For example, several landslides were observed along the North Sulawesi Trench, and some were associated with the subsidence in the extensional basin to the south of the NSFTB.

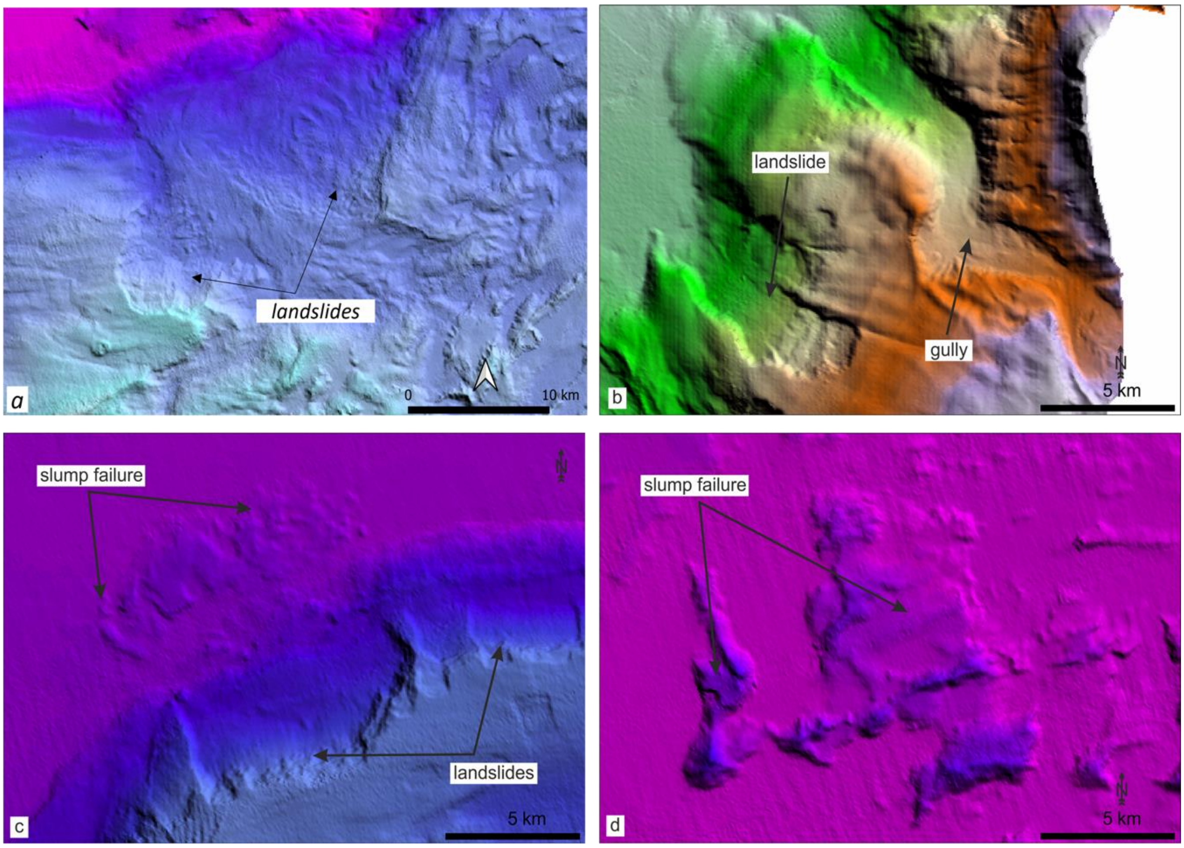

Figure 8. *Gravitational features were observed within the study area. Illumination direction from NE. (a) Sediment wave features in the Celebes Sea. (b), (c), and (d) Slope failures are characterized by landslides and slump failures. The location is shown in Figure 2 and Figure 3.*

Depositional features

Carbonate features are among the most obvious features that can be seen in this area. Relatively shallow water conditions close to the coastline along Borneo or the North Arm of Sulawesi with average water depths less than 100 m are ideal for carbonates to develop. Several stair-stepped marine terraces which are interpreted to be associated with submerged carbonate platform are observed in the southern-most of the NSFTB (Figure 9a). Their presence at depths that are now greater than 500 m indicates significant recent subsidence.

This possible carbonate platform mostly shows a typical backstepping character. Relative sea-level rise allows the carbonate to grow landward to create the morphology of backstepping carbonate. This could be due to either the sea level rise or tectonic subsidence; the latter is much more likely since recent eustatic sea-level changes of several hundred meters are impossible. Interestingly, the backstepping carbonates in this area are very close to the extensional fault system. The subsidence caused by extensional fault might be contributing to the development of this backstepping carbonate.

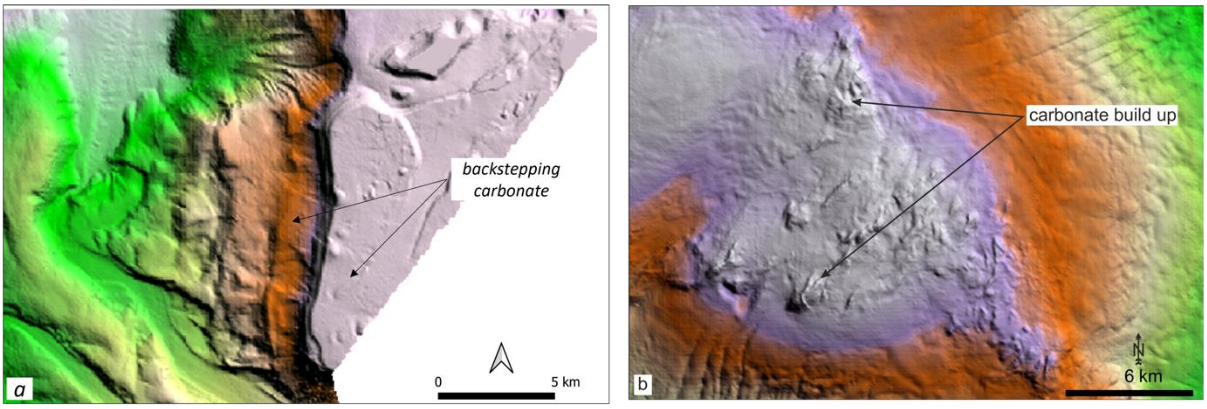

Figure 9. *Stair-stepped marine terraces which are interpreted as backstepping carbonate (a) and carbonate build up (b). Illumination direction from NE. The location is shown in Figure 2.*

Carbonate features are also observed in the eastern edge of the Mangkalihat Peninsula as a carbonate build-up (Figure 9b). The build-up morphology in this area mostly has a cone-shaped morphology and occurs in shallower water at approximately 600 m below sea level, again implying young tectonic subsidence.

Another feature observed is mud volcanoes. Several mud volcanoes lie on top of the anticline structures in the NSFTB (Figure 10a). However, there is little evidence of active mud diapirism in the seismic profiles. No seismic line crossing this feature makes it difficult to judge whether these features are mud-volcanoes-related features or not. The only evidence of active gas flow in the subsurface is the appearance of Bottom Simulating Reflector (BSR) as gas hydrates or biogenic gas-related features seen on several seismic lines as reported by Tiranda and Hall (2021, Preprint).

Similar features are observed in the Deepwater Tarakan Basin (Figure 10b). Their positions are almost in line with the fold crest of toe-thrust faults deep below the seabed observed from the seismic profile. This feature might appear as the manifestation of gas

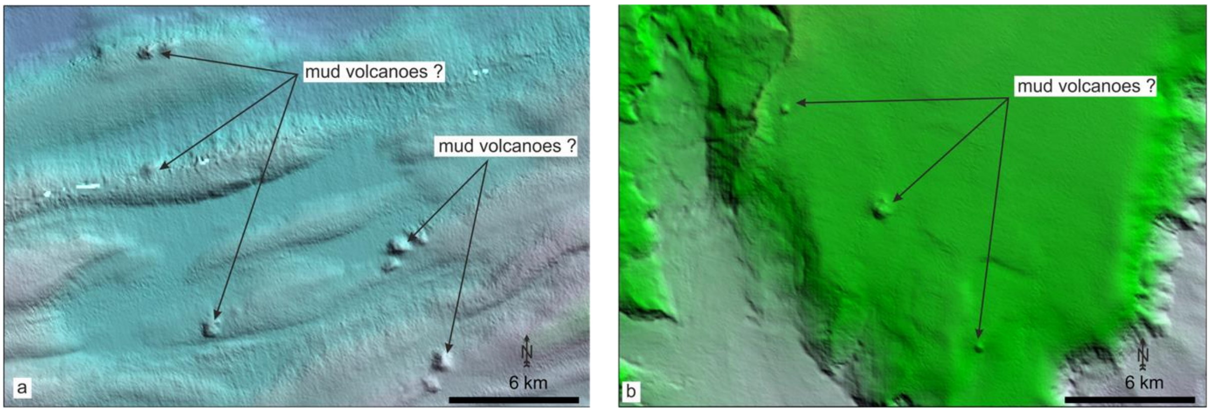

Figure 10. *Mud volcanoes-related features as observed in the study area. However, clear evidence of mud volcanoes in this area is very limited. Illumination direction from NE. The location is shown in Figure 2.*

leakage from the subsurface. Moreover, further observation of Direct Hydrocarbon Indicators (DHI) from the seismic profile indicates gas accumulation in the anticline structure from the specific interval of seismic reflection (Tiranda and Hall, 2021, Preprint).

Another obvious feature observed on the lower slope of the eastern most Muara Sub-basin and the Deepwater Tarakan Basin is the contourite feature. Their appearance shows possible contourite drift as observed from the seismic reflection. Based on Rebesco et al. (2014), the sediment drift types indicate possible mounded drift (with mounded elongate drift occurring occasionally) and plastered drift (Figure 11). Similar features have been reportedly found in the Makassar Strait, especially on the upper slope-middle slope on the western side close to the present-day Mahakam Delta shelf edge (Brackenridge et al., 2020) resulting from the bottom current of ITF (Gordon et al., 1999). According to Mayer and Damm (2012), on the ocean simulation flow of the ITF (Gordon et al., 1999; Susanto et al., 2012) or the MTF (Brackenridge et al., 2020), the strong current and volume transport within the upper 420 m has a high flow rate. This condition is sufficient for sediment to be redeposited along the slope environment in the deep-water.

CONCLUSIONS

This study describes morpho-bathymetric features of the Southwest Celebes Sea resulting from the interplay of tectonics, sedimentary, oceanography, and sea-level eustacy.

Types of morpho-bathymetric features of the Southwest Celebes Sea are structural-related tectonic features, erosional features, gravitational features, and depositional features.

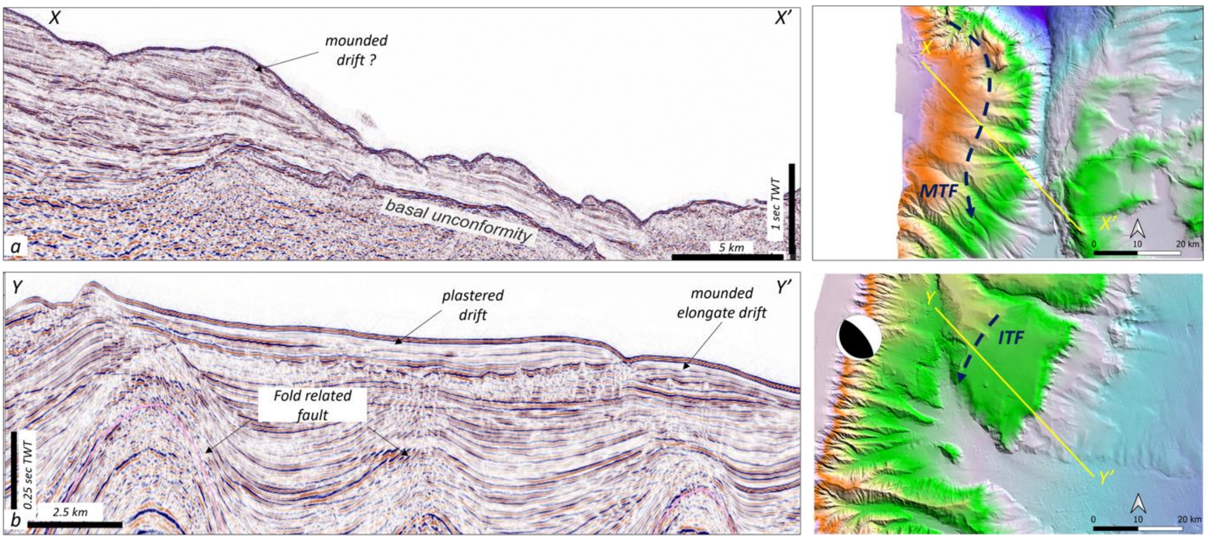

Figure 11. *Example of the contourite drift showing mounded drift and plastered drift observed from seismic reflection profiles. Multibeam bathymetry illumination direction from NE. (a) Possible mounded drift on the eastern edge of Muara Sub-basin. (b) Overlying plastered and mounded drift on top of buried fold related fault structures in the Deepwater Tarakan Basin. The location is shown in Figure 3.*

The NSFTB exhibits dominant structural related tectonic features associated with the deformation of NSFTB and Palu-Koro Fault zone with active seismicity.

In the region outside of the NSFTB (i.e., Deepwater Tarakan Basin, Muara Sub-basin), erosional and depositional features mainly occur along the slope and within the deep-marine environment.

The finding presented here carry implications for the geohazard potential and regional basin analysis.

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Kinematic analysis of Balantak Fault using fault-slip data in the Balantak area, Banggai Regency, Central Sulawesi

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ABSTRACT

Balantak is one of the sub-districts in Banggai Regency, Central Sulawesi Province. The research area is along the Balantak Strike-Slip Fault. This study presents geological mapping with focus on the deformation style that occurred within the area. The study provides an analogue of strike-slip structural trap types in convergent setting to support oil and gas field development. The research method was conducted using field observation and kinematic analysis of fault-slip data. Lithology in the study area that is part of the Banggai-Sula microplate has the characteristics of sedimentary rocks that are grainstone intercalating calcareous sandstone and rudstone consisting of limestone fragments. While part of the Sulawesi East Arm has crystalline rocks in the form of ultramafic-mafic rocks such as peridotite, serpentinite, gabbro and basalt. Structural analysis along the strike-slip fault indicates the collision of Banggai-Sula with Sulawesi East Arm on the side part of the micro-plate generates thrust fold belt along with well-developed uniform tearing faults present. The orientation and shape of the strain ellipsoid is pure shear transpression with the Balantak Fault as its plane of movement. The characteristic of the structure pattern complying with the model shows that the type of structures is en echelon thrusts and folds while the tearing faults are Riedel synthetics of the Balantak dextral Strike-Slip Fault that developed offset on the fold structures.

Keywords: *strike-slip, kinematic analysis, transpression.*

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INTRODUCTION

The tectonics of eastern Indonesia is influenced by the convergence of and interactions between Eurasia, Indian-Australia and the Pacific-Philippines plates. The tectonic record from these plates interactions can be found for example in the eastern flank of Sulawesi, where collision started from late Cenozoic. The eastern flank of Sulawesi also has petroleum potential as its petroleum system is proven and significant gas reserve has been produced in the Senoro area. The Balantak area (Figure 1) is located towards the east from Senoro gas field and is considered as the side part of Banggai-Sula micro-plate where strike-slip setting occurs. The study area is interesting for investigation because it provides potential structural trap analogues for future hydrocarbon exploration in the region. This paper presents geological structures observation along the Balantak Strike-Slip Fault Area including its kinematic analysis with fault-slip data.

GEOLOGICAL SETTING

Regional Geology

Sulawesi is located at the junction of three plates where the Pacific-Philippine and Indian-Australian plates are subducted under the Eurasian plate. As a result of this convergence, Sulawesi is composed of many fragments originating from these main plates. They include metamorphic complexes, volcanic arcs, ophiolite and micro-continental fragments and are all grouped generally into several major tectonic units (Katili, 1978; Hamilton, 1979; Taylor and van Leeuwen, 1980; Sukamto and Simandjuntak, 1983). The area of interest is the convergence between Banggai-Sula micro-continent and the East Arm of Sulawesi (Figure 2).

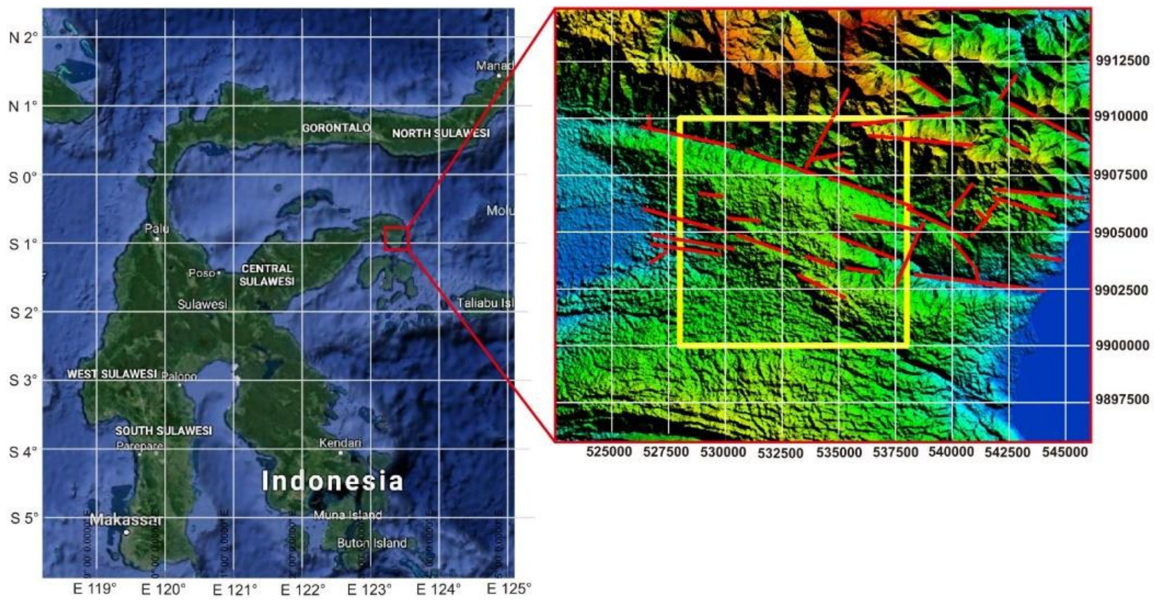

Figure 1: *Boloak Village administrative map and the study area, which is highlighted in yellow box.*

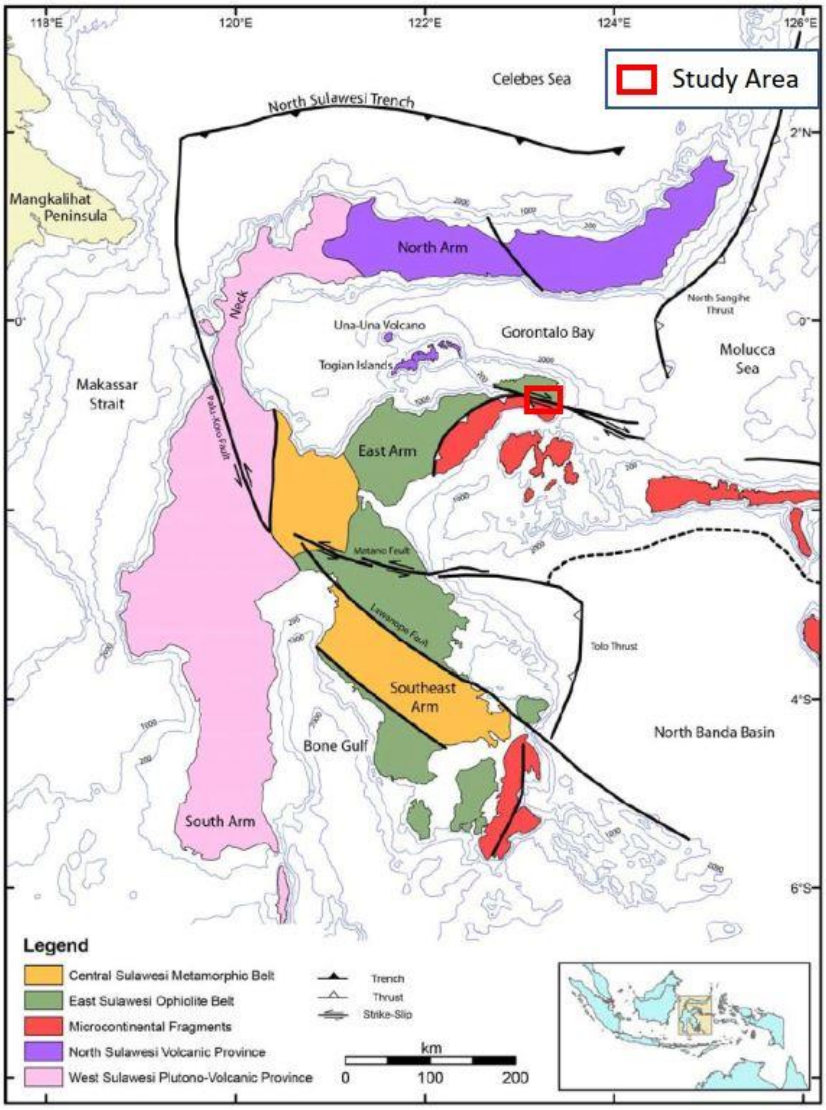

Figure 2: *Main Tectonic Groups of Sulawesi (Pholbud et al., 2012).*

According to Hall (2012) and Pholbud et al. (2012) the relationship between these different tectonic units and the tectonic development of Sulawesi is initiated by metamorphic complexes located in the west and center of Sulawesi formed by accretion of fragments of the Australian continental to Sundaland in the Middle Cretaceous. During the Early Eocene, the western part of Sulawesi separated away from Borneo to form the Makassar Strait, which coincides with the spreading of the oceanic plate in the Sulawesi Sea. In the Middle Eocene to Late Oligocene there was the formation of the Volcanic Arc in the north as a result of the subduction of the Indian Ocean into the North Arm. In the Early Miocene, the East Sulawesi Ophiolite was uplifted by north-west trending obduction during Sula's collision with the North Arm. The Central Sulawesi Metamorphic Belt includes metamorphic rocks associated with ophiolite, the Sundaland plate boundary, and the Banggai-Sula Block. Regional extension from Sulawesi to the east began in the Middle Miocene, associated with rollback subduction into the Banda. There has been magmatic activity in West Sulawesi, probably mostly related to the extensional regime, since the Middle Miocene produced high-K and calc-alkaline acid igneous rocks. To the south the subduction of the Celebes Sea under the North Arm is interpreted to have started around 5 Ma. Rollback subduction in the subduction zone of North Sulawesi started a new phase of extension in North Sulawesi which is active until now (Figure 3).

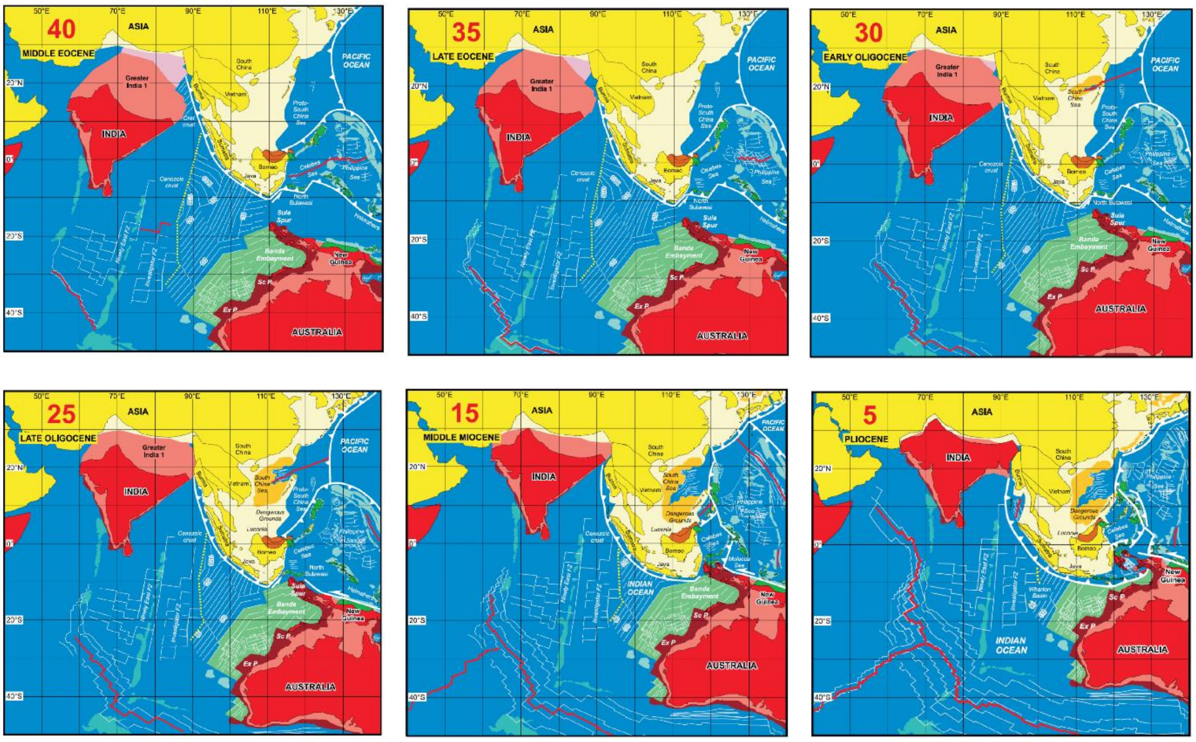

Figure 3: *Tectonic plates reconstruction of South East Asia (Hall, 2012)*

Other supporting studies shows that the Banggai-Sula microcontinent has been interpreted to have split up from Australia in the Mesozoic (Hamilton, 1979; Pigram et al., 1985; Garrard et al., 1988) which then collided with the East Arm of Sulawesi in Middle the Miocene (Simandjuntak, 1986), Middle Miocene to Pliocene (Garrard et al., 1988), Late Miocene (Hamilton, 1979), end of Miocene (Davies, 1990), and conclusively at the Neogene period from Early Miocene (Nugraha and Hall, 2018).

Batui Thrust Fault and the Poh Thrust Fault extends from the face of the thrust fault on the East Arm to the Balantak Fault continues offshore to the south then turns to north into the Moluccas Sea. The Batui Fault that stretches to the east considered to be the contact between the ophiolite and the microcontinent (Silver et al., 1983). Lots of previous research that considers the Sula Thrust Fault is considered a continuation of the Sorong Fault which is a fault stretching far to the east from New Guinea (Hamilton, 1979; Silver 1981; Silver et al., 1983; Garrard et al., 1988) (Figure 4). But after reinterpretation by Ferdian et al. (2010), Rudyawan and Hall (2012), the Sula Fault is the Banggai-Sula boundary with Maluku Sea and not the connection of the Sorong Fault because it has a different position and there is no evidence of continuity of the two faults. The Greyhound Strait Fault described by Silver, et al. (1983) as a steep fault with a northwest direction stretches about 350 km from Banggai and Taliabu Island, across the Gorontalo Bay, to the North Sulawesi arm where Katili

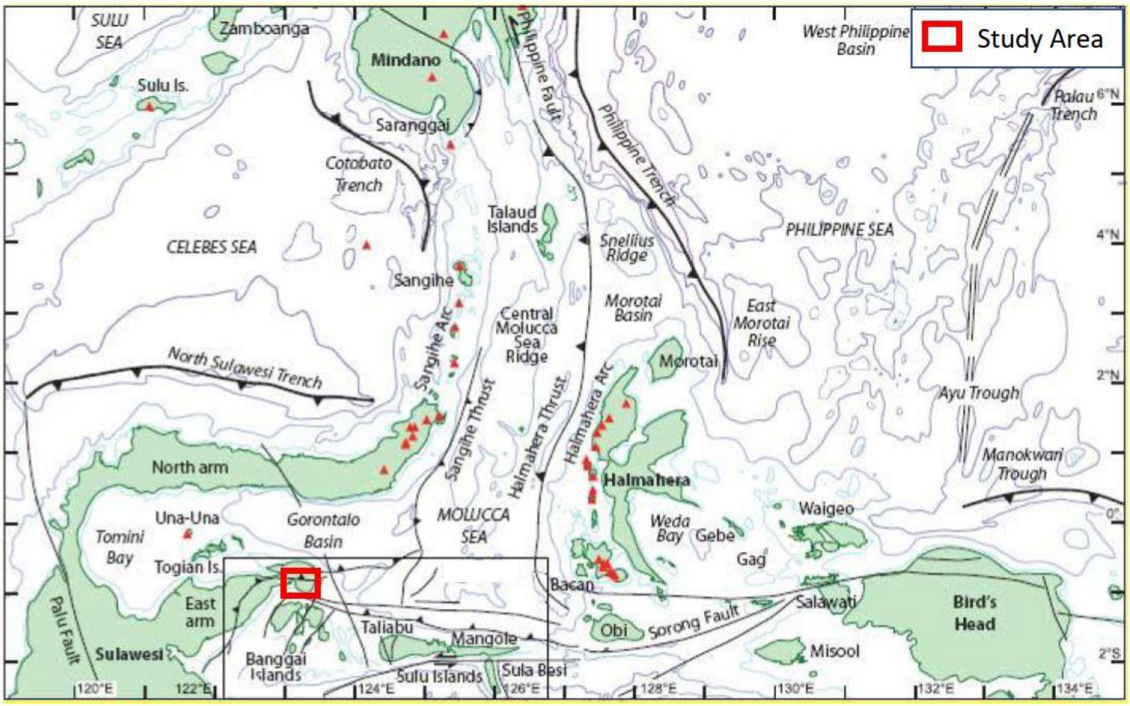

Figure 4: *Structural interpretation by Hamilton (1979) and Silver et al. (1983). Red triangles are active volcanoes and red square is Banggai-Sula Microcontinent.*

(1973) identified the Gorontalo Fault trending northwest (Figure 5).

The Balantak Fault is often represented as a continuation of the fault in the Poh Head area. Interpretation by Simandjuntak, (1989); Cottam, et al. (2011) suggest that the fault is precisely a right-lateral strike-slip fault, supported by field observations on land further to the west. The age of the fault is still unclear, but it occurred in the Pliocene to Recent because the fault probably

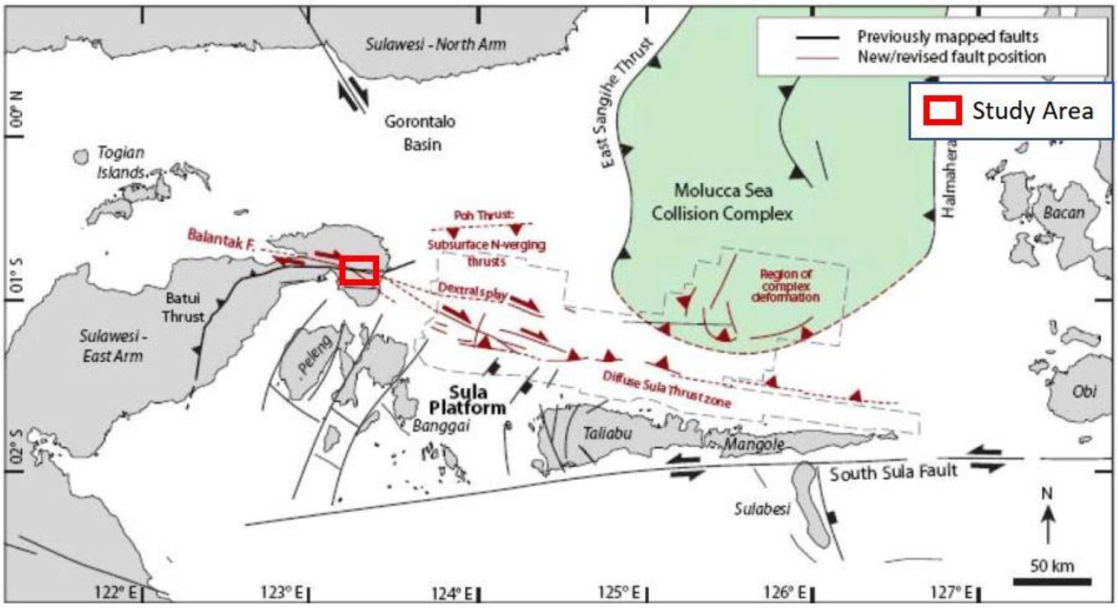

Figure 5: *Structural map and the study area (Ferdian et al., 2010).*

cut the Pliocene Volcanoclastic at Poh Head. Although the fault zone is very clearly visible on the seabed, it is not certain whether the fault is active or not. From the earthquake data under Poh Head from Global CMT (2009), it is considered to be a parallel fault surface with the Balantak Fault that shows a right-lateral strike-slip movement in the data within 14 km and a thrust fault movement with a right-lateral strike-slip component at a depth of 12 km which is almost continuous along the entire length of the 54 km from Balantak Sub-district to Teluk Poh in the West which is estimated to continue up to 30 km offshore (Figure 6).

Further studies also shows that Balantak Fault has been considered as part of the Batui Thrust Fault system (Silver et al., 1983), but the outcrop is very straight, from field observations (Simandjuntak, 1986) and changes in the direction of strike between uplift and local subsidence that indicates the fault has a steep plane with possible shear movement. Kinematic observation supports and is compatible with dextral shear sense. One of the zones in the quarter subsidence describes the termination system of the Balantak Fault off the coast to the east of Poh Head consisting of a left segment separated by folds and thrust faults. The contraction between the main left-stepping segment, which appears to be an antithetic sinistral fault with the orientation of the fold and the thrust fault is entirely kinematically compatible with the dextral strike-slip along the Balantak Fault (Watkinson et al., 2011).

REGIONAL STRATIGRAPHY

Stratigraphy that is used as reference by the author is geological map Luwuk sheet, Sulawesi by Rusmana et al. (1993), Hasanusi et al. (2012), and

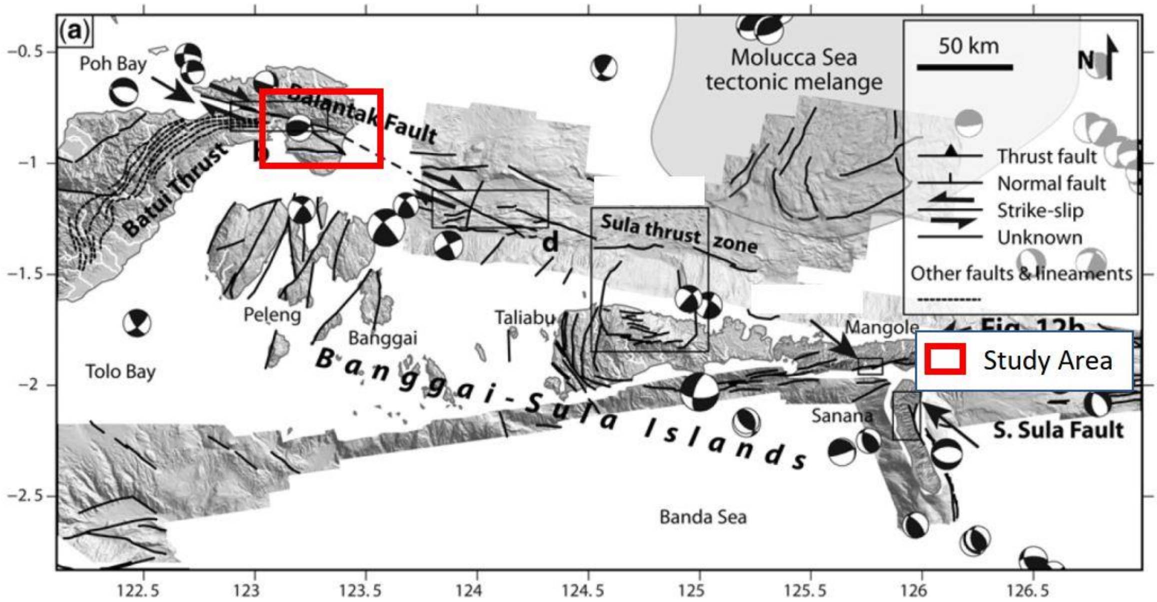

Figure 6: *DEM (SRTM) of East Arm of Sulawesi and bathymetry Banggai-Sula Island, earthquake data CMT with depth <35 km and structure that shows geomorphic proof Quarter tectonic activity (Watkinson and Hall, 2016).*

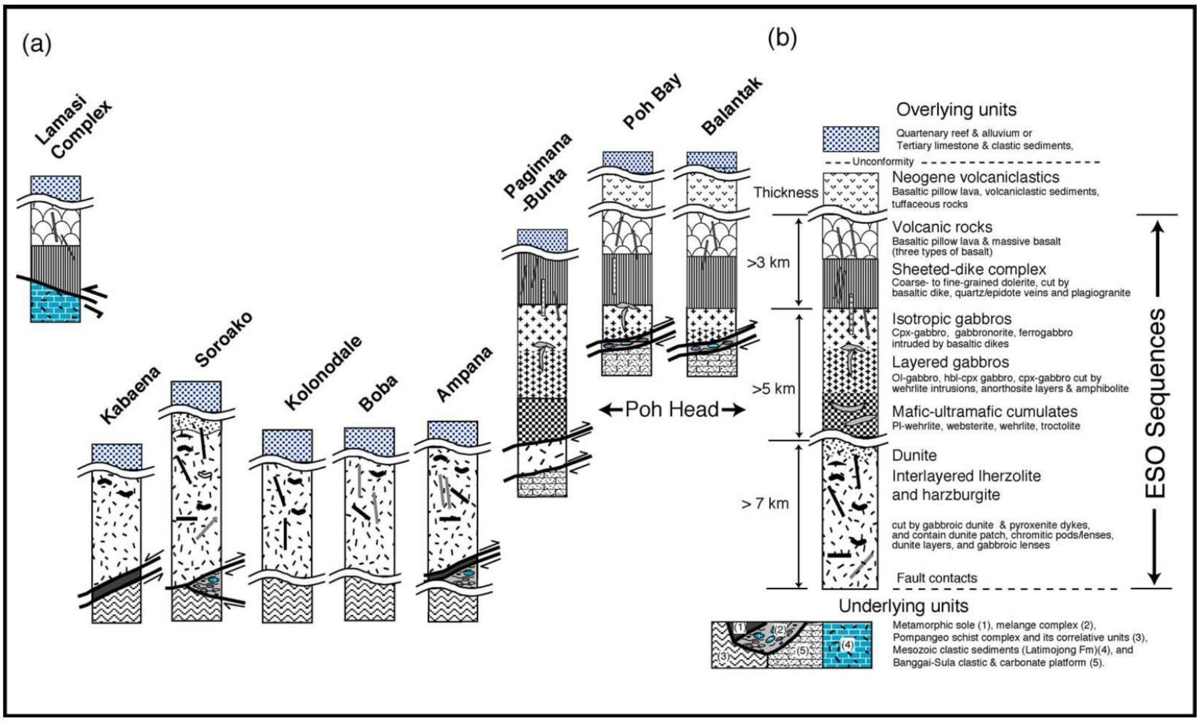

Figure 7: *(a) East Sulawesi Ophiolite column (ESO) in nine different location that is based on field investigation. (b) The reconstruction of the ophiolite series (Kadarusman et al., 2004).*

Garrard et al. (1998). Regionally, the Luwuk sheet at the study area has two main units that is Salodik Formation that consists of limestone with sandstones and Mafic Complex that consist of gabbro, basalt, serpentinite, phyllite, and schist.

Most of the Mafic Complex is found on the northern part of the study area, along the northern mountain range. The complex consists of harsburgit, dunite, pyroxenite, serpentinite, gabbro, diabase, basalt, and diorite. Schist, amphibolite, phyllite and metamorphozed gabbro are also present locally and suspected as part of an oceanic crust (Rusmana et al., 1993). According to Kadarusman et al. (2004), the Mafic Complex is a series of ophiolite rocks that compose the oceanic crust that is tectonically dismembered and spread from the centre and eastern part of Sulawesi. This ophiolite from bottom to the top consist of residual mantle peridotite and mafic-ultramafic accumulation from layered to isotropic gabbro, sheeted dolerites and volcanic basalt rocks (Figure 7). Ophiolite complex in Sulawesi indicates formation and displacement of various plate tectonics and considered very related with the triple junction plate phenomenon of Eurasia, Indo-Australian, and Pacific that is complex along the Late Mesozoic – Early Tertiary (Hutchison, 1975; Hamilton, 1979). The age of these rocks range between Middle Cretaceous until Late Oligocene, widely known as Balantak Ophiolite and considered to be part of the Eastern Sulawesi Ophiolite Belt that is far more extensive (Simandjuntak, 1986; Mubroto et al., 1994; Kadarusman et al., 2004).

Salodik Formation is widely spread on the Eastern Arm Sulawesi and locally in Banggai Island, Peleng Island, Mangole Island and a couple of surrounding small islands. Research is conducted by Sihombing et al., (2011) that divided this limestone unit into two parts: lower part that consist of grainstone-rudstone that is rich with Nummulites fossil, whereas the upper part consists of mudstone, wackestone, packstone and grainstone. The thickness of Salodik Formation is estimated to be around 1000 to 1200 meters.

According to Garrard et al. (1998), and Hasanusi, et al., (2007) the Salodik is a group that is divided into three parts that is Tomori Formation, Matindok Formation and Minahaki Formation. Tomori Formation is aged Eocene to Early Miocene, consist of reef that is underlain by clastic sediments gradually to the upper part of it and covered by limestone. Matindok Formation is aged Middle Miocene that consist of clastic sediments with lignite interbedding. Minahaki Formation is aged Late Miocene and consist of carbonate shelf deposition (Figure 8).

Husein et al. (2014) proposed on dividing the formation to three facies that is Nummulitic Grainstone-Rudstone that is deposited in Early Eocene to Late Eocene, grainstone with interbedding calcareous sandstone that contains smaller Nummulitic fossil, and rudstone with interbedding reefal limestone that is aged Early Eocene to Middle Miocene which these facies are characterized as framestone and a couple of bindstone that consists of coral, mudstone algae, and grainstone that has Nummulitic fossil.

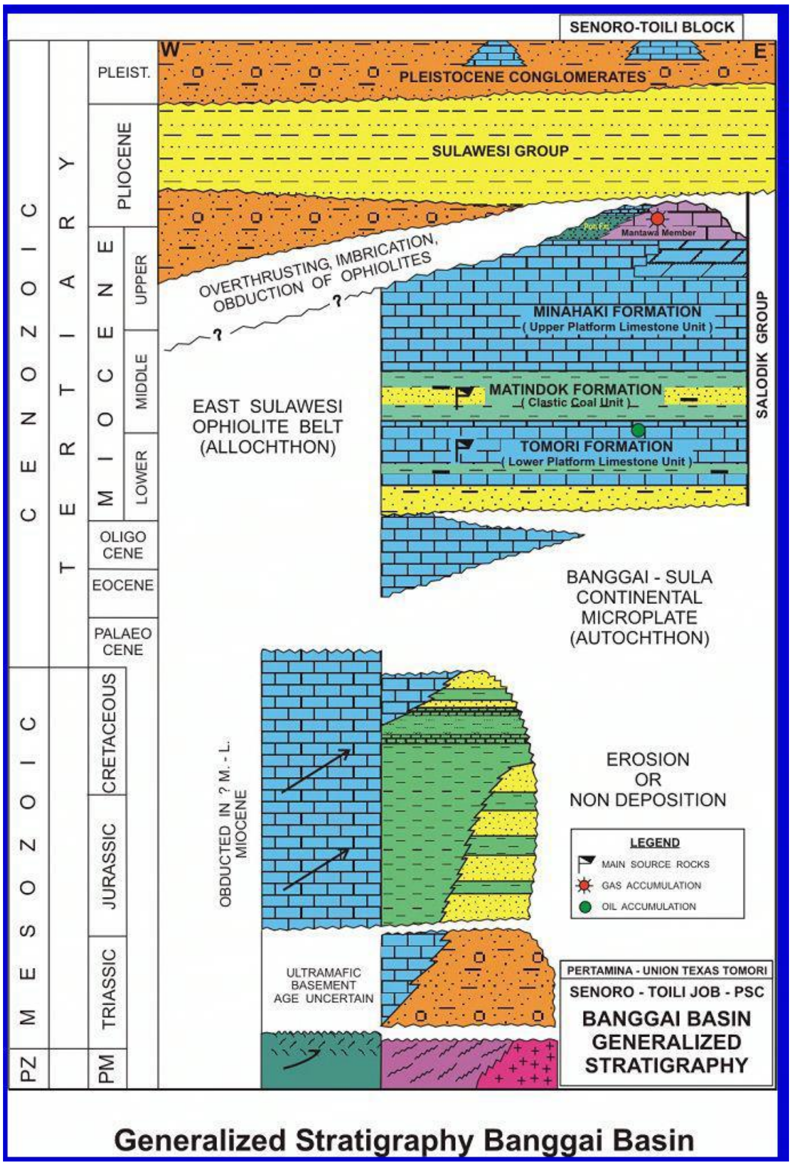

Figure 8: *Regional Stratigraphy Luwuk-Banggai Basin (Garrard et al., 1998; Hasanusi et al., 2007).*

Surono et al. (1994), Rusmana et al. (1994), and Husein et al. (2014) analyzed fossils in Salodik Formation that are *Proporocyclina*, *Numulites* sp., *Marginospora* sp., *Amphistegina* sp., *Operculina* sp., *Lepidocyclina* sp., *Fasciolites* sp., *Cycloclypeus* sp., *Alveolinella* sp., *Sorites* sp., *Rotalia* sp., *Flosculinella* sp., *Brizolina* sp., *Planulina* sp., *Heterostegina* sp., *Miogypsina* sp., *Globorotalia menardii*, and *Orbulina universa*. This indicates the depositional environment was shallow waters on the fore-reef shelf. Surono and Sukarna (1993) conducted biostratigraphy analysis and bring up the age of Salodik Formation to be Early Miocene to Middle Miocene. Rusmana et al. (1994) on the other hand proposed a different age that is Eocene to Late Miocene while Husein et al. (2014) conclude the age is Early Eocene to Middle Miocene.

Based on data taken in the field and results from laboratory analysis, the stratigraphy of the study area consists of four unofficial rock units from the oldest to the youngest, starting with Cretaceous Ultramafic Units formed in the oceanic crust environment, Limestone Unit 1 that consist of grainstone intercalating calcareous sandstone which the age is around Middle Miocene with a backreef depositional environment and nearshore-inner neritic forereef shelf, Limestone Unit 2 that consist of rudstone with limestone fragments which the is Late Miocene age with a backreef depositional environment and outer neritic foreref shelf, and Alluvial Plains Unit of Recent age, which was deposited in a terrestrial environment.

DATA AND METHODS

Field Structural Geology

The geological structure of the study area consists of faults and folds. The fault structure found in the study area is the strike-slip fault, blind thrusts with repetition of sedimentary rock strata and tear faults that offsets the thrust fold belts. The folded structure found in the study area is in the form of synclines and anticlines from different directions of the bedding planes (Figure 9).

The formation of geological structures in the study area is influenced by the collision between the Banggai Sula microcontinent and the Eurasian continent in the Ophiolite section of the East Arm of Sulawesi in the Pliocene (Hall, 2012).

In the study area, the outcrops have a bedding with a NW-SE strike directions and there are also variations in the inclination of the bedding (Figure 10). The closer to the thrust, the steeper the inclination of the bedding on the hanging wall, while the inclination at the footwall and the crest of the anticline is gentle. This is interpreted as a fault propagation fold with blind thrusts which causes changes in the stance and inclination of rock strata in the study area.

The fold structures in the research area that can be mapped well are the anticline which is commonly found in the field and synclines. The syncline fold structure in the Rau area is interpreted based on the trellis river pattern on the Kiloma River and the Balantak River. This is supported by

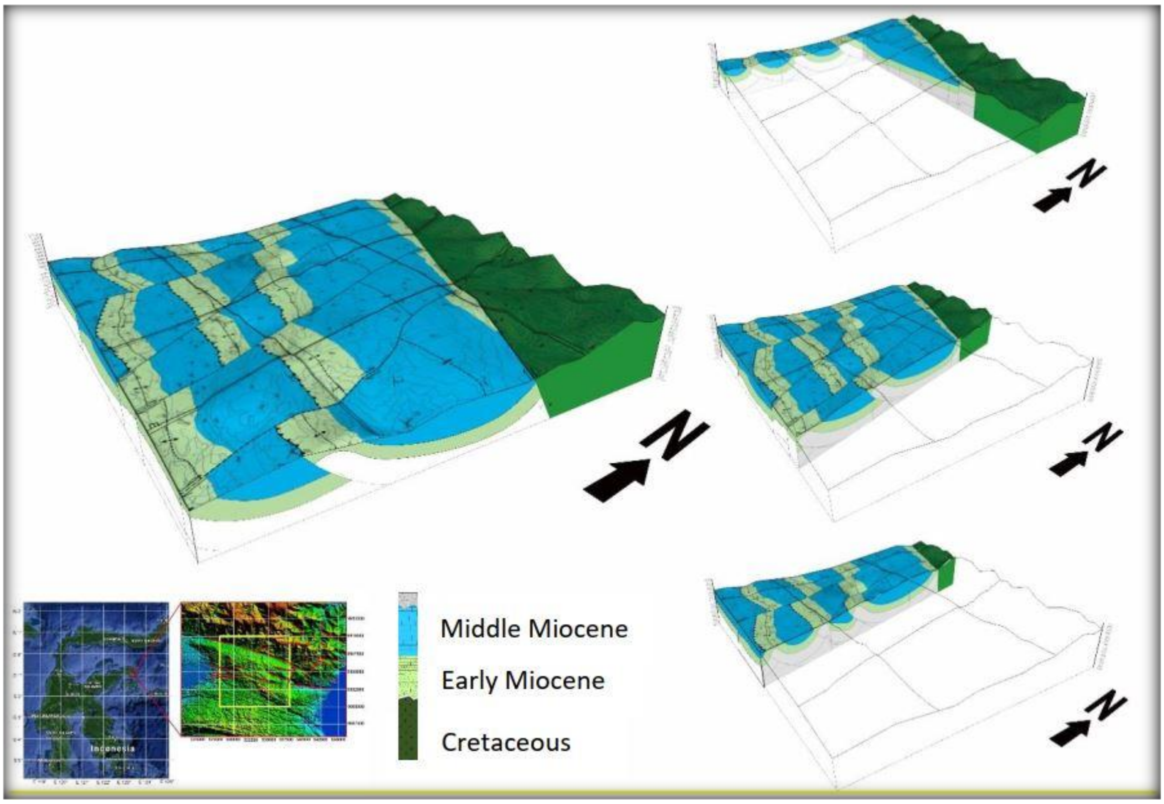

Figure 9: *Block Diagram of the study area showing the geological structures from field observation, the colours show the lithology units.*

the difference in the position of the rocks in the two rivers with opposite inclination direction. Limestone in the Balantak River has a bedding inclination towards the Southeast (Figure 11a). Meanwhile, the Kiloma River has a rock layer slope to the Northwest (Figure 11b).

Figure 10: *The inclination of the NE-SW strike bedding in Limestone Unit 1 caused by deformation. Yellow lines show the lithology units.*

The anticline fold structure in the Boloak area is interpreted based on the pattern of the trellis river and there is a lot of anticlinal repetition from north to south. This is

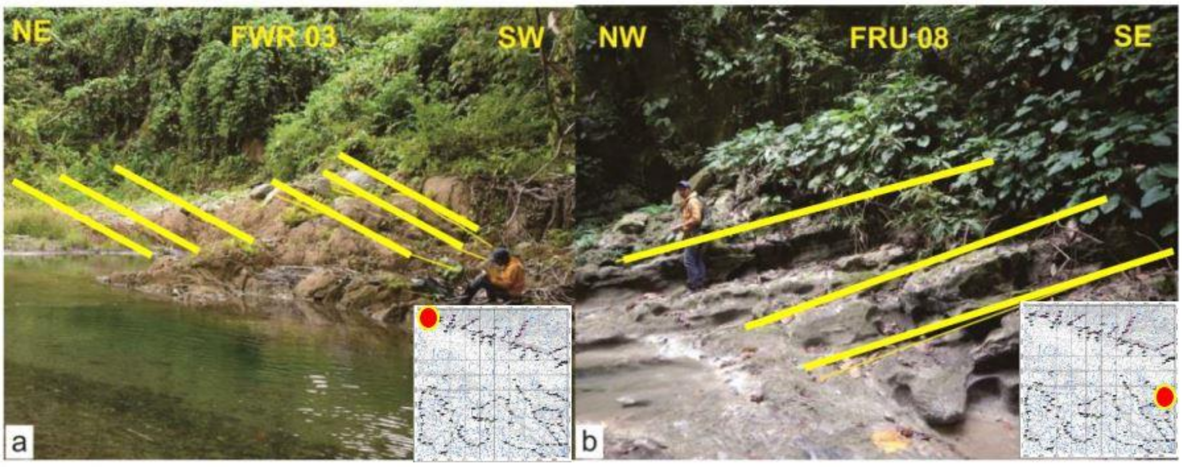

Figure 11: *Bedding inclination in Limestone Unit 1 a) Balantak River and b) Kiloma River*

supported by differences of the inclination direction of the rocks in the rivers of the Boloak area. The Limestone Unit 1 in the Boloak River on the left of the river has a northward bedding (Figure 12a). While the right side of the river has a slope of rock layers to the south (Figure 12b).

Structures found on the sedimentary rocks from field observations are considered as blind thrust faults (Figure 13) with tear faults, folds, and repetitions of rock layers which is commonly interpreted as thrust fold belts.

The fault structure in the study area is interpreted to occur in one deformation stage. The deformation that occurs is convergent, namely the collision between the Banggai Sula microcontinent and the Eurasian continent in the East Arm of Sulawesi in the Pliocene (Hall, 2012). The Balantak Fault which is a right-lateral strike-slip fault shown from slickenside observations in the field along the Balantak River is very suitable to be the main fault that develops other structures. The deformation is interpreted as still going on until Recent, which is supported by

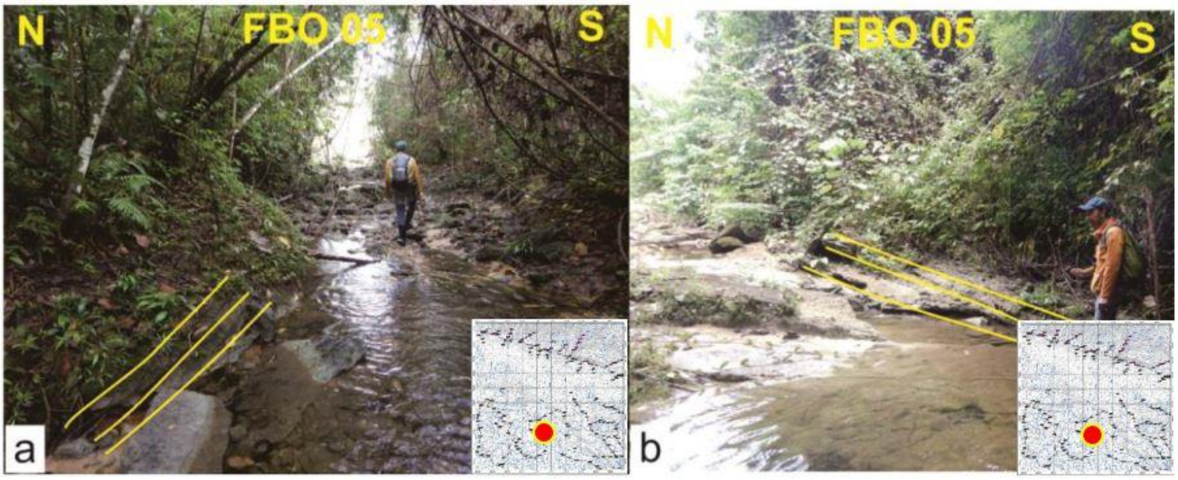

Figure 12: *Bedding inclination in Limestone Unit 1 a) Boloak River on the left and b) Boloak River on the right.*

two seismic data from Global CMT (2009) which show seismic activity on the Balantak Fault. This tectonic event is considered as forming a shear zone (Figure 14) along the Balantak River which shows structures including quartz boudinage from quartz veins and brecciation of ultramafic rocks.

Kinematic Analysis of Balantak Fault

The overall regional deformation can be explained by local deformation. At the point where geological structure data is taken, in addition to representation of geological structures in the research area, it will also be used as kinematics analysis that occurs in the research area. The collision between the Ultramafic Unit and other units in the study area originating from the Banggai-Sula microcontinent began in the Late Cenozoic. The geological structure of the study area is in the form of right-lateral strike-slips fault, thrust fold belts, and offset folds on limestone, as well as the Balantak Strike-Slip Fault as a boundary between the Ultramafic Unit and other structurally related rock units. The results of the n fault-slip kinematic analysis (n = total data) apply the Marrett and Allmendinger (1990) method (Sapiie, 2016). Each dominant structure and major fault zone are shown separately. FaultKin analysis was carried out on slickenside data taken along the Balantak Fault.

According to Marrett and Allmendinger (1990) (in Sapiie, 2016), finite strain estimation is required for deformation quantification. Theoretically, finite strain can be calculated using fault-slip data through tensor summation. However, this method requires information on the magnitude of the displacement to calculate the fault slip factors given the weighting of several factors. One approach is to measure the gouge width to estimate displacement, but this method is only applicable if the fault gouge width is fractal. No fault gouge was found in the field that can support this quantitative analysis, so it is necessary to assume that all faults in each segment have the same displacement and that the faults are fractalized through an infinite strain approach. If so, the P and T axes can be used as the basis for adding

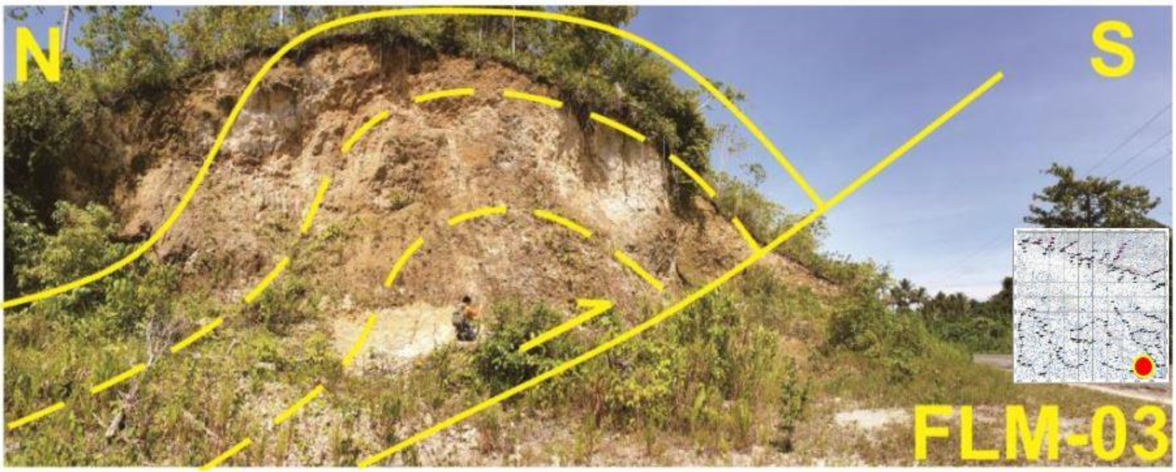

Figure 13: *Limestone Unit 1 outcrop showing a folded thrust fault structure.*

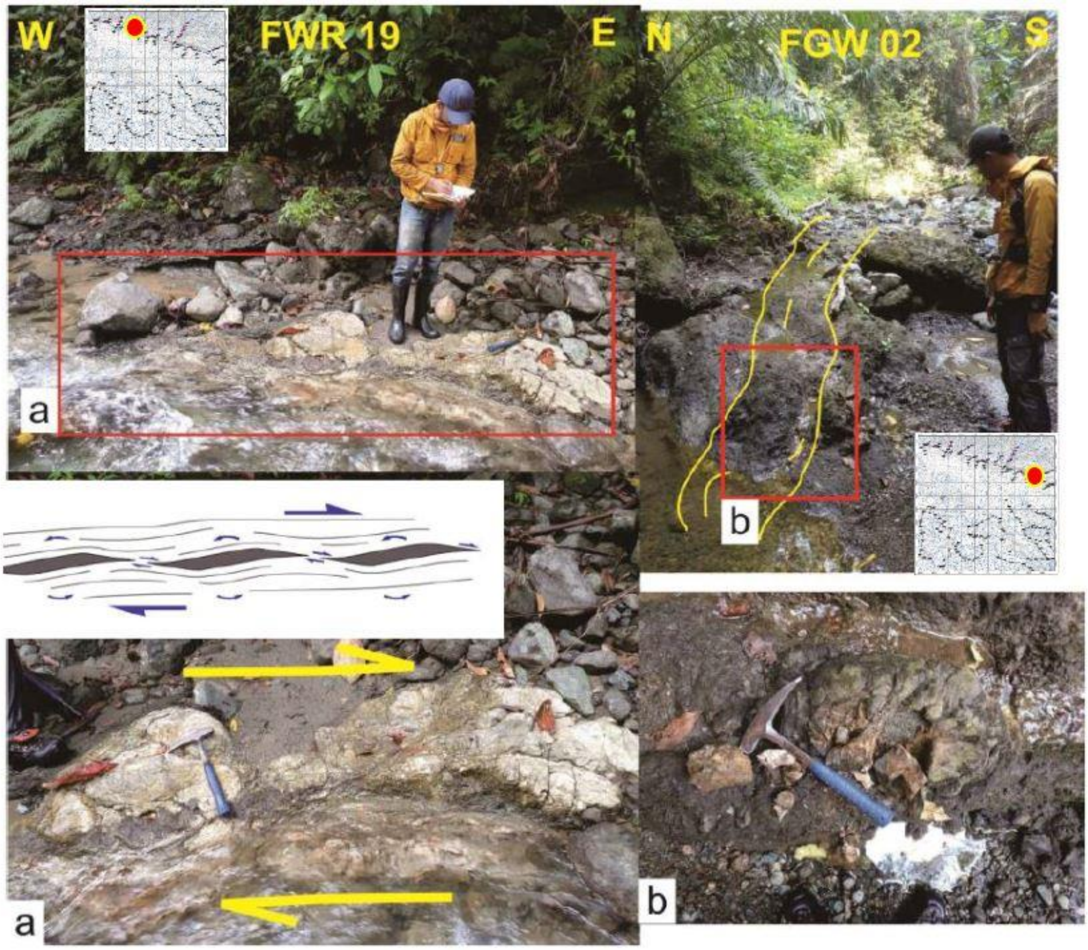

Figure 14: *The shear zone of the Ultramafic Unit shows a) boudinage with a right-lateral movement (Fossen, 2010) and b) brecciation.*

weightless tensors by using Bingham statistics that connect the P and T axes to each other (Marret and Allmendinger, 1990; in Sapiie, 2016).

The Marret and Allmendinger method produces a shortening axis (P) and an elongation axis (T) from a population of faults that have the same displacement. The basis for calculating the kinematic axes is through the infinite strain approximation. The shortening (P) and extension (T) axes of heavily contoured data used the method of Kamb (1959) to obtain the distribution and orientation of the principal stresses. The kinematic axes P and T are made by dividing the two perpendicular planes to then obtain the solution of the fit fault plane along with the shear vector and the normal vector of the faults that form 45° angles to each other. (Figure 15).

In analysis, the P and T axes are equivalent to the eigenvectors and the eigenvalues can determine their magnitude (Marrett and Allmendinger, 1990). In the kinematic analysis plot diagram, P and T are equivalent to the eigenvectors and positional. The eigenvectors also define the magnitude of the vector (Marret and Allmendinger, 1990; in Sapiie, 2016). The finite strain

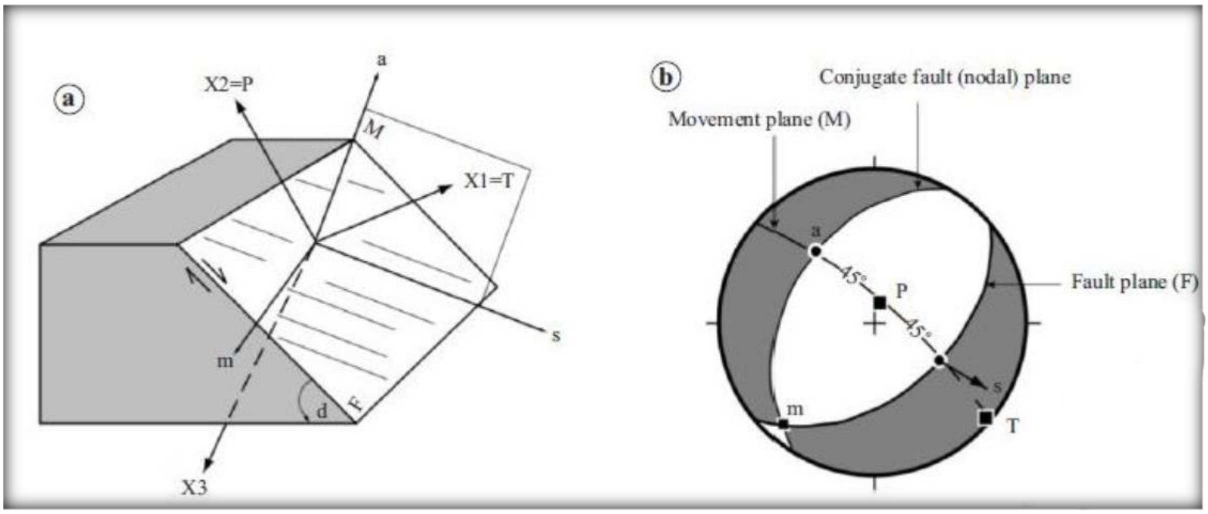

Figure 15: *a) The fault-slip geometry and kinematic coordinate system shows the relationship between the kinematic axes (X1, X2, X3), the fault plane (F), the slip direction (S), and the movement plane (M) where a = fault-pole, m = pole-plane of motion, d = fault. b) The same area projection depicts a graphical representation of the P and T axes where P and T are the main shortening and extension (modified from Marrett and Allmendinger (1990) in Sapiie, 2016).*

axes (e1, e2, e3) are plotted in a Flinn diagram to see variations in the ellipsoid strain formed in the study area. After obtaining the ellipsoid classification, it is possible to determine the type of deformation mechanism by the Balantak Fault.

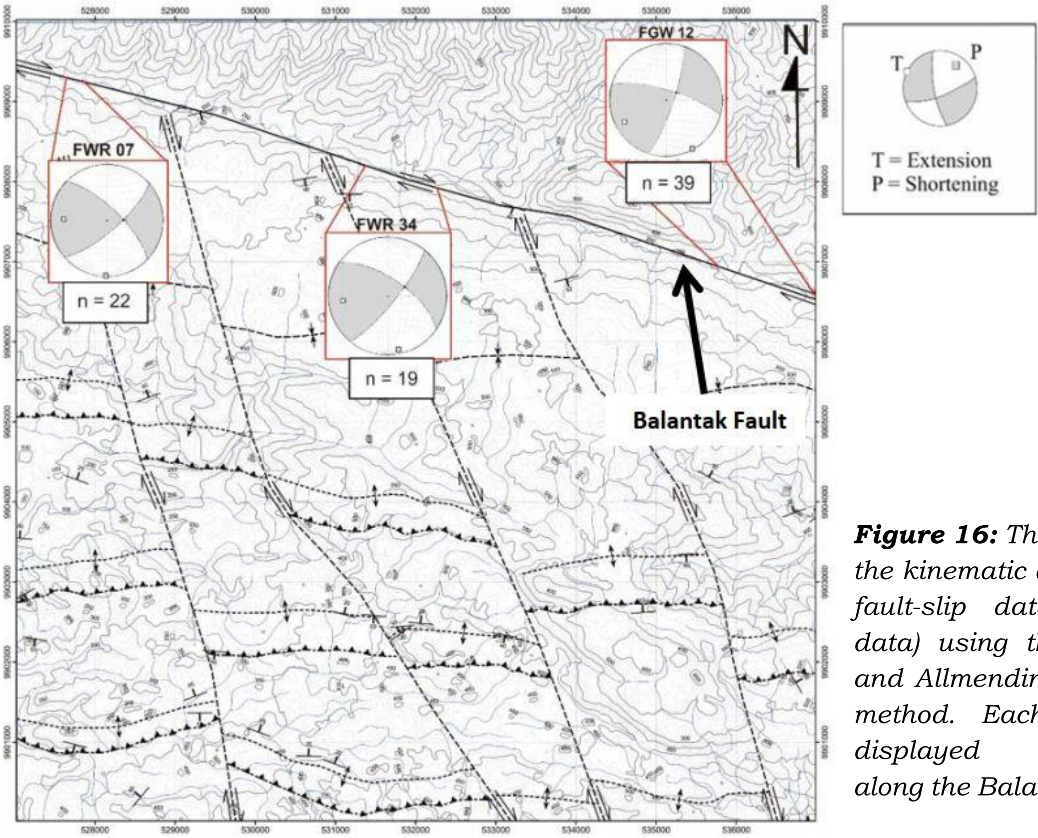

Figure 16: *The results of the kinematic analysis of fault-slip data (n=total data) using the Marrett and Allmendinger (1990) method. Each data is displayed separately along the Balantak Fault.*

Fault Slip Analysis of Balantak Fault

We can see that all fault plane solutions at three observation points along the Balantak Fault show a right-lateral movement (Figure 16). Using Fautkin's software, 80 fault slickensides have been shown to show a homogeneous kinetic axis in the direction of NW-SE shortening. The values of e1, e2, e3 are finite magnitudes and we can plot them onto a Flinn diagram to see the variation of strain formed at each measurement point (Figure 17).

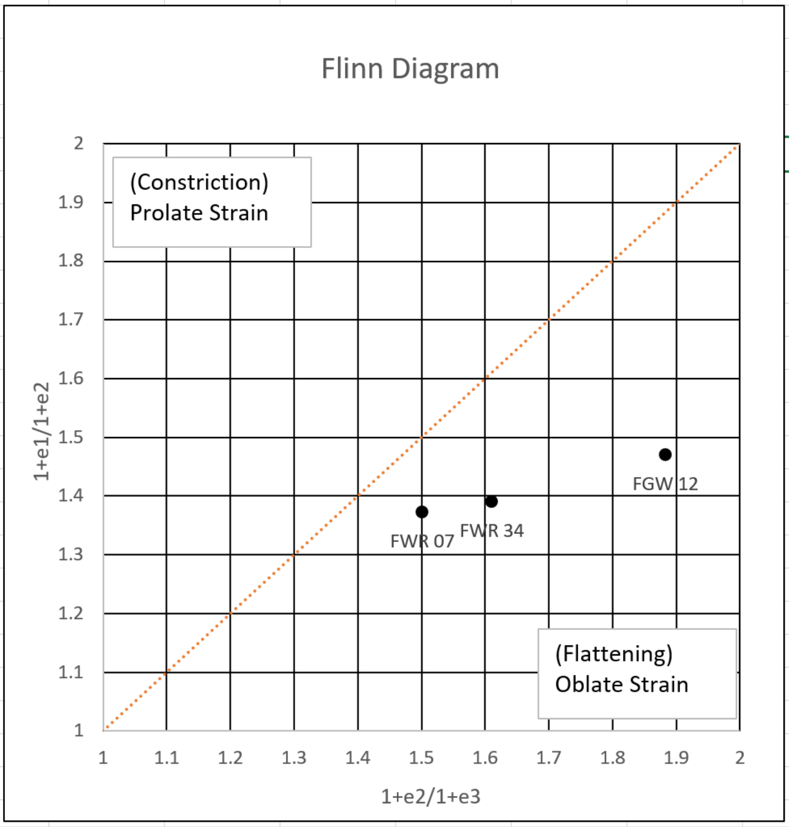

Figure 17: *Flinn diagram showing the three-dimensional shape of the strain ellipsoid determined from fault-slip data obtained from each area (Fossen, 2010).*

The calculated ellipsoid strain has the form of an oblate strain at each station. Oblate strains are considered to be in a convergent strike-slip system (Sanderson, 1984; Ratcschbacher, et al., 1993; Little, 1996 in Sapiie, 2016). Hall's (2012) tectonic setting considers the Banggai-Sula microplate to come from the southeast. We can calculate the general direction of arrival of the Banggai-Sula microcontinental plate by the average direction of the shortening axis (P) which is considered the greatest stress axis, namely 346.2° or 166.2°, NW-SE shortening (Table 1).

RESULTS AND INTERPRETATION

The angle between the maximum strain (T) and the shear zone can determine the class of the strain ellipsoid which is calculated in the illustration above (Figure 18). The observation of the results of the data

Table 1. *The method uses FaultKin which produces the relative value of the ellipsoid strain axis magnitude (e1, e2, e3) from the data for each point. pl = plunge, tr = trend.*

Structure Area	P axes (pl, tr)	T axes (pl, tr)	e1	e2	e3
FWR 07	1.5°, 177.2°	24.2°, 267.9°	0.3552	-0.0128	-0.3424
FWR 34	8.7°, 169.7°	25.2°, 263.8°	0.3852	-0.0038	-0.3814
FGW 12	2.4°, 151.7°	18°, 242.5°	0.468	-0.002	-0.47

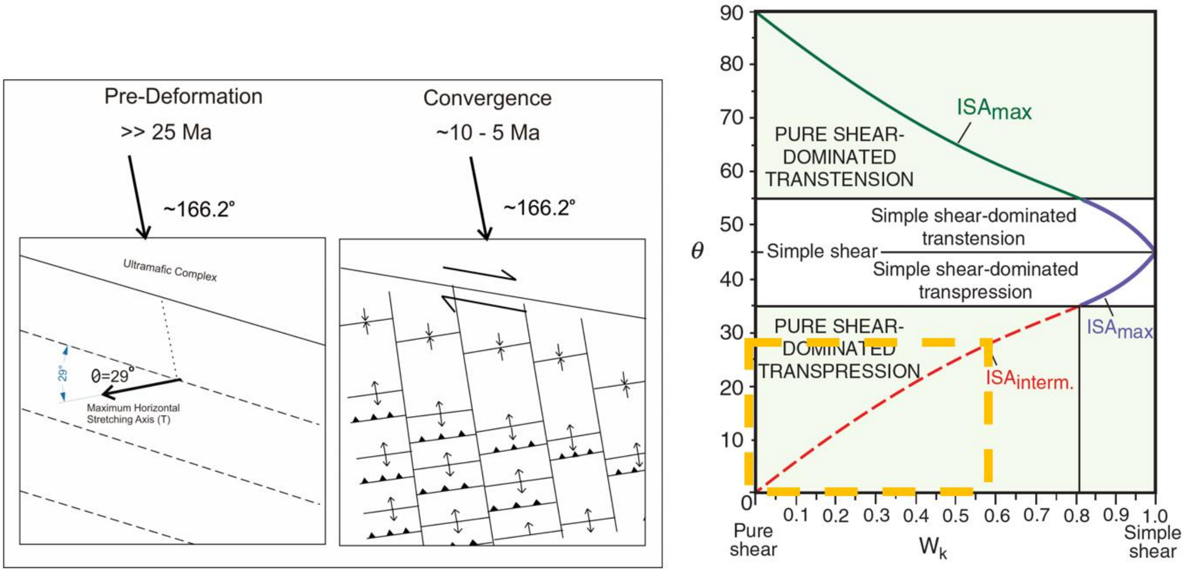

Figure 18: *The relationship and Wk where is the angle between the maximum horizontal strain (T) and the shearzone (Balantak Fault) based on Fossen and Tikoff (1993).*

analysed indicates that the pure shear component is more dominant than the simple shear with a W_k value of 0.6 which means that it is included in the transpression category (Figure 19).

This explains the formation of many folded thrust faults in almost the entire field because the vertical axis of the ellipsoid will be longer than the displacement distance. The classification of pure shear-dominated transpression is the most suitable ellipsoid strain to describe the deformation shape of the study area (Figure 20).

The results of this analysis match the regional tectonics which is a convergence area. After being analyzed it also shows that the research area is an oblique convergence in the Balantak area because the Banggai-Sula microcontinent is not head on colliding with the East Arm of Sulawesi as in the Batui area. The

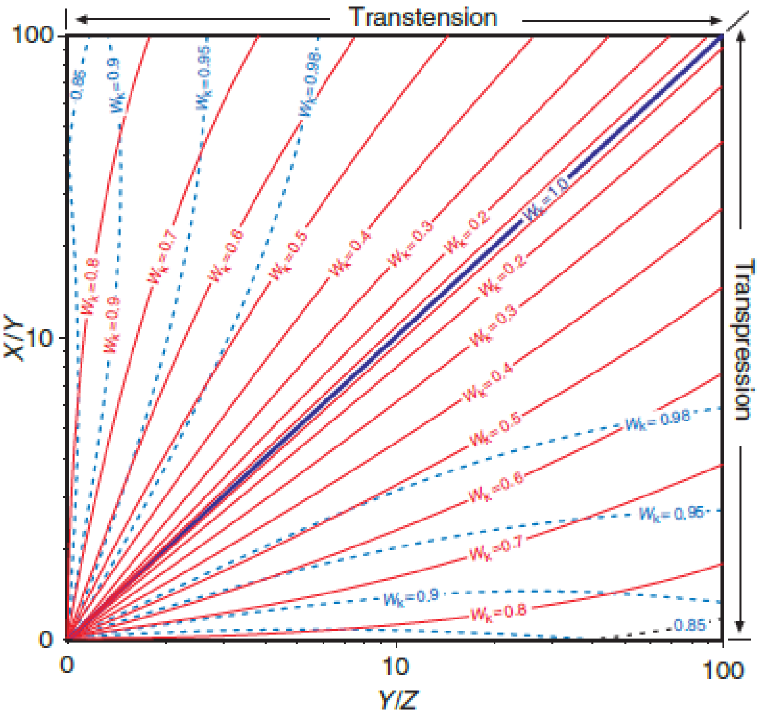

Figure 19: *Calculations show that the third point strain has an oblate strain ellipsoid that undergoes transpression with Wk = 0.6 based on Fossen and Tikoff (1993).*

eastern part of Sulawesi has been described by Hall (2012) Banggai-Sula microcontinent coming from the Australian Plate and colliding with the Ultramafic Complex of the East Arm of Sulawesi from the direction southeast in the Pliocene. The structure formed as a result of this collision is the dextral strike-slip of the Balantak Fault by including evolutionary structures such as thrust faults and tearing faults. The similarity of the structural pattern with the model indicates that the research area is interpreted as a wrench tectonic setting (Figure 21).

The research area whose structure is formed by dextral strike slip causes the type of trap formed to be different from the trap type due to ordinary pure shear at the Poh Area. The structure of the study area forms an en echelon thrust and fold trap type. Meanwhile, tear faults, which are synthetic Riedel from the Balantak Fault, form an offset fold trap type (Figure 22).

The Late Miocene to Pliocene collision between the Banggai-Sula microcontinent and the East Arm of Sulawesi deformed the rock intensively. This collision occurred due to the docking process of the microcontinental plate. The docking occurred because the microcontinent oceanic plate that was subducted into the East Arm of Sulawesi has run out. In the study area, the collision occurred in oblique convergence and the Balantak Fault is the boundary between the two plates.

The strike-slip fault movement occurred between Banggai-Sula crystalline rock and Sulawesi East Arm crystalline rock (Ultramafic Unit) and affected the sediments above Banggai-Sula (Limestone Unit 1 and Limestone Unit 2) during the collision period between the Sulawesi East Arm plate

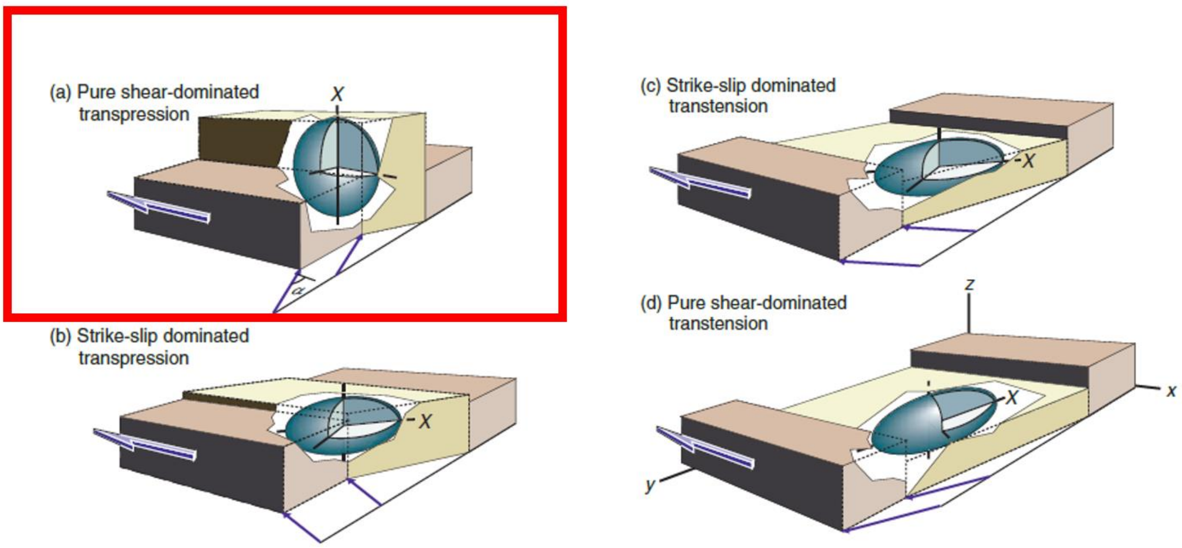

Figure 20: *The orientation and shape of the finite strain ellipsoid in the four classes of transpression/transtension. Balantak is in the form of an ellipsoid strain of pure shear dominated transpression (Fossen, 2010).*

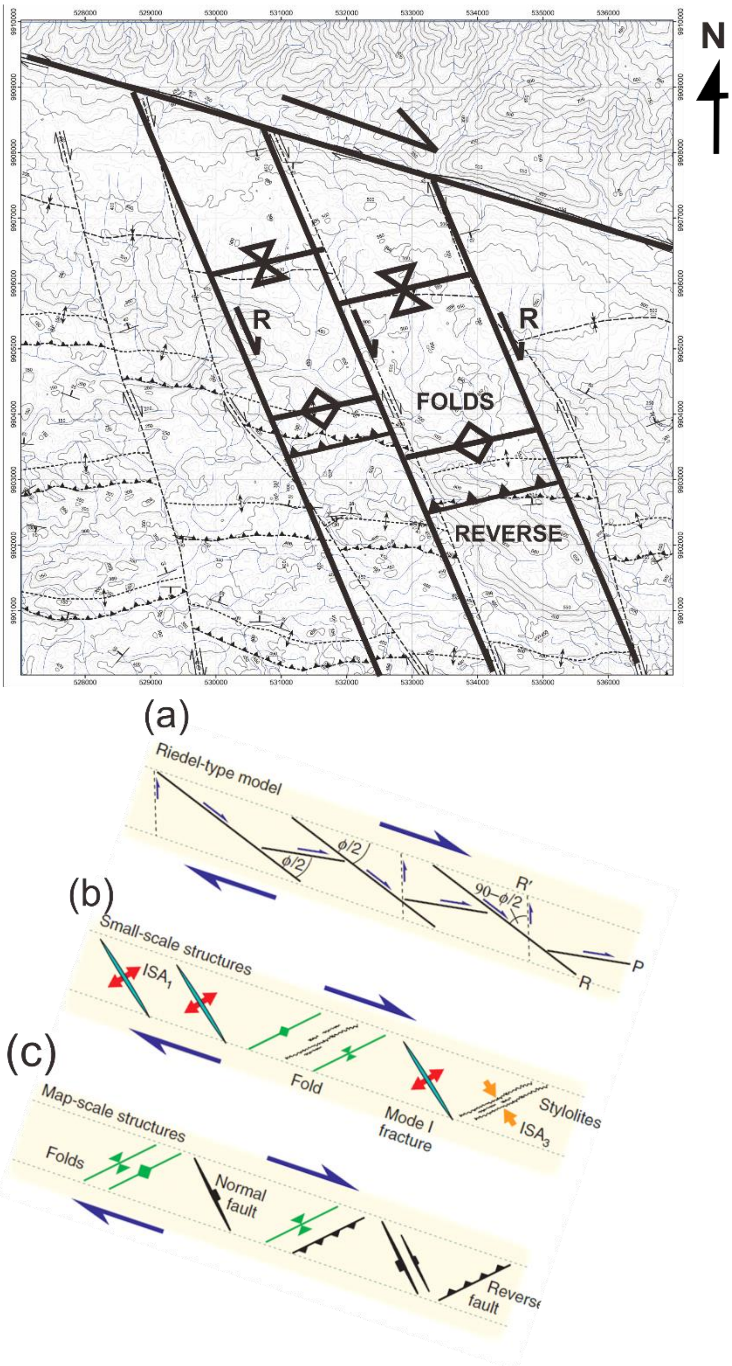

Figure 21: *The geological structure of the study area is juxtaposed with the ideal model of the strain pattern by dextral shear fault movements. (a) Riedel-model where R = synthetic Riedel and R' = antithetic. P-shears are secondary structures associated with the R and R' surfaces. is the internal shear angle. (b) Small-scale structures that can form in shear fault zones. (c) Large-scale structure. (Fossen, 2010).*

and the Banggai-Sula microcontinent which shows the current geological conditions (Figure 23).

CONCLUSION

The pattern of the tear fault close to the main fault of the Balantak Fault resembles the pattern of the minor fault in the classical experiment. The tear fault is interpreted as R (synthetic Riedel fracture). Anticlines, synclines and thrust faults perpendicular to these tear faults are interpreted as concurrent structural features. The main fault is the Balantak Fault on the surface parallel to the primary shift zone in the bedrock. Kinematics analysis revealed that the study area near the Balantak Fault has a structurally uniform domain in character.

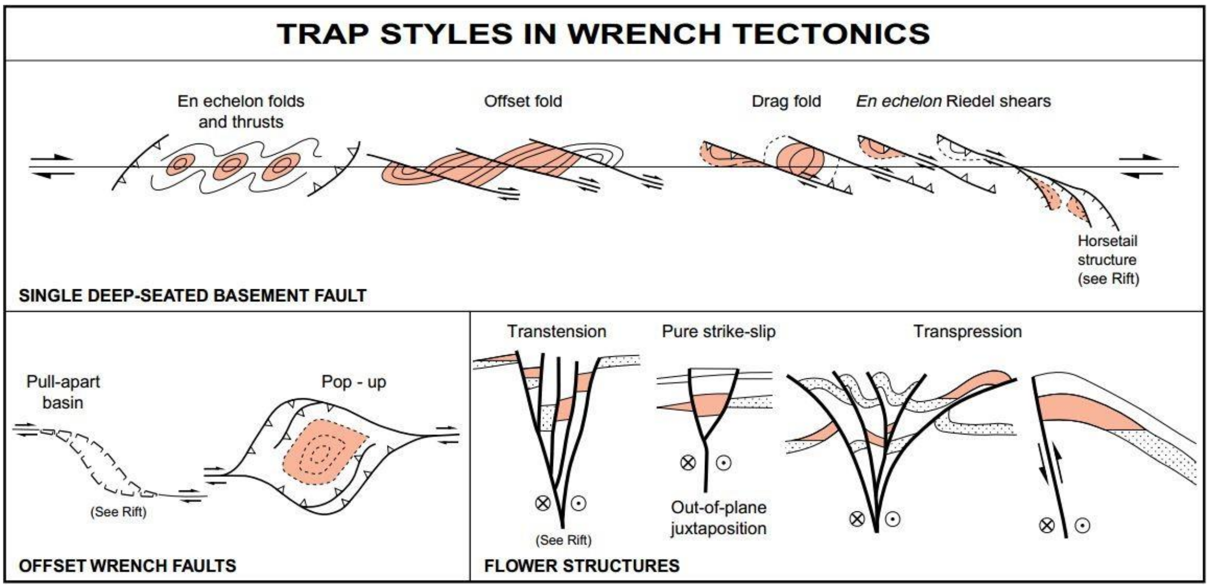

Figure 22: *Trap types within the wrench tectonic setting (E&P Geology Forum, 2009).*

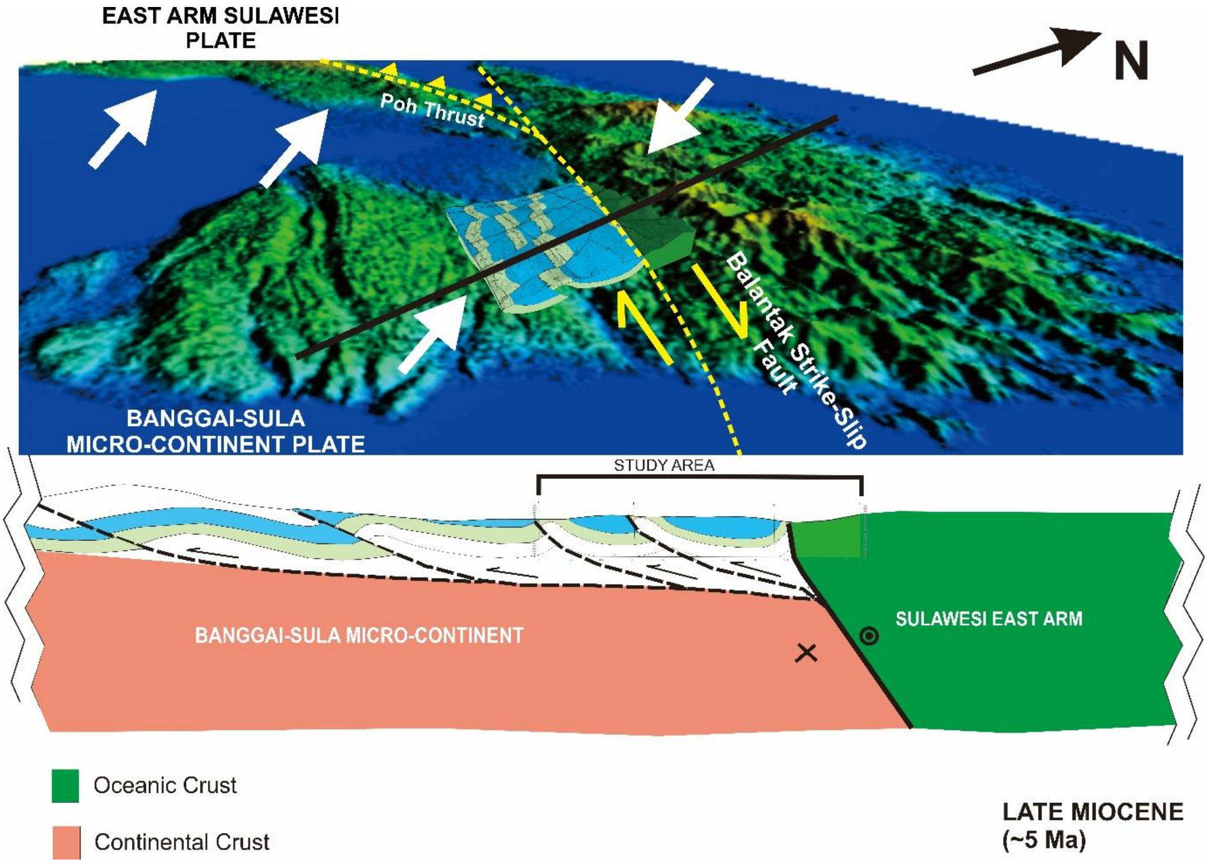

Figure 23: *A simple model of the research area as it exists today. Oblique convergence at the Banggai-Sula plate border with the East Sulawesi arm in the Balantak area during the docking process due to the depletion of oceanic crust belonging to the microcontinent.*

The discovery of anticline, syncline, and thrust fault structures in the dextral strike slip system of the Balantak Fault is the background for the kinematics analysis. The results of the study stated that the ellipsoid strain found in the field was a pure shear dominated ellipsoid. This explains that the greatest strain actually occurs vertically so that even in the shear system, folds and thrust faults can be found as in the study area. The type of trap structure due to this arrangement will be slightly different from the usual, namely en echelon thrust fault folds and offset folds.

Further study is needed such as integration with subsurface data to confirm if the structures on the surface is similar with the structures in the subsurface.

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Abiogenic gas seepage from serpentinite at Tanjung Api, Tomini Bay, East Sulawesi

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INTRODUCTION AND SUMMARY

Oil and gas seeps are common across the Indonesia region and are usually associated with breached anticlines or faults in Cenozoic or Mesozoic sedimentary basins, where they were generated from biogenic or thermogenic conversion of organic matter in sediments. In contrast, the methane gas at Tanjung Api in East Sulawesi is emerging from an area of ultramafic mantle rocks, which are part of the large East Sulawesi Ophiolite Complex (Figures 1 and 2).

Tanjung Api is a prominent cape along the South side of Tomini Bay (also called the Gorontalo Basin, along the north shore of the East Arm of Sulawesi). The name means 'Fire Cape' and reflects the presence of several burning gas seeps on the beach. This phenomenon must have been active and known for more than 150 years, as the name was already shown on Dutch topographic maps in 1869, and possibly earlier (Figure 3).

In this brief review of the enigmatic Tanjung Api gas seeps, we argue that the gas is not a conventional, organic-derived hydrocarbon gas, but an abiogenic (or abiotic), gas, dominated by isotopically anomalous methane and hydrogen, which formed from the serpentinization of ultramafic rocks.

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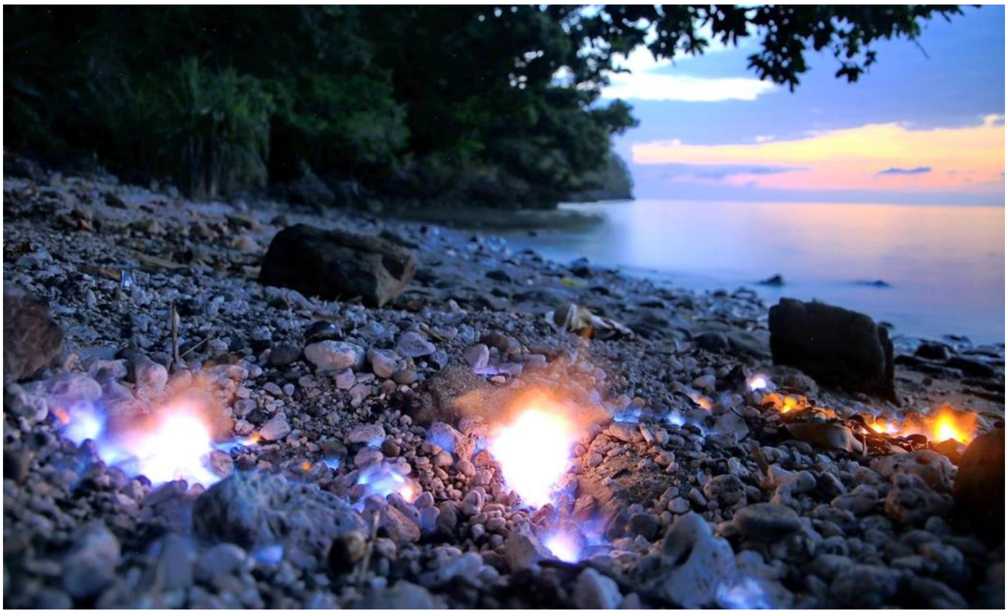

Figure 1. *Burning gas seeps on beach at Tanjung Api, Tomini Bay, East Arm of Sulawesi (Mark Levitin 2019; www.itinari.com/ eternal-fire-on-the-beach-tanjung-api-sulawesi-ivid).*

Figure 2. *Smokeless burning gas on the beach at Tanjung Api (Chien Lee 2014, www.naturepl.com, image00541862).*

Most petroleum geologists outside Russia did not accept that abiogenic hydrocarbon gas generation could exist. The overwhelming majority of oil and gas discovered could indeed be proven to have formed by thermogenic or biogenic conversion of organic material in sedimentary rocks. However, the peculiar composition of the Tanjung Api gas and the presence of very similar methane-hydrogen gases in many other ophiolite complexes in the world (Abrajano et al., 2018; Etiope et al., 2011; Etiope, 2017; Vacquand et al., 2018) shows rather convincingly that methane gas can also be generated by inorganic chemical processes, usually associated with serpentinization of ultramafic rocks.

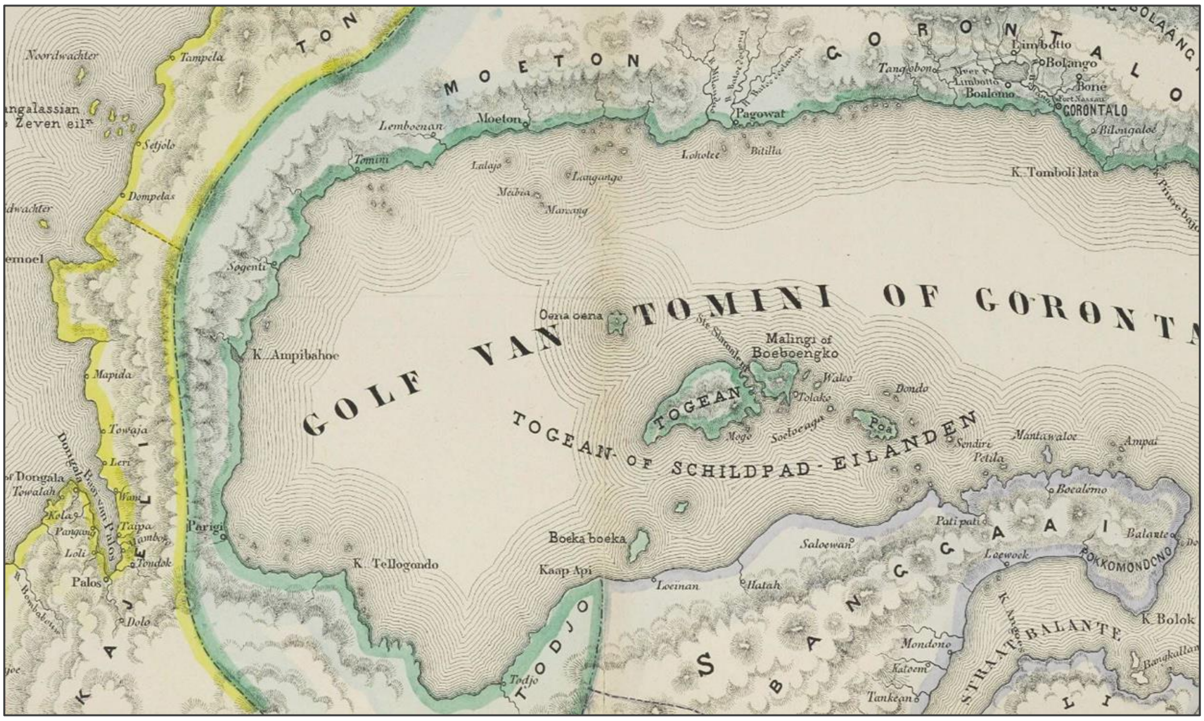

Figure 3. Part of the 'Celebes and de Molukken' topographic map in the 'Atlas van Nederland en zijne overzeesche bezittingen' by I. Dornseiffen (1870). The location of Tanjung Api ('Kaap Api') is shown on the SW side of the Gulf of Tomini, in the Sultanate of Todjo in the Residency of Manado (green outline), near the border with the Banggai District of the Ternate Residency (light blue outline). This map does not accurately portray the protruding cape of Tanjung Api, but the name does show that the burning seeps were already known before 1870.

TANJUNG API GAS SEEPS – SETTING & EARLY DISCOVERY

A prominent, rugged cape in a remote, sparsely populated area along the South side of Tomini Bay has long been known as Tanjung Api (named Kaap Api on some of the oldest Dutch topographic maps of Serne and Versteeg (1869) and Dornseiffen (1870; Figure 3). The name obviously refers to the long-active burning gas seeps here. Other names for Tanjung Api include Cape Api, Tandjong Api, Oedjoeng Api, Ujung Api or Tj. Api. The name in the local Barre language is Ngudju Apu.

The first description in the western literature of the burning gas seeps and rock types at Tanjung Api came from the well-known Dutch Calvinist missionary and ethnographer Albert C. Kruijt, who was the first European to settle in the Poso area of Central Sulawesi in 1891. Kruijt sent the information and rock samples to C.E.A. Wichmann, Professor of Geology at the University of Utrecht, who published the first petrographic descriptions of the rocks from the seep area and identified them as 'serpentinized pyroxene-olivine rocks' (Wichmann, 1896).

Kruijt's observations on the gas seeps, from a visit in August 1892, were later published in Adriani & Kruijt (1912, p. 71). He described flames of natural gas coming from the ground along the beach. He noted that when the flames were covered by seawater the flames continued to burn above the sea water. Nearby, in 1-2 m water depth, were

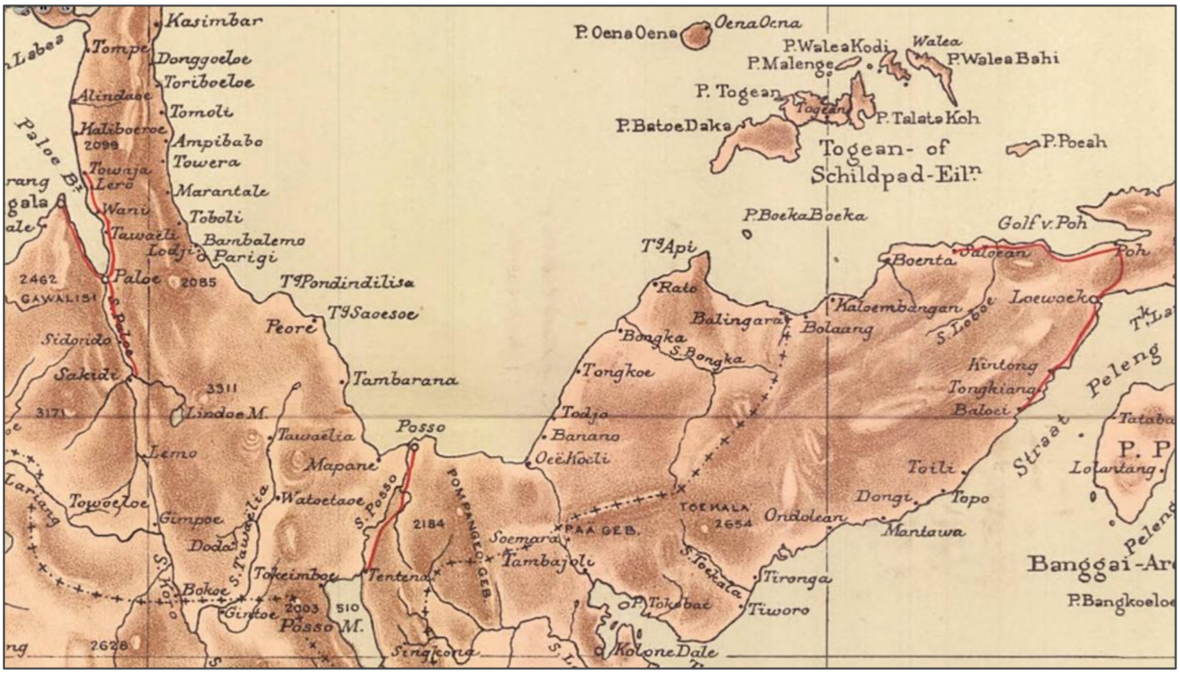

Figure 4. *Part of a more recent and more accurate Dutch topographic map of Celebes (Amsterdam, 1910), with the location of 'Tg. Api' in center of image.*

several spots of bubbling water, which according to the locals were fresh water springs with gas.

Soon afterwards, in 1903, the coastal seeps at Tanjung Api were visited and described in more detail by Dutch mining engineer Marcus Koperberg (preliminary report 1905, final report 1929; Fig. 5). He was the first professional geologist/ mining engineer to visit Tanjung Api during the 'Geological-mining Reconnaissance Project of the Manado Residency' by the Geological Survey (Dienst van het Mijnwezen).

Koperberg (1929, p. 442) noted that the rocks in the gas seeps area were mainly serpentinite and serpentinized peridotites, but he suggested those might be blocks in very coarse conglomerate, which also might contain hornblende schist (not confirmed by later workers). He also noted that the burning gas was odorless, that the flames were hardly visible during daylight hours, and that the seeps could be extinguished with water, but appeared to self-ignite again soon afterwards.

The famous early Sulawesi explorers P.and F. Sarasin (in 1895) and C. Abendanon (in 1909-1910) did not visit Tanjung Api. However, there was more interest in the geology of the East Arm of Sulawesi from the oil company Koninklijke Petroleum (Royal Dutch; BPM-Shell) in the early 1900s, probably driven by reports of oil and gas seeps along the south side of the East Arm, and they possibly also had prior knowledge of the Tanjung Api gas seeps along the North coast.

The first BPM geologist to survey the East Arm of Sulawesi was Johannes Wanner in 1905 (Wanner, 1910, 1913). It is not clear if he visited Tanjung Api, but he did report another oil seep from fractures in ophiolite gabbro in Babason creek near Dolong, which he

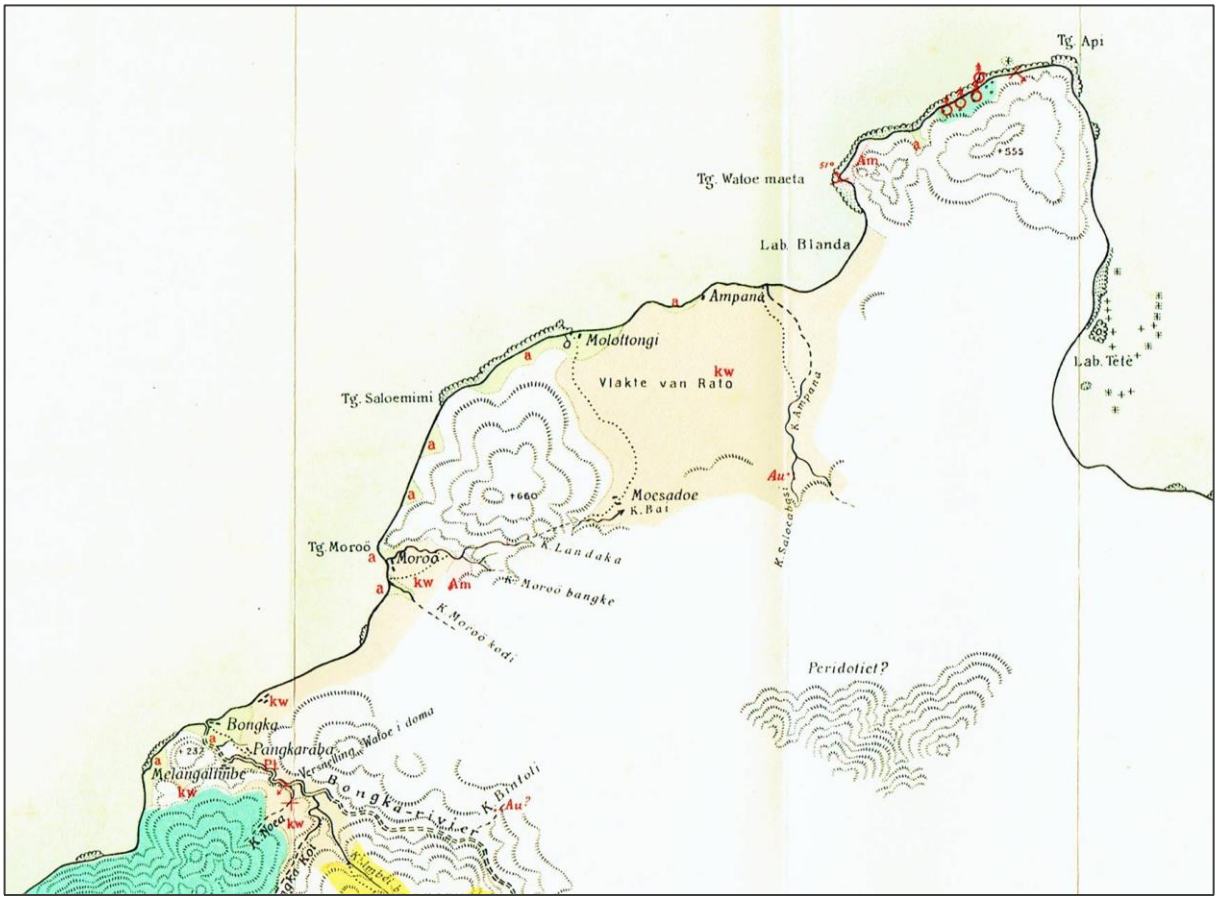

Figure 5. *Part of the geological map by government geologist M. Koperberg (1929), based on a 1903 survey. It shows areas of peridotites in green, in the SW (South of the Bongka River), NE (Tanjung Api) and probably also in the mountainous parts of the interior. Along the coast and rivers are Late Neogene- Quaternary deposits. Red symbols along the NW-facing part of the cape 'Tg. Api' are the 3-4 locations of gas seeps.*

suggested was sourced from underlying (overthrusted) Tertiary sediments. BPM geologist Hans Hirschi (1913) visited the area in 1909 and probably visited Tanjung Api, but he did not mention the gas seeps in his 1913 publication, perhaps due to BPM confidentiality policies.

Government geologist W.C.B. Koolhoven (1930) mapped the geology of the eastern part of the East Arm of Sulawesi in 1923 for the Dienst van het Mijnwezen (Geological Survey) and was one of the first to interpret the East Sulawesi ophiolite as a broad thrust sheet, derived from the North and covering imbricated Mesozoic-Cenozoic marine sediments. The age of emplacement was believed to be Middle or Late Miocene.

Government geologist J.H.F. Umbgrove briefly visited the gas seeps of Tanjung Api in 1930 and described the serpentinitic rocks around the self-igniting gas seeps as lherzolite (Umbgrove, 1930).

A second phase of more systematic geological fieldwork by BPM in the East Arm of Sulawesi was conducted in 1927-1930 by Swiss and Hungarian geologists F. Weber, L. von Loczy and E. Kundig. They also viewed the East and SE arms of Sulawesi as an alpine

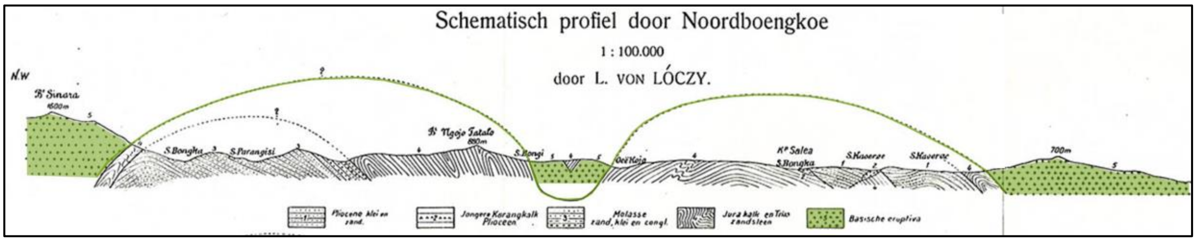

Figure 6. *NW-SE cross section from North Bungku to the Gulf of Tolo, showing folded/imbricated Mesozoic- Early Tertiary sediments in windows below an extensive overthrust sheet of gabbro-type ultrabasic rocks (Von Loczy, 1934).*

thrust belt with SE and E-directed thrusting of a large ophiolite sheet over highly-deformed Triassic- Early Miocene marine sediments (Figures 6 and 7).

It was only in the 1980s that the tectonic framework of the East Arm of Sulawesi was properly understood as the result of the arrival of a microcontinental block (the

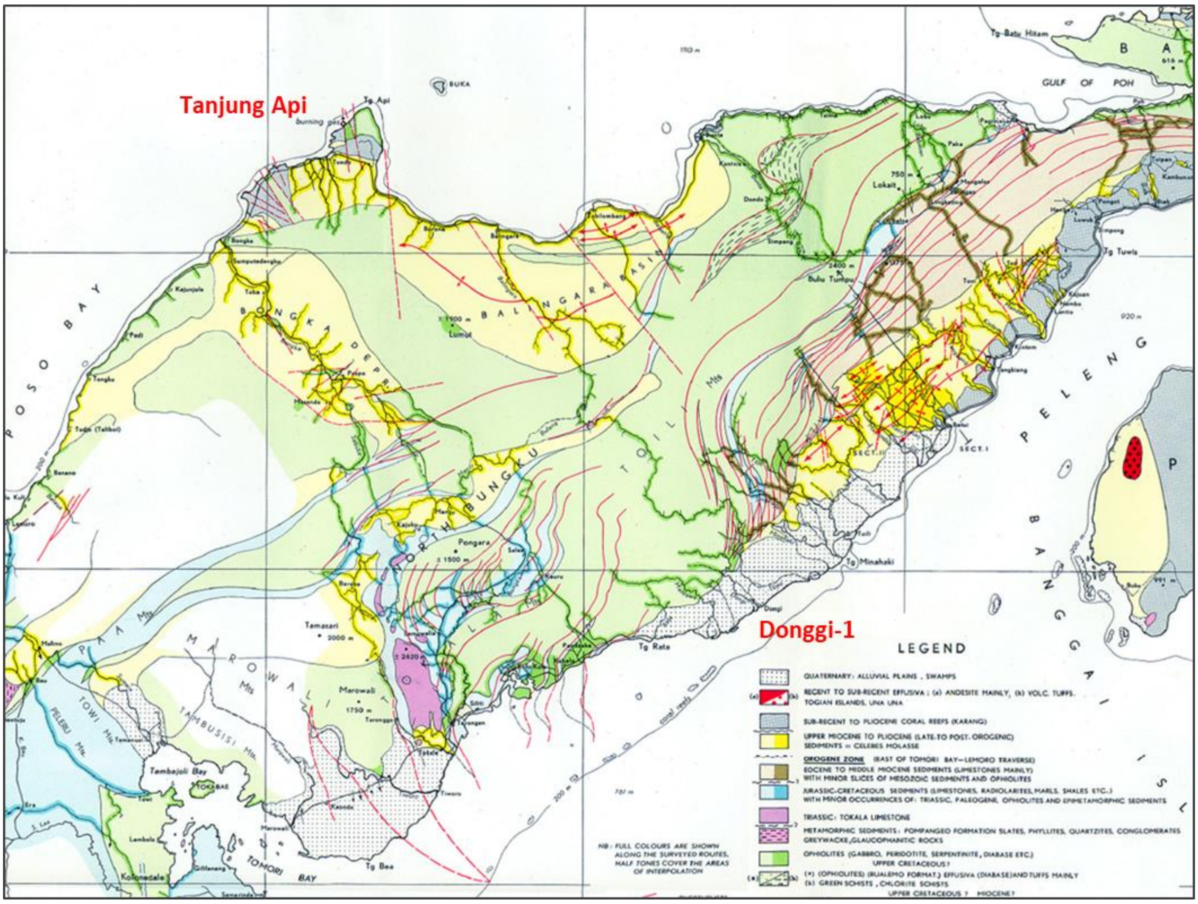

Figure 7. *Geologic map of the East Arm of Sulawesi from Kundig (1956; part), compiled from the Kundig, Von Loczy and Weber BPM fieldwork in 1929-1930, as well as earlier published work. In green is the large East Sulawesi Ophiolite sheet, with windows into underlying imbricated Late Triassic limestones (violet), Jurassic-Cretaceous pelagic limestones (light blue) and Eocene-Middle Miocene limestones (tan). In yellow Late Miocene-Pliocene post-orogenic 'Celebes Molasse'.*

Gondwana-derived Banggai-Sula block) at a subduction zone/volcanic arc. The buoyance of the subducted parts of the continental block eventually choked the subduction process and resulted in slab break-off and uplift, resulting in the apparent 'obduction' of the East Sulawesi Ophiolite (upper plate oceanic mantle and crust) over the scraped-off Mesozoic-Tertiary sediment cover of the partly subducted Banggai-Sula block (Simandjuntak, 1986). The timing of the main deformation phase was placed in Middle Miocene by Kundig (1956), mainly based on the presence of Late Miocene *Lepidocyclina* at the base of the post-orogenic 'Celebes Molasse'.

TANJUNG API GAS COMPOSITION & ANALOG OPHIOLITE OCCURRENCES

The first (and only?) chemical analysis of the gas from Tanjung Api revealed its rather unusual composition, different from 'normal' organics-derived hydrocarbon gases, like the gases produced from wells in the Tomori Gulf in the South of the East Arm of Sulawesi (Subroto et al., 2004). The gas is dominated by methane (CH_4; 52%), nitrogen (N_2; 23%), hydrogen (H_2; 16%) and oxygen (O_2; 7.3%), as well as small amounts of higher hydrocarbons (ethane C_2H_6, propane C_3H_8; 1.5%).

N_2 and O_2 are not generally parts of ophiolite-generated gases. The nitrogen-oxygen ratio in the Tanjung Api gas sample is similar to that of atmospheric gas, so these components in the sample are likely to represent about 30% atmospheric contamination during sampling, as also suggested by Subroto et al. (2004). Eliminating the N_2 and O_2 presence in Tanjung Api gas leaves us a likely actual composition of 75% methane, 1% ethane and 23% H_2.

Another typical feature of the Tanjung Api gas is the unusually heavy carbon isotope values. In nature, carbon is represented by two stable isotopes, ^{12}C and ^{13}C. Plants and marine organisms with calcareous shells preferentially assimilate the lighter ^{12}C carbon isotope into their tissues. The ratio $^{13}C/^{12}C$ (generally expressed in the formula $\delta^{13}C$ [PCB]) is therefore lower than normal in organic carbon.

The $\delta^{13}C$ values of Tanjung Api methane and ethane are -19$^{o}/_{oo}$ and -22$^{o}/_{oo}$, much 'heavier' than the usual values of biogenic hydrocarbon gas (typically near -60$^{o}/_{oo}$ for biogenic methane and -40$^{o}/_{oo}$ for thermogenic methane; e.g. Fig. 8). This clearly suggests that the carbon in the Tanjung Api gas is inorganic. Subroto et al. (2004) already recognized the unusual Tanjung Api gas as probably abiogenic, but other options were left open as well. This was the first record of possible abiogenic methane in Indonesia. Satyana (2005) explored the theory of abiogenic petroleum genesis by serpentinization in basal peridotites of overriding ophiolite complexes in Indonesian collision zones, via 'Fischer-Tropsch-type' reactions, but did not include the example of Tanjung Api (or any other ophiolite-associated gas in SE Asia).

Since the Subroto et al. (2004) paper was published, many similar abiotic CH_4-H_2 rich gas occurrences have been reported from exposed ophiolite bodies worldwide, all with'heavy' $\delta^{13}C$ values (Figure 9; Etiope, 2017; and other references), and also in many oceanic

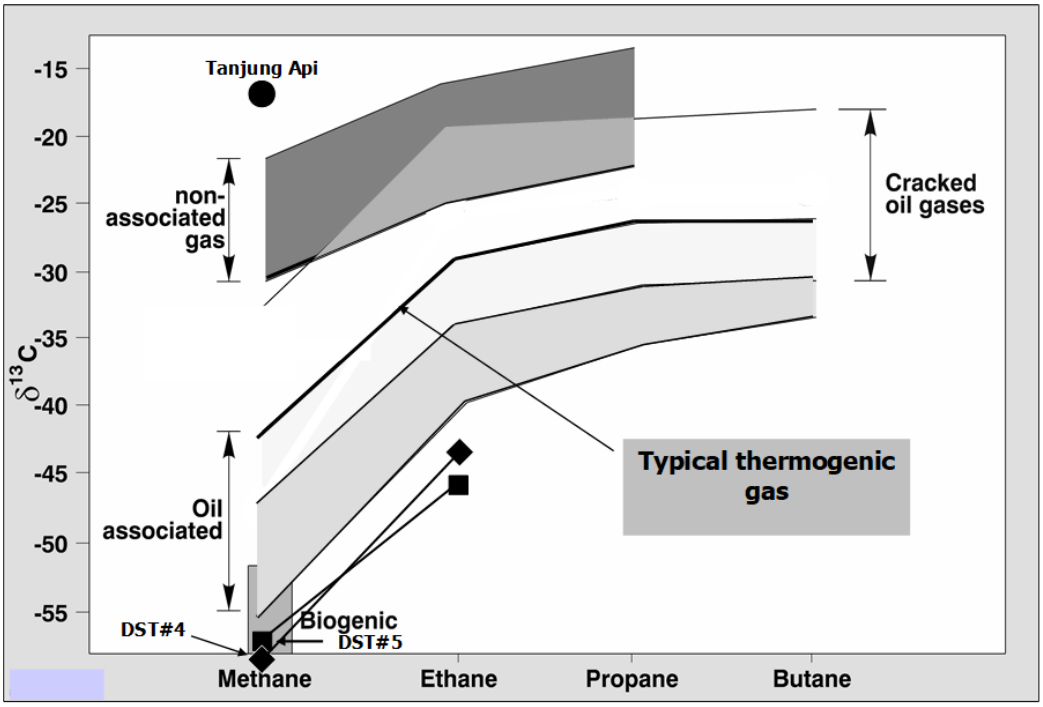

Figure 8. *Graph showing differences in [13]C carbon isotope values in methane gas samples from East Sulawesi: abiogenic ophiolite gas from Tanjung Api and biogenic methane and ethane from DST 4 and 5 in the Donggi-1 well in the Tomori area (Subroto et al., 2004).*

settings. In today's oceans such gas has been also been demonstrated from multiple hydrothermal vents along mid-oceanic ridges and transform fracture zones, typically where serpentinite is exposed at of near the ocean floor (Welhan and Craig, 1979; Deville et al., 2018). It is also documented from fluid inclusions in mafic rocks exposed on the seafloor (Klein et al., 2019; etc.).

Dr. Giuseppe Etiope, a leading Italian authority on abiogenic gas from ophiolites, confirmed that the Tanjung Api gas composition and its isotope data as reported by Subroto et al. (2004) are indeed "very, very similar to that of Chimaera (ophiolite), in Turkey, definitively mostly abiotic" (personal comm., January 27, 2022).

The generation of H_2 and CH_4 in ophiolite complexes is now well understood as the result of inorganic chemical processes during serpentinization. Serpentinization occurs where ultramafic rocks react with water, which transforms the common ferromagnesian minerals (olivine, pyroxenes) into hydrous minerals of the serpentine-group and secondary minerals like iron oxydes. This reaction also generates H_2, heat and reducing conditions. The H_2 gas thus created is then capable of reducing CO_2, if present, into methane/CH_4.

Above subduction zones, dewatering of subducted sediments is a significant source of water. CO_2 may be sourced from breakdown of subducted carbonate sediments or perhaps also from other surface sources. In the case of Tanjung Api, a carbonate source is quite likely to be present below the East Sulawesi ophiolite, which was

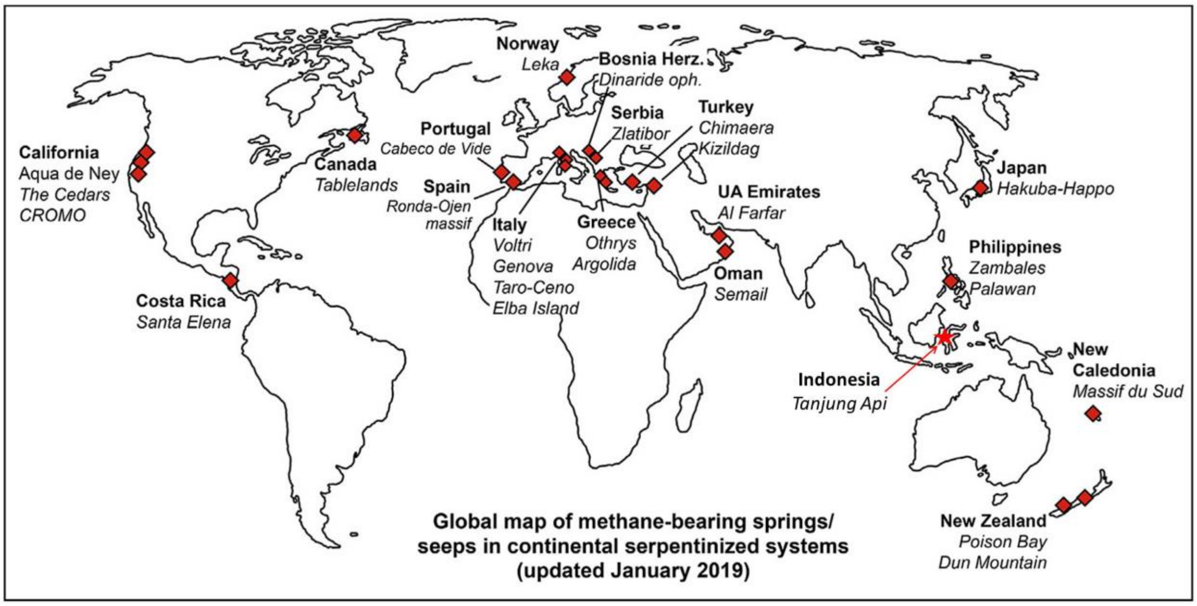

Figure 9. *Global distribution of well-documented abiotic methane occurrences from onland serpentized ophiolite complexes (after Etiope and Whiticar, 2019; with Tanjung Api shown as red star).*

'obducted' over the carbonate-rich Mesozoic-Cenozoic sediments that covered the subducted parts of the Banggai-Sula microplate.

OTHER ABIOGENIC GAS OCCURRENCES IN INDONESIA?

Until now, the abiogenic gas seeps at Tanjung Api in East Sulawesi seem to be a unique feature in Indonesia. However, similar conditions may exist in any of the other Indonesian ophiolite bodies, like in other parts of the East Sulawesi Ophiolite in the East and SE Arms of Sulawesi, or in the ophiolite complexes of Papua and nearby islands, the Meratus Range in SE Kalimantan, Halmahera, Timor and other Banda outer arc islands, as well as in Malaysian North Borneo. These all might yield similar, as yet unreported, abiogenic methane seeps.

ABIOGENIC GAS SEEPS-IMPLICATIONS FOR HYDROCARBON EXPLORATION

1. Tanjung Api and similar abiogenic gas occurences worldwide demonstrate that not all hydrocarbon gas is derived from organic sources, but it can also be generated by inorganic chemical reactions in certain geological settings without organic carbon. So far, this process has been proven only in serpentinized ultramafic rocks in obducted ophiolite complexes and in mid-oceanic ridges and fracture zones with ultramafic rocks close to the seafloor;

2. Abiotic gas may be more common than previously thought. Scrutiny of gas analyses of existing 'conventional' gas fields may reveal hitherto unrecognized contributions of abiogenic gas, a possibility not usually entertained by the petroleum industry;

3. An important implication is that methane gas shows in wells, seeps, hydrates, seismic bright spots or as fluid inclusions in rocks, are no longer proof of a working hydrocarbon system sourced from organic-rich sediments, unless carbon isotope analyses can exclude an abiogenic origin. This is especially relevant in basins with potential subcropping ultramafic rocks. For example, unpublished reports of hydrocarbon inclusions in the basal basaltic-andesitic volcanics in the Rangkong 1 well in North Makassar Straits were interpreted as proof a working hydrocarbon system and nearby source rocks by Bacheller et al. (2011; see also Satyana, 2015), although the well penetrated typical 'Celebes Sea-type' Middle Eocene-Recent deep water oceanic stratigraphy. Carbon isotope analyses should now be required before concluding that such hydrocarbon inclusions are evidence of biogenic gas generation from nearby source rocks, especially when the gas also contains H_2.

4. Today, abiogenic gas is not a target of hydrocarbon exploration. Although its existence is a fact, there are no good estimates of volumes and rates of gas that could possibly be generated from serpentinized ultramafic rocks. Although it may be a slow process, it is tempting to speculate that improved understanding of abiogenic gas generation in ophiolite complexes may someday identify 'sweet spots', from where unconventional abiogenic methane and hydrogen gas can be produced commercially.

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Geological investigations of Sulawesi (Celebes) before 1930

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I. INTRODUCTION AND SUMMARY

This paper is an overview of the early discoveries of the geology of Sulawesi, from the first naturalist expeditions in the 1820s until the 1930s. Most of the contributions to the knowleddge of the geology of Sulawesi during the Dutch colonial era came between the late 1880s and 1930, after which geological and mining investigations essentially stopped for four-decades. Before Indonesian Independence in the 1940s, Sulawesi Island had been called Celebes, a name introduced by Portuguese explorers in the early 1500s.

Geographically, Sulawesi is rather unique among the larger islands of Indonesia. Unlike the other three large islands Sumatra, Borneo and Java, Sulawesi has four ‘arms’, which are all surrounded by deep seas, and virtually the entire island is mountainous terrain without major rivers or delta systems. Active volcanism is limited to the eastern half of the North Arm and the lone Una-Una volcano in the Tomini Gulf, while Miocene and recently extinct volcanoes are present in SW Sulawesi.

Geologic exploration was challenging. Surveys into uncharted territories before 1920 (before the arrival of detailed topographic maps, air photos and satellite imagery), required topographic surveying of all itineraries with chain and compass, and with a barometer for estimating altitudes.

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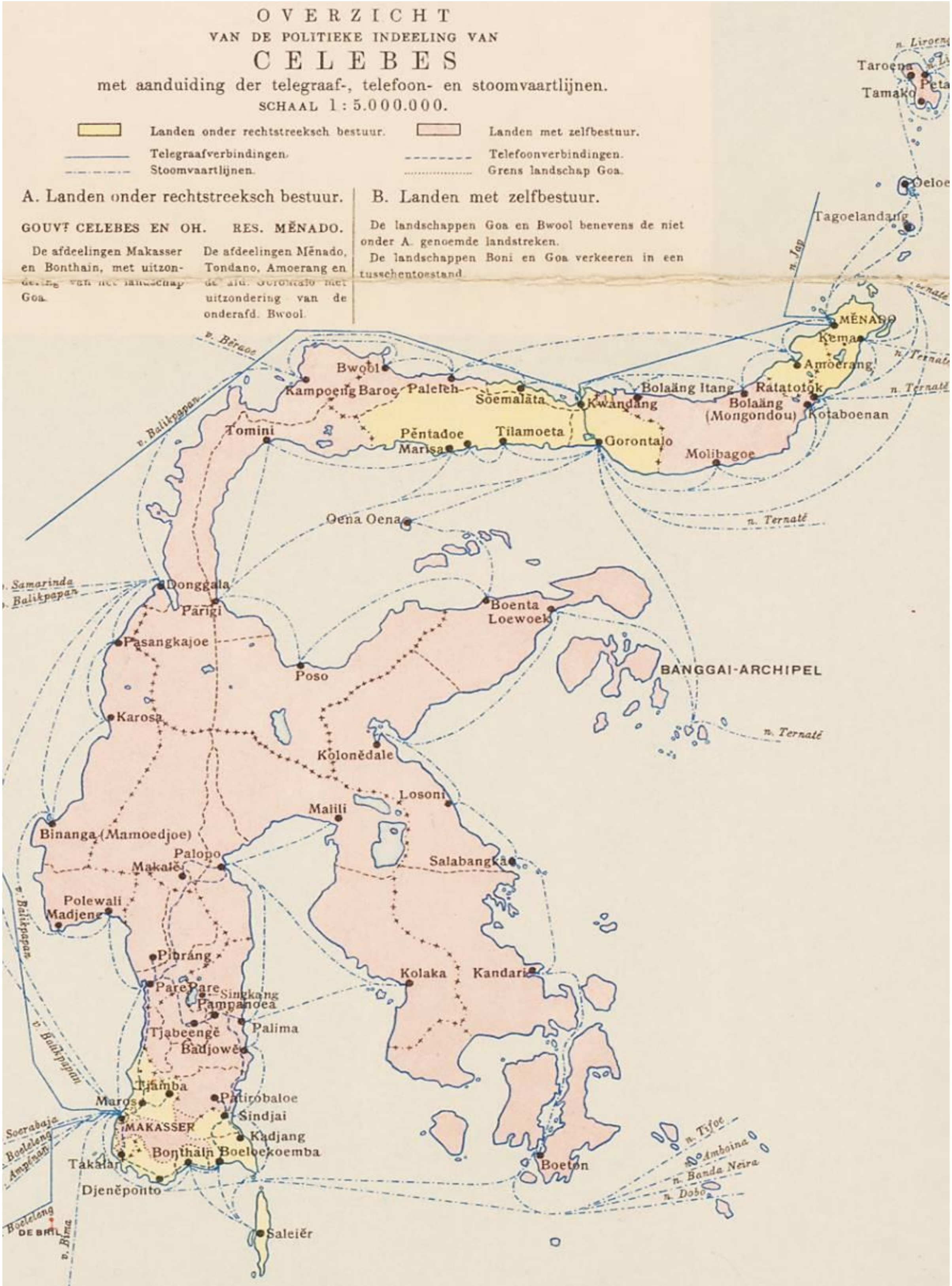


__Figure 1.__ Map of Sulawesi, showing the political situation in 1909. In yellow are the 'lands under direct Netherlands Indies government administration'. In pink are 'lands with self-government', i.e. areas ruled by numerous small 'rajahs' (Topographische Inrichting Batavia).

Economic minerals of Sulawesi are limited mainly to gold and nickel, while iron was a valuable commodity among the native people. Small Eocene coal deposits are present near Maros in SW Sulawesi, but ever since the first evaluation survey by Schreuder (1854) these coal deposits were deemed to be uneconomic, until some exploitation started during the Japanese occupation.

Some of this report was taken from the book *'Pioneers and Milestones of Indonesian Geology'* (van Gorsel, 2022, 4 volumes, Institut Teknologi Bandung). For references not included at the end of this paper, see the '*Bibliography of the Geology of Indonesia and surrounding areas'* (www.vangorselslist.com)

General timeline of discovery (1880s-1930s)

Until around 1890, most of Sulawesi was a collection of partly self-governed small states, not under direct Dutch government administration. The VOC (Dutch East Indies company) had established trading posts (forts) and small settlements along the coasts of Sulawesi since the 1600s and exercised indirect influence through treaties and trading pacts with local 'rajahs'. Much of the interior of Sulawesi was inaccessible and dangerous for European travelers until around 1905-1910, by which time most of Sulawesi had been brought under some form of administration under the Netherlands Indies government.

The main reason for the initial lack of interest in Sulawesi from the VOC and the relatively late Dutch annexation was probably because Sulawesi did not produce any of the valuable spices that initially brought the Dutch to the Moluccas. Also, its mostly rugged, inaccessible terrane limited its agricultural capacity, and little or nothing was known about its mineral potential. As a result, interest in the geology of Sulawesi also remained dormant until the 1880s.

The geology of the island of Sulawesi long remained poorly known, compared to other parts of the Netherlands Indies. By 1890, initial geological mapping surveys had been carried out in large parts of Java (Junghuhn 1840s, Verbeek and Fennema 1880s), Sumatra (Verbeek 1870s), SE Kalimantan (Schwaner 1840s, Verbeek (1870s, Hooze 1880s) and West Kalimantan (Van Schelle in the mid-1880s, Wing Easton and Koperberg in late 1880s-1890s), but the geology of Sulawesi remained largely unknown until the late 1800s-early 1900s.

A significant increase of geological reconnaissance and prospecting for gold (and minor coal) in Sulawesi happened after the late 1880s until the 1920s (see also below). Probably not entirely coincidental is that after the increased interest in North Sulawesi gold, North Sulawesi was rapidly annexed and brought under direct Dutch colonial rule in the late 1880s and early 1890s. Other areas followed later: Dutch administration over Central Sulawesi was established only by 1905.

II. EARLY EXPEDITIONS (1821-1929)

II.1. Key surveys and expeditions

During the 1800s, scientific travels to Sulawesi were all conducted by government-sponsored and privately funded 'naturalists', many of whom were primarily zoologists or botanists, but some also made observations on rocks and geological features. In the late 1800s they were followed by gold prospectors, in the early 1900s by petroleum explorers and later in the early 1900s by government geologists in Geological Survey projects.

The main pioneering efforts in geology and mining in Sulawesi between the early 1800s and 1930 were:

- The first naturalist travels to Sulawesi (C. Reinwardt, H. von Rosenberg, H. Zollinger, A. Wallace; 1821-1864);
- First private gold prospecting and first prospecting support by Mijnwezen in North Sulawesi (1886- early 1900s);
- First geological reconnaissance of SW Sulawesi, by Prof. A. Wichmann (1888-1889)
- First Central Sulawesi sampling by Dutch protestant missionary A.C. Kruyt in 1895 (Wichmann, 1896);
- First systematic geological-mining reconnaissance by Mijnwezen, in North Sulawesi-Manado (1896-1906);
- Gold prospectivity evaluations for private entrepreneurs by visiting European academics H. Bucking, F. Rinne, G. Molengraaff and J. Ahlburg (1898-1909);
- Celebes expeditions by F. and P. Sarasin (1893-1896 and 1902-1903);
- Sulawesi geological reconnaissance by R. Verbeek (1899; Moluccas Expedition);
- Midden-Celebes Expeditie of E.C. Abendanon (1909-1910);
- Sulawesi East Arm surveys by petroleum geologists (1905-1929)
- Dienst van het Mijnwezen/Mijnbouw geological-mining survey projects, 1909-1930;
- Central Sulawesi expedition by H.A. Brouwer-Hetzel (1929).

By 1930 all geoscience expeditions came to a halt, probably as a direct result of the global economic crisis. Systematic geological mapping and research in Sulawesi did not restart until the 1970s, by the Indonesian Geological Survey (Sukamto, Simandjuntak, etc.)

II.2. The first Naturalists and Geologists' travels to North Sulawesi (1821-1864)

The first scientific naturalist explorer in Sulawesi was probably the German botanist Prof. Casper G.C. Reinwardt (founder of the Bogor Botanical Gardens in 1817), who traveled across parts of North Sulawesi in October 1821 and reported on some of its active volcanoes and on several small native small gold mines in Gorontalo, Sumalata, etc. (Figure 2). He was the first to describe how native miners wash gold from intensely weathered veins in the granites, volcanic breccia and porphyrite. Reinwardt was the first European to climb the Soputan volcano in North Sulawesi, in 1821 and

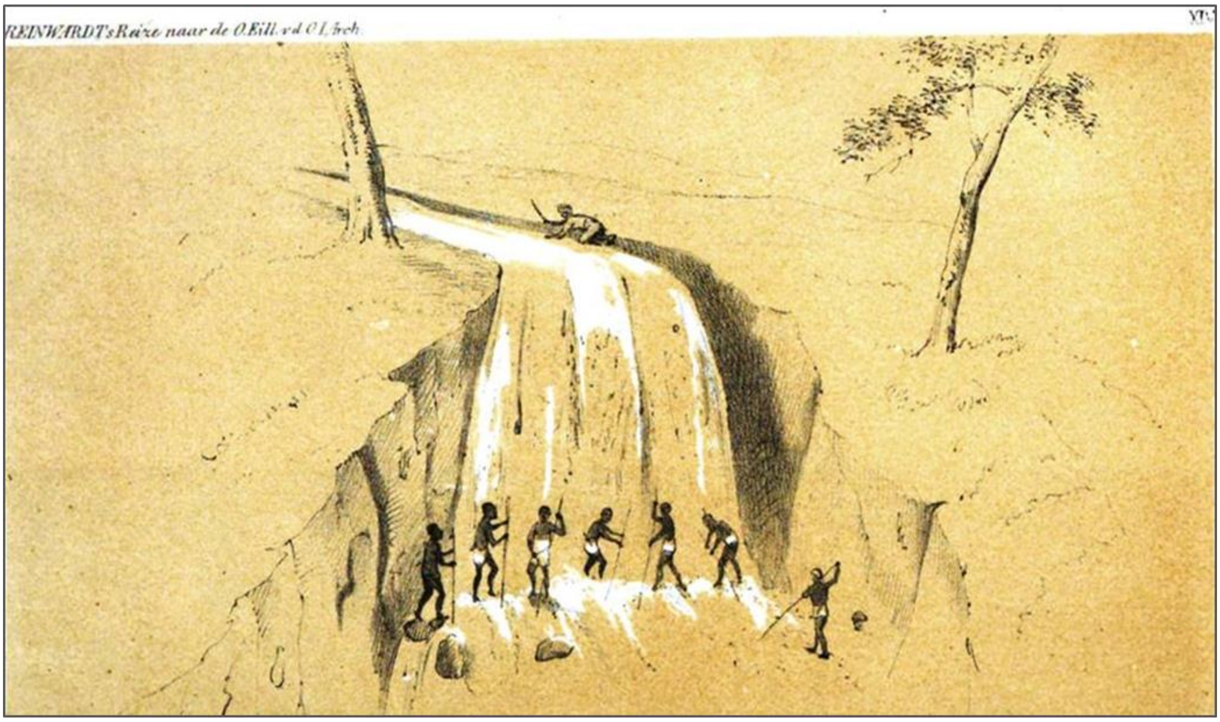


Figure 2. *Native gold diggings in Gorontalo, North Sulawesi, as observed and drawn by C. Reinwardt in 1821.*

noted the unusual obsidian volcanic rocks.

Next came E.A. Forsten, a young Dutch medical doctor with a strong interest in plants with medicinal properties. He arrived in the Netherlands Indies in 1838, as a naturalist for the Dutch Natuurkundige Commissie (Natural History Committee) in Leiden. The instructions for his multi-year mission to Celebes from late 1838 until early 1843, were to collect zoological and botanical specimens, but as-per-usual for members of the *Commissie*, he was also instructed to observe the geology and economic minerals and collect rock samples. Forsten was the only *Commissie* member to set foot in Sulawesi. He was accompanied on his travels by German surveyor/illustrator Heinrich von Gaffron, who would later conduct his own expeditions in Borneo.

Like Reinwardt, Forsten inspected a number of local gold diggings in 1840 and 1841 and collected gold samples. Unfortunately, he died of disease in Ambon in 1843, at age 31. Forsten's collections reached the Natural History Museum in Leiden, but due to his untimely death, the results of his travels were never documented or published.

In 1863, Netherlands Indies Army officer/surveyor and naturalist Hermann von Rosenberg traveled across the Gorontalo District in the North Arm of Sulawesi, sponsored by the Netherlands Indies government. One of the more interesting chapters in Von Rosenberg (1865, 1878) is on his October visit to the gold mines at

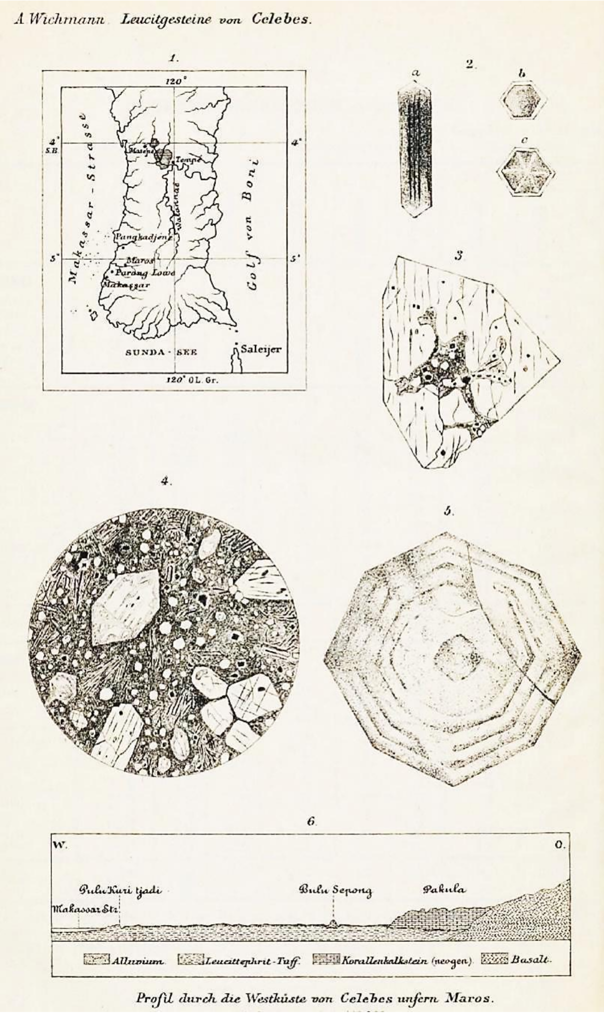


Figure 3. *Thin section of leucite basalt from SW Sulawesi (Wichmann, 1893, Leucitgesteine von Celebes).*

Soemalatta (Sumalata) from the village of Kwandang on the North coast. Gold-bearing quartz veins had been discovered here 50 years earlier by native people and had been mined from 26 pits, 15-90m deep. All but two of the shafts were abandoned at the time of Von Rosenberg's visit. Von Rosenberg (1878) made occasional references to rock types in the Gorontalo area. He also collected rock samples, but it is not clear if these were ever studied.

Two private naturalist travelers worth mentioning who spent time in SW Sulawesi included Swiss naturalist Heinrich Zollinger in 1847 and British Alfred R. Wallace in 1857. Both funded their travels by collection botanical and zoological specimens, which they sold to museums in Europe.

II.3. First SW Sulawesi geological reconnaissance by Prof. A. Wichmann (1888-1889)

Prof. Arthur Wichmann of the University of Utrecht traveled extensively through the Eastern Indonesia islands in 1888-1889, sponsored by the Netherlands Geographic Society. In 1888 he visited SW Sulawesi. In the Maros area he was the first to discover leucite basalt and tuffs in the Pajangkene and Walanae Rivers (Figure 3). He was probably also the first to describe common glaucophane-bearing metamorphic schists from SW Sulawesi, in float of the Pajangkene River (Wichmann, 1893; presumably derived from the Bantimala basement terrane).

Kruijt also sampled serpentinized ultramafic rocks NE of Poso, at Tanjung Api along Tomini Bay, the locality of an enigmatic burning gas seep (described in more detail by M. Koperberg in, 1905; see also separate paper on Tanjung Api in this journal). A.C. Kruijt also accompanied Mijnwezen geologist/mining engineer R. Fennema and J.F. de Corte in November 1897, when Fennema accidentally drowned in a boating accident on Lake Poso during a sudden rainstorm.

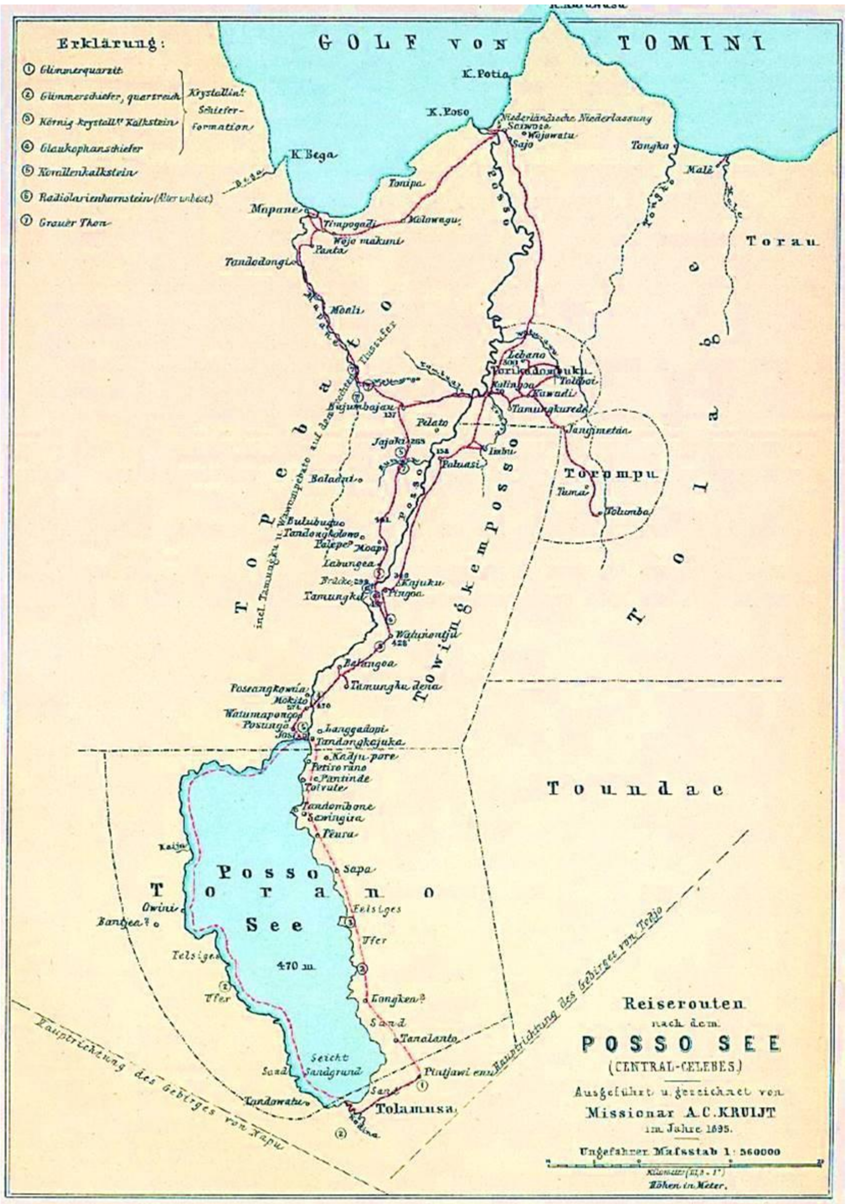


Figure 4. *Itinerary and sample localities of missionary Alb. C. Kruijt in November 1895, with the first records of crystalline schists and quartzites (1,2,3) around Lake Poso and glaucophane blueschist (4) and Mesozoic radiolarian chert (6) North of Lake Poso (in Wichmann, 1896). The Sarasin cousins had probably visited the lake just before this, but no results had been published at the time of the Wichmann paper.*

Another interesting Wichmann 'first' was from Central Sulawesi, in his 1896 description of the metamorphic rocks of the Poso Lake area, based on the samples collected by Dutch Calvinist missionary Albert C. Kruijt in 1895 (Figure 4). Kruijt (1869-1949) was the first European to settle in the Poso area in 1891 but was more interested in studying the geography and the ethnography and sociology of the Toraja peoples of Central Sulawesi than in converting them to Christianity: his first conversion to Christianity was only in 1909.

II.4. The Sarasin Celebes naturalist-geological expeditions (1893-1896 and 1902-1903)

Two well-known, major, privately funded naturalist expeditions were conducted across all parts of Sulawesi by two Swiss naturalist cousins Paul and Fritz Sarasin, the first in June 1893-March 1896, the second in March 1902-April 1903. The Sarasins

__Figure 5.__ Itineraries of the Sarasin cousins in North, Central, SW and SE Sulawesi in 1893-1896 and in 1902-1903 (Sarasin and Sarasin 1905).

contributed much new knowledge about the geography of parts of Sulawesi (especially Central Sulawesi), areas which had never been visited before by European naturalists or geologists. Much of their interest was in freshwater molluscs and in zoogeography and the position of the Wallace Line (which separates the Indo-Malayan and Australian-Papuan faunal-floral provinces).

During the first expedition, the Sarasins journeyed across the Minahasa province of North Sulawesi and across Central Sulawesi. One of the more significant journeys was across Central Sulawesi, from the Gulf of Bone via Lake Poso to the Gulf of

Figure 6. Up: *Fritz and Paul Sarasin during their second Sulawesi expedition in 1902 (Coll. Tropenmuseum).* ***Right:*** *'Orographic map of Celebes' from Volume 4 of 'Materialien zur Naturgeschichte der Insel Celebes', a simplified version of mountain ranges of Sulawesi (Sarasin and Sarasin, 1901).*

Tomini early 1895. This was the first visit by geologists/naturalists to Lake Poso (only a Dutch government official and a missionary had traveled here before). During their second Celebes expedition in March 1902-April 1903, the Sarasins made additional crossings of Central and SW Sulawesi (Figure 5).

The extensive Sarasin reports mainly documented their geographic and ethnographic reconnaissance, but they also included data on the geology along the way and collected rock samples. The results of the first expedition were documented in four volumes (Sarasin & Sarasin, 1898-1901). Volume 4 documents the geographic and geological results, with brief descriptions of rocks samples by Prof. H. Bucking in Strasbourg and Prof. C. Schmidt in Basel.

The Sarasins were the first to describe several rock complexes that are now well known:

- Metamorphic rocks in Central Sulawesi, including the subduction zone indicator glaucophane schist;
- Peridotites, gabbro and serpentinites the Matano and Towuti Lakes area of eastern Central Sulawesi and in the SE Arm of Sulawesi.
- Eocene-Miocene limestones and coal in the Maros District of SW Sulawesi, etc.

The Sarasins were probably the first to describe the prominent WNW-SSE trending Palu River valley and Palu Bay in NW Sulawesi. It is now known as the Palu-Koro rift valley and is believed to represent a pull-apart basin along the Palu-Koro sinistral strike-slip fault zone (Katili, 1970). In a tribute to the Sarasins pioneering expeditions in Celebes, Abendanon (1915-1917) named it the 'Fossa Sarasina' (the graben of the Sarasin's).

II.5. The Abendanon Midden-Celebes Expeditie (1909-1910)

Dutch mining engineer E.C. Abendanon conducted an extensive series of geological traverses across Central Sulawesi in April 1909- August 1910, sponsored primarily by the Koninklijk Nederlands Aardrijkskundig Genootschap (KNAG, Royal Netherlands Geographic Society). This was first geologic-geographic expedition in Central Sulawesi since the more geographic/ethnographic- focused travels of the Swiss cousins P. and F. Sarasin in the late 1800s.

Abendanon traversed Sulawesi for 200 field days, about 2000 km on foot, 400 km on horseback and about 1000 km in canoes (Figures 7 and 8). The expedition was an impressive feat in logistics across areas that had long been inaccessible and had never been visited by European scientists before. A large amount of new information was gathered by Abendanon, but it obviously was a reconnaissance survey.

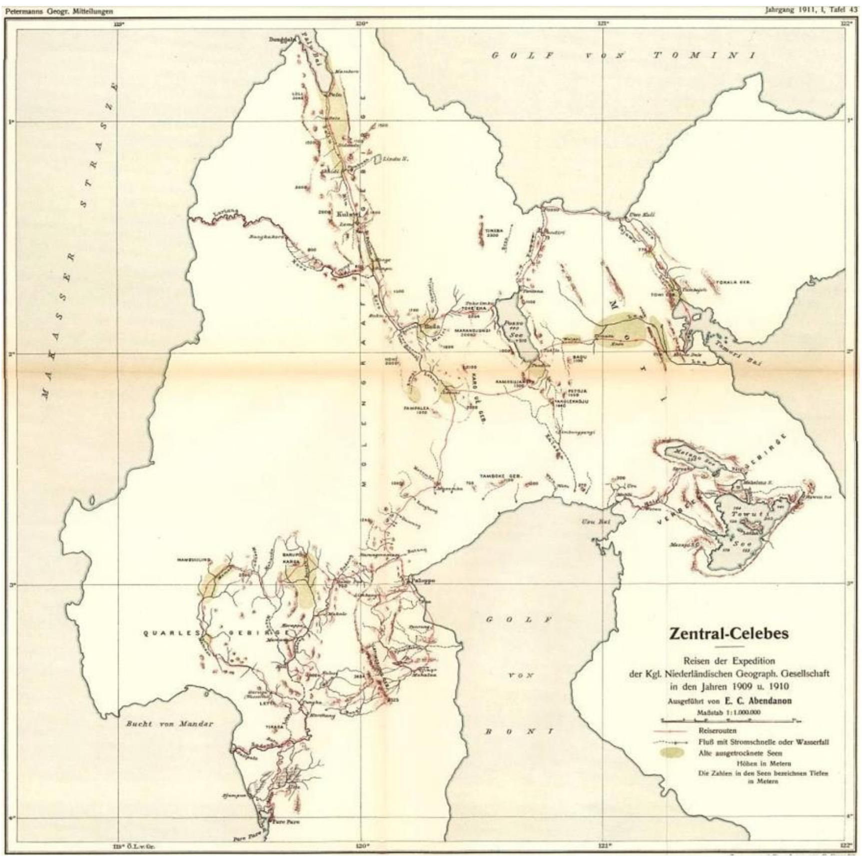


Figure 7. *Itineraries of E.C. Abendanon in Central Sulawesi in 1909-1910 (in red).*

The results of the Sulawesi Expedition of Abendanon were published in a voluminous 4-volume set of books and an Atlas volume, in both Dutch and French editions (Abendanon, 1915-1917; for more see the Abendanon chapter in Van Gorsel, 2022). The reports include chapters on petrography by W.F. Gisolf, Cretaceous-Tertiary fossils by French paleontologist G.F. Dollfus and Mesozoic radiolaria by British micropaleontologist G.J. Hinde.

Tectonics of Sulawesi (Abendanon, 1912, 1916)

In 1912 Abendanon published his version of the principal tectonic elements of Sulawesi, which, for the first time reasonably well characterizes its main building blocks, from East to West (Figure 9):

1. Large and thick peridotite complex of eastern Central Sulawesi, named the Verbeek Mountains by Abendanon, and was investigated by around the Matano and Towuti lakes (green on Figure 9).

2. N-S belt dominated by mica-schists and quartzite without any granites across Central Sulawesi, named the Fennema Range (light blue);

3. N-S belt of granites and gneiss-type metamorphics, named the Molengraaff Range, from the 'neck' of Sulawesi to the south (pink);

4. Not addressed on Figure 9 are the SW Sulawesi area of Neogene granites and extinct volcanoes with potassic volcanics, and the North Arm, dominated by 'normal' calk-alkaline arc volcanics.

Another interesting observation and conclusion of Abendanon was that the tops of the igneous-metamorphic mountains in the Molengraaff and Fennema mountain ranges are relatively flat and not higher than 2000m in altitude. From this he concluded that the central parts of Sulawesi had been eroded to a flat peneplain by Oligocene time and was subsequently uplifted by ~2000m in Late Tertiary time. After this uplift,

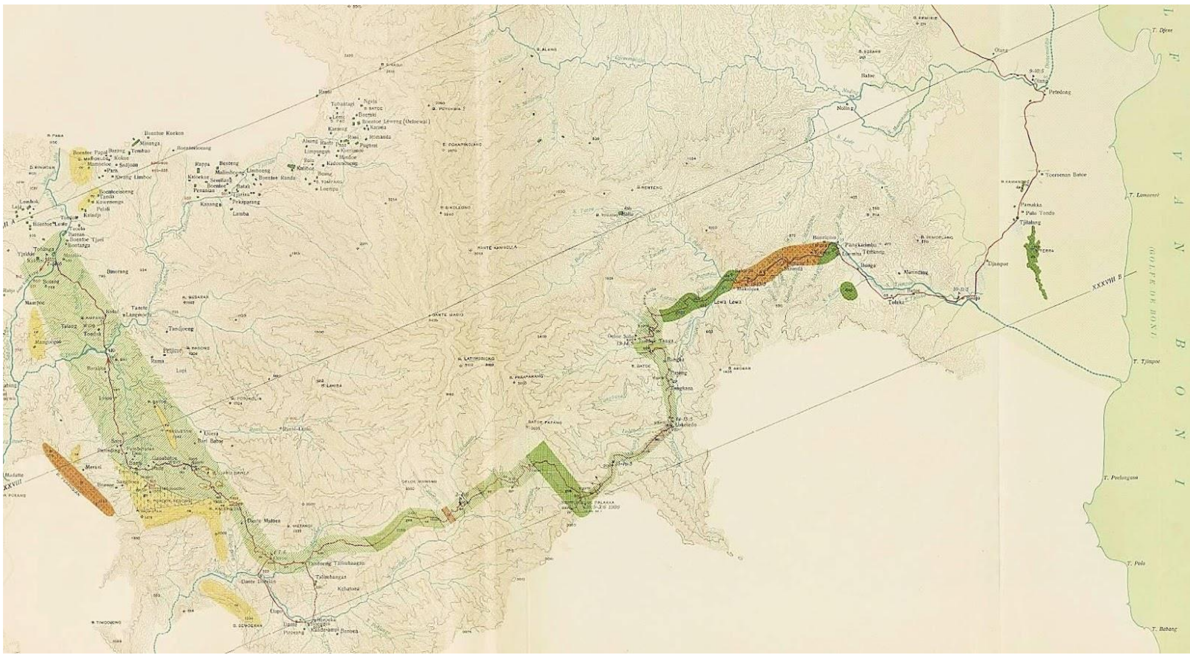


Figure 8. *Example of part of Abendanon's documentation of the geology along his 1909-1910 traverses, from the Gulf of Bone to Makassar Straits via the Latimojong basement high (Abendanon, 1915).*

significant erosion/incision followed, with deposition of the 'Celebes Molasse' along the margins (Abendanon, 1912, 1916).

In 1916 Abendanon also made important observations about the 7000 km2 large peridotite massif in the Verbeek Mountains of Eastern Sulawesi, which amounted to the first accurate description of 'Oceanic lithosphere stratigraphy' (although he did not recognize it as such). The observed stratigraphy, from bottom to top, includes:

1. A peridotite core, at least 1100m thick (= mantle);

2. This core is enveloped by a succession of gabbros, overlain by diabase (= basalt), diabase breccias and diabase tuffs (= typical oceanic crust);

3. The basaltic rocks are overlain by remnants of a thin sediment cover, composed of up to 200-300m of radiolarites and pelagic limestones of Jurassic-Cretaceous-age (typical pelagic ocean floor sediment).

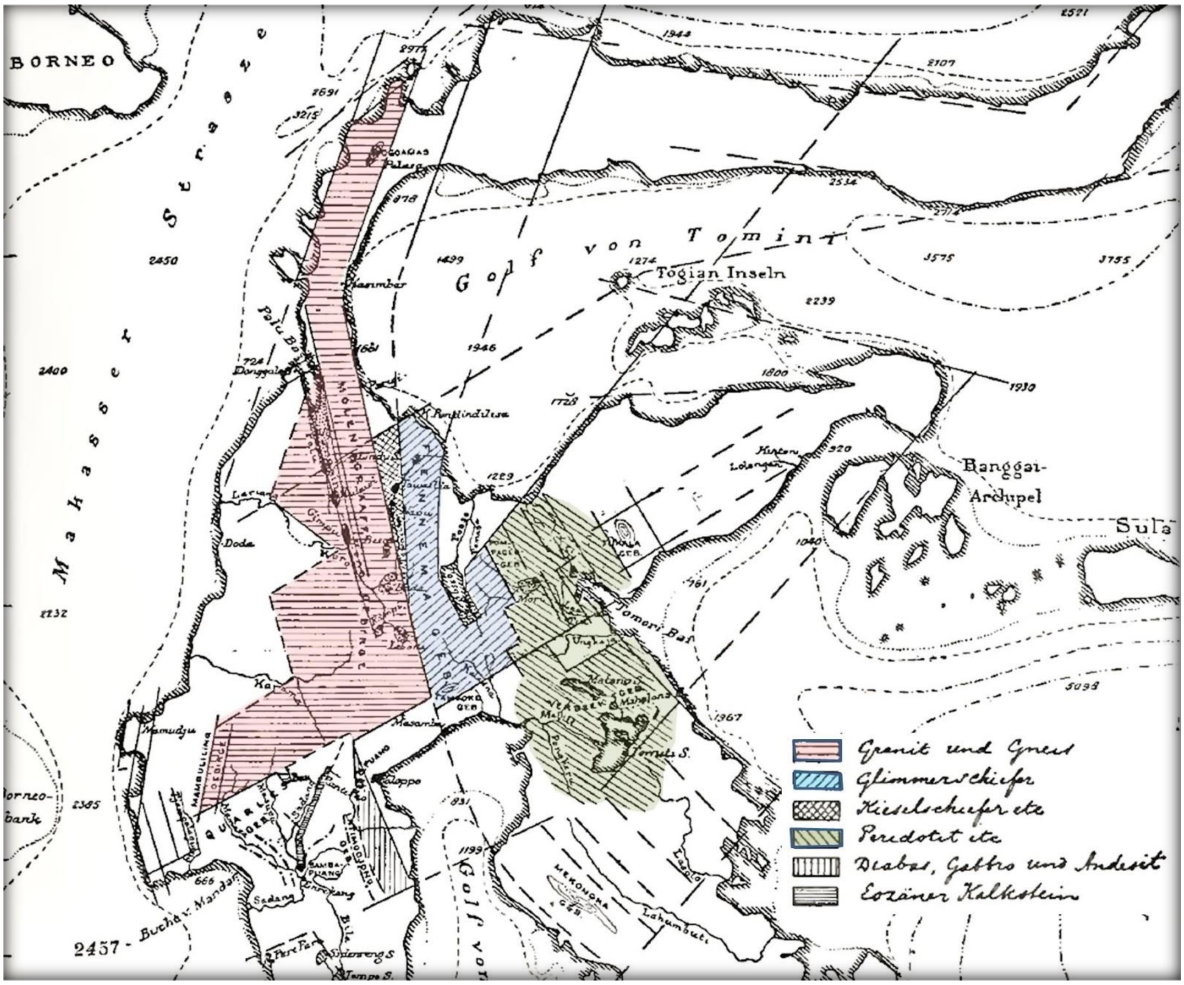


Figure 9. *A map of the main tectonic elements of Central Sulawesi by Abendanon (1912).*

From literature data, Abendanon (1916) assumed that similar successions of peridotite cores with gabbro-diabase envelopes are present in other parts of eastern Indonesia, like Halmahera-Waigeo, Obi, Ambon- East Ceram and Timor-Moa).

Finally. the pronounced NNW-SSE trending Palu River valley and Palu Bay (now known as the Palu-Koro strike-slip fault zone) was recognized as a young 'rift' and was named the Fossa Sarasina (Sarasin Trough), in honor of the Sarasin cousins.

Nickel deposits of Eastern Central Sulawesi (Abendanon 1912-1918)

One of the most significant results of the Abendanon Sulawesi expedition was the recognition of iron and nickel-chromium ores in the lateritic weathering zones of the large ultramafic rock outcrops near the Towuti and Matano lakes in eastern Central Sulawesi. Some of the iron ores had already been exploited by native populations. The Sarasin cousins had also observed ultramafic rocks in the area in 1896, but their samples were never analyzed for nickel content (Sarasin and Sarasin, 1901). In volume 4 of his main opus on the Celebes Expeditie (1917) Abendanon described the ore deposits, with chemical analyses by Prof. S.J. Vermaes of the TH Delft, confirming the presence of potentially commercial nickel content.

In his book and several later papers (e.g. Abendanon, 1918), Abendanon argued that 'the volume of nickel ore in the Verbeek Mountains will make the Netherlands Indies one of the richest nickel-producing countries in the world' (De Ingenieur 22, 2 June 1917). This opinion was disputed by various mining engineers at that time, but the nickel deposits identified by Abendanon have since been successfully mined by private and government enterprises since the 1960s, and today the Sorowako area is indeed part of the largest nickel-producing region in the world

Abendanon's discoveries led to follow-up evaluation surveys of nickel deposits by the Dienst van het Mijnwezen between 1917 and 1922 (Dieckmann, 1919, 1925; Adam, 1922) and later by the private Billiton mining company in 1940-1950 (led by G.L. Krol, a son of Mijnwezen engineer L.H. Krol). Although small-scale nickel mining was conducted here by two private companies in the late 1930s (and continued by the Japanese occupation force in 1942-1945), significant commercial nickel production started only in the 1970s (by PT INCO, PT Vale, PT Aneka Tambang).

Status of geological mapping of Indonesia (Abendanon, 1915)

After his return from the Sulawesi, Abendanon was commissioned by the Royal Netherlands Geographic Society (KNAG) and the Maatschappij tot Bevordering van het Natuurkundig Onderzoek der Nederlandsche Kolonien, to compile the first country-wide Geologische schetskaart van Nederlandsch Oost-Indie (Geological sketch map of the Netherlands Indies). The work was conducted between 1911 and 1913 and was published in 1914, in 6 sheets at 1:2.5 million scales. Perhaps the most useful part of the Abendanon map today is to realize how much of Sulawesi was still unexplored in 1913 ('blank' areas; Figure 10).

II.6. The Brouwer-Hetzel-Straeter Sulawesi expedition (1929)

Although supported by the Geological Survey with logistics and personnel, the expedition across Central Sulawesi was essentially a private academic undertaking. H.A. Brouwer, Professor of Geology at the University of Amsterdam was in Bandung for the Fourth Pacific Science Congress in 1929. After the congress, Brouwer embarked on a 4.5-month expedition to Central Sulawesi from June until October 1929, accompanied by Mijnbouw geologists W.H. Hetzel and H.E.G. Straeter (published as Brouwer 1934). Hetzel was a former Brouwer student in Delft, who had been seconded to the MGO Oost Celebes (Mining-Geological Survey East Sulawesi) project in 1925-1929, based mainly in Bau-Bau on Buton Island.

By this time, the main patterns of the geology of Central Sulawesi had

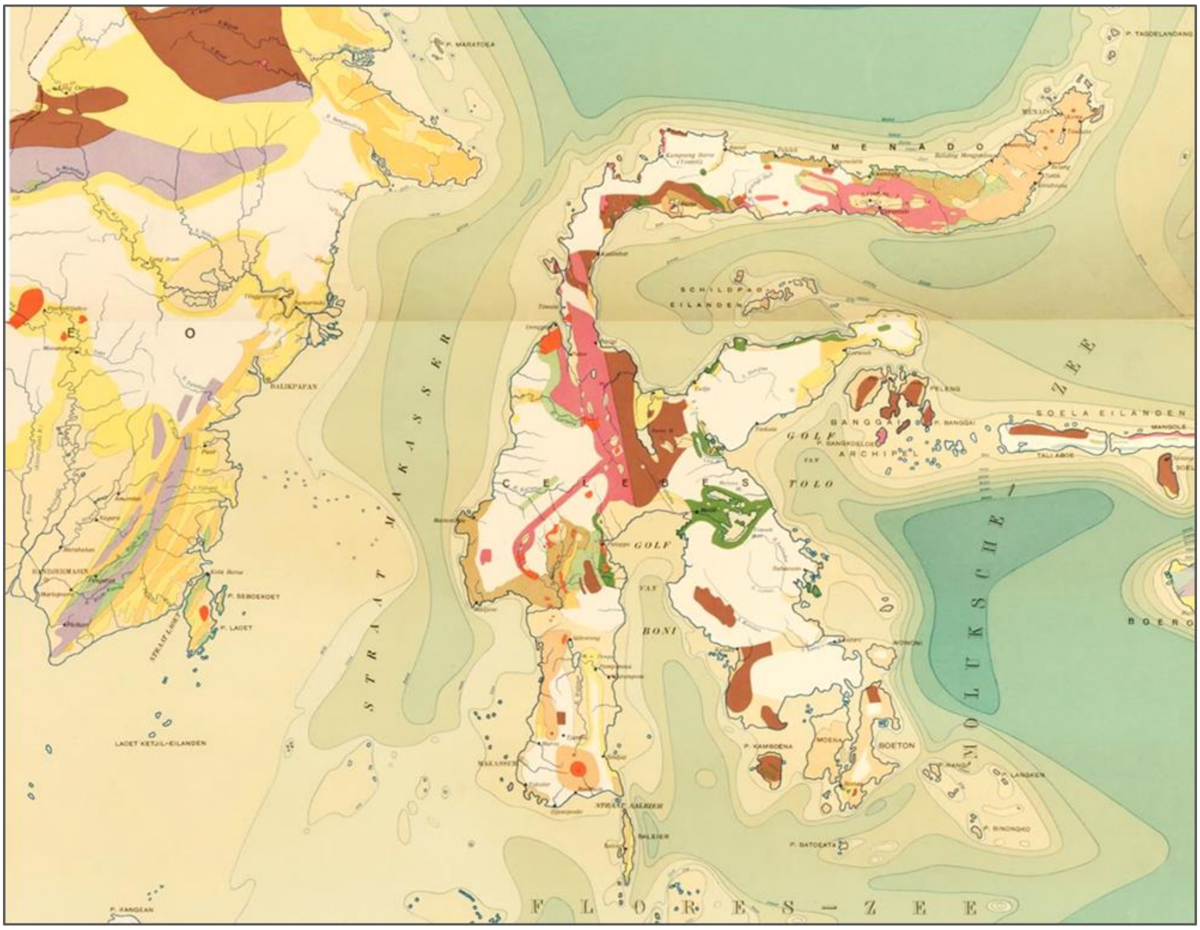
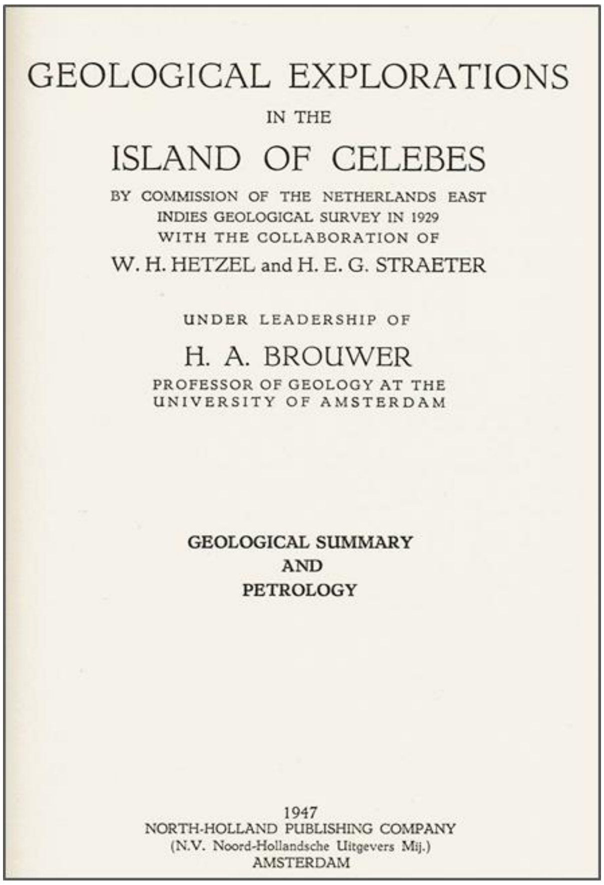


Figure 10. *Detail of the first 'Geologic overview map of the Netherlands Indies' by Abendanon (1915). After the Abendanon expedition more of the geology of Sulawesi is known than at the time of Verbeek (1908). However, half of Sulawesi is still completely unexplored (white areas), and much of the colored areas still need to be viewed as geological reconnaissance (Van Waterschoot van der Gracht, 1915c).*


GEOLOGICAL EXPLORATIONS
IN THE
ISLAND OF CELEBES
BY COMMISSION OF THE NETHERLANDS EAST INDIES GEOLOGICAL SURVEY IN 1929
WITH THE COLLABORATION OF
W. H. HETZEL and H. E. G. STRAETER

UNDER LEADERSHIP OF
H. A. BROUWER
PROFESSOR OF GEOLOGY AT THE UNIVERSITY OF AMSTERDAM

GEOLOGICAL SUMMARY
AND
PETROLOGY

1947
NORTH-HOLLAND PUBLISHING COMPANY
(N.V. Noord-Hollandsche Uitgevers Mij.)
AMSTERDAM

Figure 11. *Cover of the report on the results of the Brouwer Sulawesi expedition of 1929 (Brouwer, 1947).*

become clear. Brouwer (1930) distinguished three main zones: (1) an eastern zone with abundant imbricated basic-ultrabasic igneous rocks, radiolarian cherts and Mesozoic limestones; (2) a central zone dominated by crystalline schists, with deformational strike directions mainly N-S; (3) a western zone with abundant granitic rocks and with Mesozoic sediments of different facies from zone 1 (Figure 12).

Samples of metamorphic rocks collected during the Brouwer 1929 expeditions were described later at the University of Amsterdam by Willems (1937), De Roever (1947) and Egeler (1947). These were groundbreaking works in classification of metamorphic rocks into 'metamorphic facies':

1 The petrographic study of Willems (1937) on metamorphic rocks showed all rocks to be of epi- to meso-metamorphic grade, with a general increase in metamorphism from East to West;

2. The Egeler (1947) petrographic work on rocks from the northern part of western Central Sulawesi and the southern part of the Sulawesi 'neck' documented intense contact metamorphism around the young ('alpine') granodioritic intrusions of West Sulawesi, which was superimposed over older regional metamorphism;

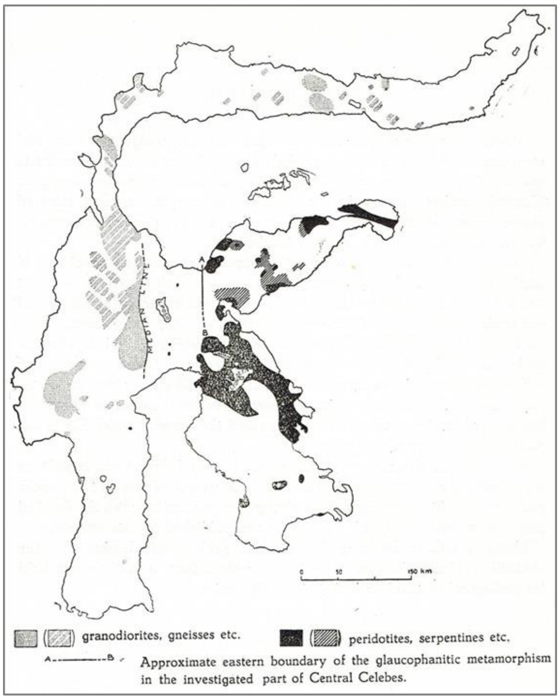


Figure 12. *Map showing the main geologic terrains of Sulawesi: mainly granites in the West, crystalline schists in the center and ultrabasic igneous rocks and Mesozoic deep marine sediments in the East (Brouwer, 1947).*

3. The petrographic work on metamorphic rocks from eastern Central Sulawesi by De Roever (1947) suggested two metamorphic facies: (1) an older intermediate P/T epidote-amphibolite facies, overprinted in the west by (2) high P glaucophane blueschist facies (generally associated with subduction zones).

III. GEOLOGICAL SURVEYS/ GEOLOGICAL MAPPING (1855-1930s)

III.1. The role of the Geological Survey (Dienst van het Mijnwezen) in Sulawesi since 1855

As had happened several times before in other areas, the Geological Survey/Bureau of Mines of the Netherlands Indies (Dienst van het Mijnwezen/ Dienst van den Mijnbouw) did not proactively conduct geological-mining surveys in poorly known areas of Sulawesi, but it limited its initial surveys to areas around existing native mines, or it waited until after private entrepreneurs had discovered mineral deposits of economic interest. In North Sulawesi, Mijnwezen personnel first arrived in 1885 when it requested by a private investor to evaluate gold occurrences in North Sulawesi, where native gold mining had been known since the early 1800s. This led to the surveys by Mijnwezen engineers Van Schelle in 1886 and Fennema/Koperberg in 1896-1906. Another example was the Mijnwezen evaluation of nickel deposits in the Verbeek Mountains of eastern Central Sulawesi in 1917-1922, after private explorer Abendanon had demonstrated their existence around 1910-1915 (see also below).

Unlike in Sumatra and Java in the 1920s-1930s, there never was a comparable systematic geological mapping program for Sulawesi by Mijnwezen. However, six multi-year Geological and Mining surveys (GMO, MGO) and a number of smaller surveys had been conducted between 1896 and 1930, which greatly enhanced the geological knowledge of large parts of Celebes (Sulawesi).

III.2. First geological-mining reconnaissance by Mijnwezen, North Sulawesi (1896-1906)

After private gold exploration and mining activities in North Sulawesi had rapidly increased in North Sulawesi in the 1890s, the Dienst van het Mijnwezen (Geological Survey) decided to support of the many small gold-mining operations here with a geological mapping project and regional assessment of the gold regions in the Menado and Gorontalo Residencies, in a project named the GMV Geologische en mijnbouwkundige verkenning van de Residentie Menado (Geological-Mining Investigations of North and Central Celebes project).

The North Sulawesi survey work in was started by R. Fennema and J.F. de Corte in 1896-1897. Unfortunately, Fennema accidentally drowned in Lake Poso during a survey in the western part of the Menado Residency in November 1897. After a year of hiatus, the project was resumed by Ir. M. Koperberg from late 1898 until early

1905, assisted by P. Hovig from 1903. Members of the project were based in Menado.

The results of the 10-year fieldwork project were compiled in a 3-volume, 840-page report entitled 'Building blocks for the geology of the Manado Residency' (in Dutch) (North and northern Central Sulawesi). It was compiled by Koperberg during his retirement in the Netherlands and was published more than twenty years after the survey work was completed (Koperberg, 1929; see more in Koperberg chapter in Van Gorsel 2022, vol. 2).

III.3. Sulawesi geological reconnaissance by R. Verbeek (1899)

During R.D.M. Verbeek's island-hopping Moluccas survey in March-December 1899, Verbeek made various brief stops in Sulawesi. The extensive Verbeek (1908) book and Atlas contain information on localities (briefly) visited by Verbeek, but also review earlier research around the areas visited. These included several North Sulawesi coastal locations in July, around Menado in early November and around Makassar in SW Sulawesi in mid-November (with an excursion to Maros-Pangkajene) (Verbeek, 1908).

The geological map compiled by Verbeek (1908) captures the geological knowledge after the works of Van Schelle, Koperberg, Bucking, Ahlburg,

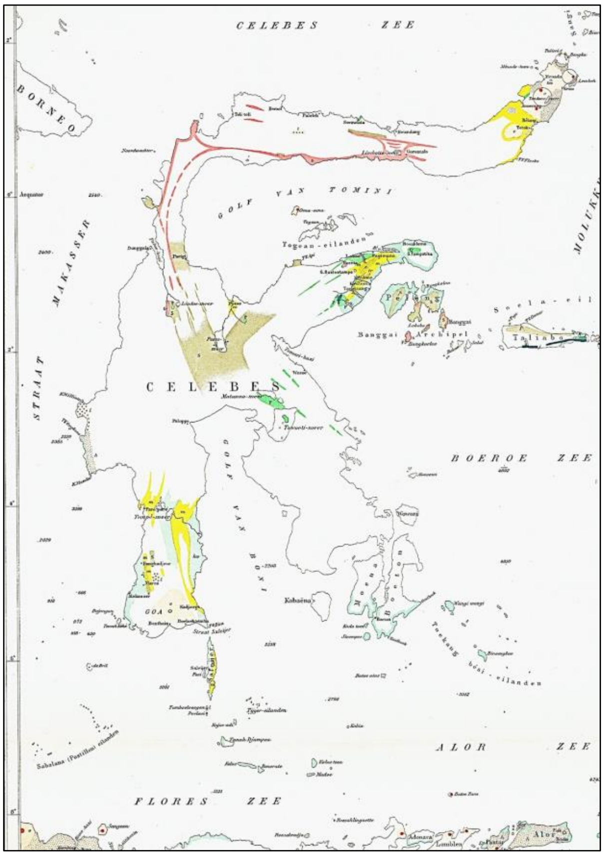


Figure 13. *Part of the geologic sketch map of the eastern Netherlands Indies by Verbeek (1908), showing that most of Sulawesi was still geologically unknown territory at that time. This was after the initial surveys of Van Schelle, Fennema/Koperberg, Wichmann, the Sarasin cousins, Wanner, Bucking and Ahlburg, but before Abendanon and the post-1908 works by the Geological Survey.*

the Sarasin cousins and himself, and shows how much of Sulawesi was still completely unknown at that time (Figure 13).

Although the Maros area in SW Sulawesi had been described several times before, Verbeek added some useful corrections to the work of Wichmann (1898), Bucking (1898) and the Sarasin cousins (1901). He documented that the famous Maros limestones contained both Eocene and Miocene larger foraminifera (like many other 'Tonasa Limestone' occurrences in other parts of Sulawesi, as would be established later) (Figure 14).

Geology of Selayar Island, south of the SW Arm of Sulawesi (1908)

One of Verbeek's most useful contributions to the understanding of Sulawesi geology was perhaps on the geology of islands near Sulawesi, like Salayar, and his interpretation of its geological history. Noting the relatively simple geology of West-dipping Miocene sediments and the fact that water depths East of Salayar rapidly deepened to 1000-3000, 20km to the East, Verbeek concluded that the East side of Salayar island had to represent a large normal fault. We know now how well this fits with Salayar being a rift shoulder at the western margin of the Neogene opening of Bone Bay and the Banda Sea.

III.4. Geological-mining projects by the Geological Survey (1909-1930)

The Dienst van het Mijnwezen/ Mijnbouw (Bureau of Mines/ Geological Survey of the Netherlands Indies) was created in 1850, but for the first four decades of its existence, projects in Sulawesi were probably limited to the brief investigation of coal in SW Sulawesi by Schreuder (1854) and the gold mining survey in North Sulawesi by Van Schelle in 1886 (see also above). The first more regional survey work by Mijnwezen was the Menado Residency fieldwork of 1896-

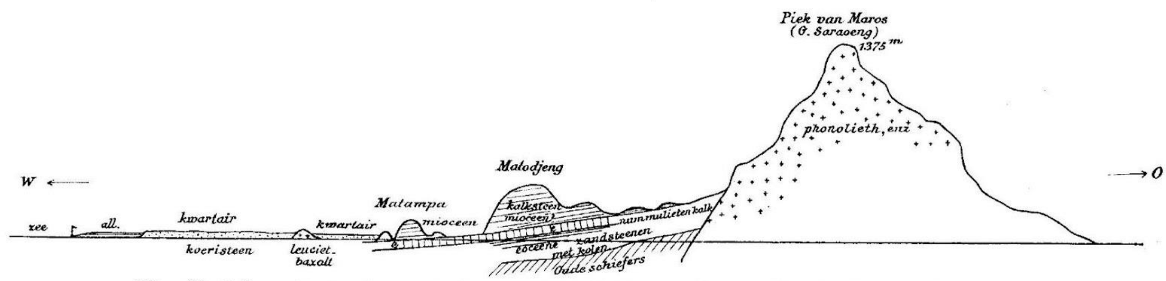


Fig. 45. Schematische doorsnede door de vlakte Makasser - Maros - Pangkadjéne en het aangrenzend gebergte, van W. naar O.

Figure 14. *Diagrammatic cross-section of Makassar Plain- Maros- Pangkajene and adjacent mountains in SW Sulawesi (Verbeek, 1908). It shows the west-dipping 'old schists' overlain by Eocene sands, coal and Nummulites limestone, overlain by Miocene limestone, intruded by the younger 'phonolith' of the Maros Peak. Some of this now-classic stratigraphy had been described earlier by Wichmann (1893), Bucking (1898) and the Sarasin cousins (1901).*

1906 by Fennema and Koperberg (see III.2, above).

From 1909 until 1930, Mijnwezen/ Mijnbouw was reasonably active in Sulawesi, with five significant geological-mining investigation projects. All this came to a halt after budget cuts during the 1930s, due to the global economic crisis. This was followed by non-activity during the Japanese occupation of 1942-1945 and the war of Independence in the late 1940s. During the first 2-3 decades after Indonesian Independence, little or no work was done in Sulawesi by the Indonesian Geological Survey, suffering from limited funding during the poor economic situation and lack o South f trained personnel after the loss of Dutch geological expertise.

Geological-mining reconnaissance and Central Sulawesi (1909), MO Celebes en Onderhoorigheden (1911-1917)

J. de Koning Knijff and H. Cool of the Dienst van het Mijnwezen (Geological Survey) conducted some reconnaissance surveys of South Sulawesi and the southern part of Central Sulawesi in 1909. Its results were summarized in De Koning Knijff (1914). It led to led to the creation of a large mining investigation project (MO) between 1911 and 1917, the MO Celebes en Onderhoorigheden. Its purpose was the evaluation of potential economic mineral deposits of Central Sulawesi, especially copper and iron ore. Key Mijnwezen personnel included J. van der Kloes, J. Reijzer, C.A.F. Macke and H. Wolvekamp. Its results were summarized in Anonymous (1920) and Reijzer (1920). The project failed to prove any commercially viable mineral deposits in Central and South Sulawesi.

Van Waterschoot van der Gracht, 1913

In 1913 W. van Waterschoot van der Gracht undertook two weeks of government-sponsored fieldwork in the Toraja lands, accompanied by Mijnwezen mining engineers/ geologists P. Hovig and J. Reijzer, mainly to investigate the stratigraphy. Its results were summarized in Van Waterschoot (1915, a, b). Van Waterschoot was critical of the earlier work by Ahlburg and Abendanon, while, in turn, his conclusions were heavily criticized by Abendanon (1915).

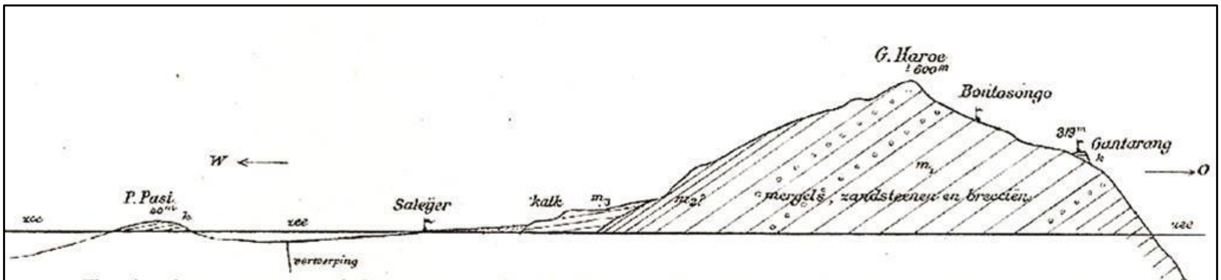


Fig. 4. Geologisch profiel van het eiland Saleijer, tusschen de hoofdplaats Saleijer en Gantarang.
Horizontale schaal 1:100,000. Vertikale schaal 1:25,000.

Figure 15. *West-East cross-section of Selayar island, showing 8-13 ° West-dipping ?Miocene sediments, correctly interpreted as a rift shoulder with a major normal fault on the East side (Verbeek, 1908).*

GMO Zuidelijk Celebes (South Sulawesi), 1913-1916

After the reconnaissance work of Wichmann, Bucking and the Sarasin cousins, the only significant work in the south (SW) Arm of Sulawesi was the multi-year Mijnwezen project by C.W.A.P. ‘t Hoen and K.G.J. Ziegler, who conducted fieldwork from December 1912 until March 1915 (’T Hoen & Ziegler, 1917; Figure 16). Rocks from the project were described by Von Steiger (1915).

The project provided new documentation of the Pretertiary complexes of steeply-dipping schists, unconformably overlain by Cretaceous greywackes. It also clarified the Tertiary stratigraphy of Eocene coal-bearing sandstones, Late Eocene Nummulites limestones and the late Tertiary volcanics. It included detailed maps of the Eocene coal fields Tondong Koerah, Podo, Batoekoe and Malawa, but the only time that these Sulawesi coals were exploited was during the Japanese occupation.

Worth mentioning here is a brief sampling trip in Sulawesi around the same time by American geologist-petrographer Prof. Joseph P. Iddings, who was on a mission to sample leucitic lavas around the world. In SW Sulawesi in 1914 he collected potassic lavas of the Maros Peak area and other areas formerly sampled by H. Bucking and R. Verbeek (Iddings & Morley, 1915).

GMO Verbeekgebergte (Malili), 1917-1922

This Mijnwezen project in the Verbeek Mountains of eastern Central Sulawesi from 1917-1922 was an evaluation of the iron, nickel and chromium deposits associated with the weathering of the large ultramafic complex of East Sulawesi, after these had just been discovered by E.C. Abendanon in 1910 (Abendanon 1915-1917, Dieckmann 1919, Dieckmann and Julius 1925). It was conducted mainly by J.W.H. Adam, M.H. Caron, W. Dieckmann, C. Macke, M. Julius and W. Benschop Koolhoven.

In an appendix of Dieckmann & Julius (1925), Van der Vlerk distinguished three groups of pelagic rocks which formed the sedimentary cover of the East Sulawesi ophiolite complex: red radiolarian chert (Jurassic-

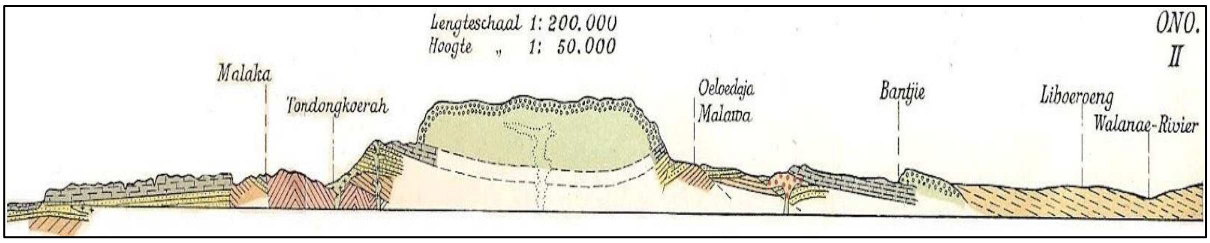


Figure 16. *Example of a WSW-ENE regional cross-section across SW Sulawesi (‘t Hoen & Ziegler, 1917). With near Tondongkoera folded Pre-Tertiary metamorphics in pink. overlain by Eocene sandstones (yellow) and limestones (grey), and as topographically highest formation thick post-Eocene volcanics (light green).On right Late Tertiary sediments of the Walanae River valley.*

Cretaceous?), red shales with *Globigerina linneana* (= Late Cretaceous *Globotruncana*) and grey shale with Late Cretaceous or Early Tertiary planktonic forams. The report also contains petrographic descriptions by W.J. Gisolf.

GMO Oost Celebes en onderhoorigheden (East Sulawesi), 1922-1930

This project was a systematic geological-mining investigation of East Sulawesi and dependencies, with Buton island and its asphalt deposits as a focus area. The main members were J.J. Reijzer, W.C. Benschop Koolhoven, A.C.D. Bothe, W.H. Hetzel and H.E.G. Straeter. During the early part of the project in 1923 Koolhoven did a reconnaissance of the Banggai islands and the East Arm of Sulawesi (Koolhoven, 1930; Figures 17, 18). Later, Koolhoven expanded on the work of Dieckmann and Julius (1925) in the nickel-bearing peridotite terrains between the Towuti and Matano Lakes (Koolhoven, 1932).

During the late 1920s most of the team was based in Bau-Bau, Buton. The key

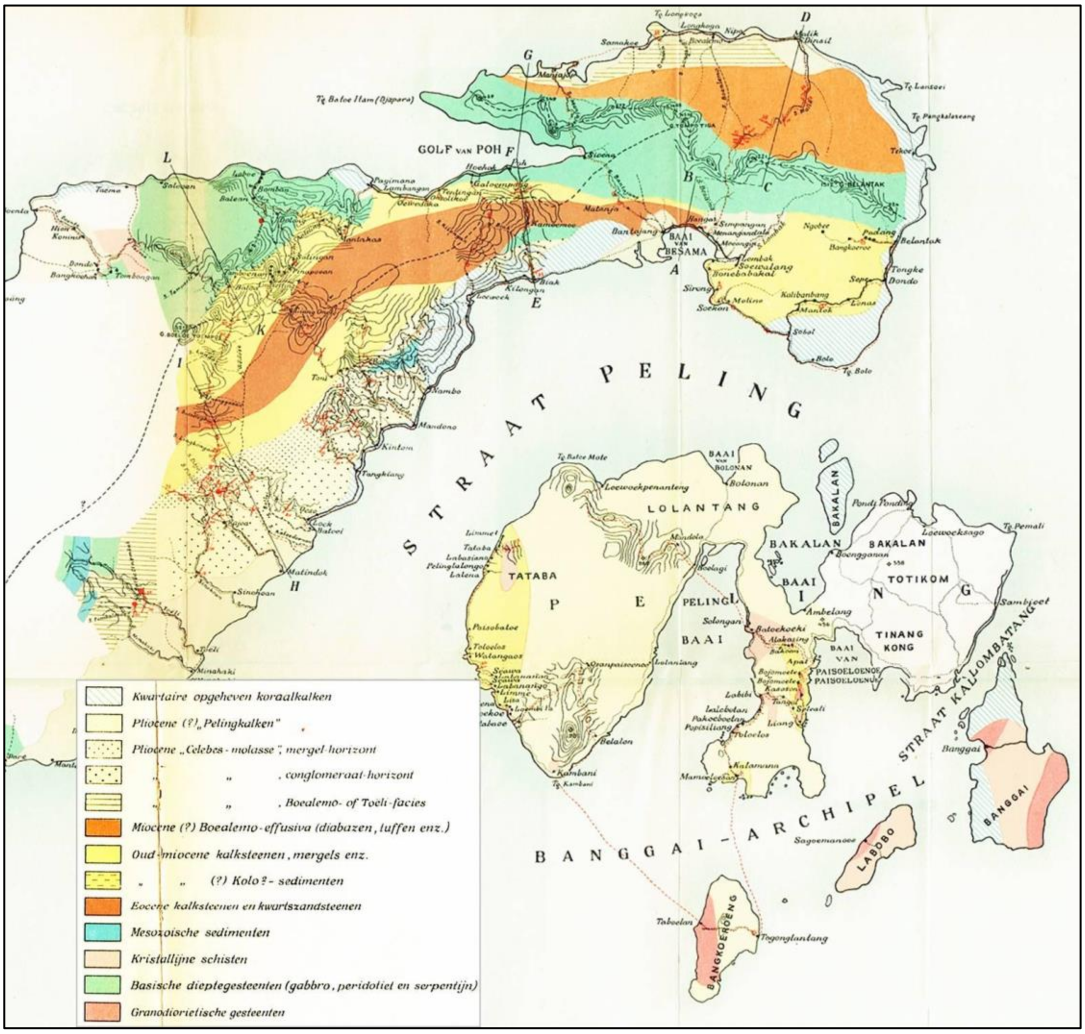


Figure 17. *Geologic map of the eastern part of the East Arm of Sulawesi (Koolhoven, 1930).*

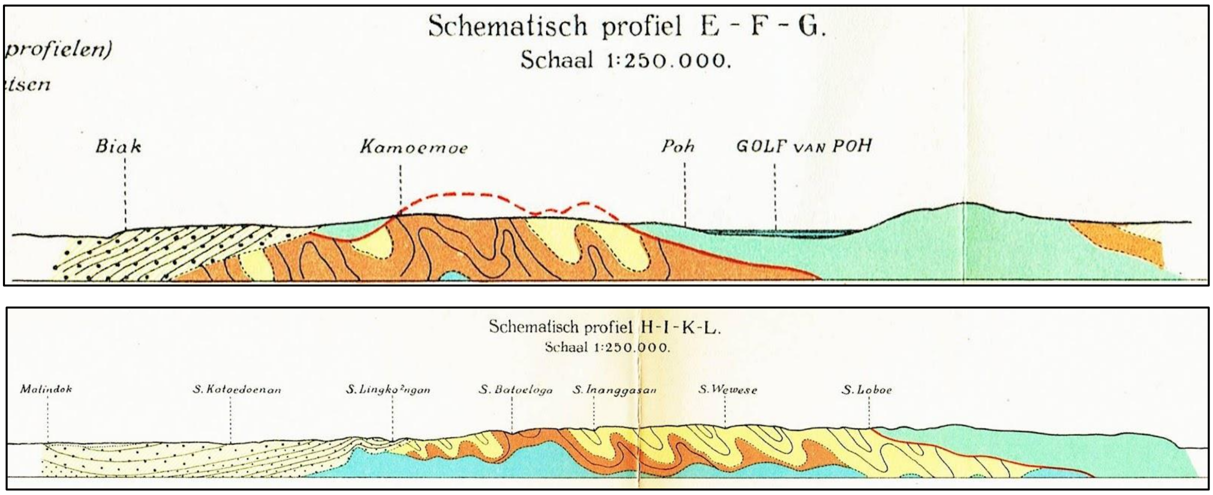


Figure 18. *Two south-to-north cross-sections across the eastern part of the East Arm of Sulawesi, E-F-G (top) and H-I-K-L (bottom) (Koolhoven, 1930). Both show a sheet of ultramafic igneous rocks (gabbro, peridotite, serpentinite) thrusted from the north over imbricated Mesozoic sediments and Eocene and Early Miocene limestones (= scraped-off sedimentary cover of the Banggai block margin). All Early Miocene and older rocks are unconformably overlain by Pliocene 'Celebes Molasse' in the south (left), which contains erosional detritus of ultramafics.*

reports from this time are by Koolhoven (1930) on the East Arm and Hetzel (1936) on the geology and asphalt deposits of Buton island.

IV. EARLY GOLD EXPLORATION AND MINING

The earliest gold diggings in parts of Sulawesi had been conducted possibly for centuries by native miners. After the first gold discoveries at Sumalata, North Sulawesi, in the early 1800s, the Netherlands Indies government signed a contract with the local rajah for annual deliveries of certain amounts of gold at a fixed price, but by 1846-1848 production from the native mines had virtually stopped (Von Rosenberg, 1878). The area would later become the site of European gold exploitation by the Mijnbouw Maatschappij Soemalata and the Kwandang Soemalata company from 1896-1908.

The first European interests in Sulawesi gold date back to the mid- and late 1800s. A significant increase of geological reconnaissance and prospecting for gold (and minor coal) in Sulawesi happened after the late 1880s until the 1920s, with a real 'gold rush' in the late 1890s (see also below).

IV.1. First gold prospects evaluation in North Celebes by Mijnwezen (1886)

The first 'official' investigation of gold occurrences in North Sulawesi by a government geologist was in 1886, when Mijnwezen mining engineer C.J. van Schelle surveyed an area with small native gold mining sites in the Gorontalo and Sumalata districts. This happened after a request for assistance in 1885 to Mijnwezen by J.A. Parmentier of the Gorontalo-based trading company Bauermann en Parmentier (and later gold concession

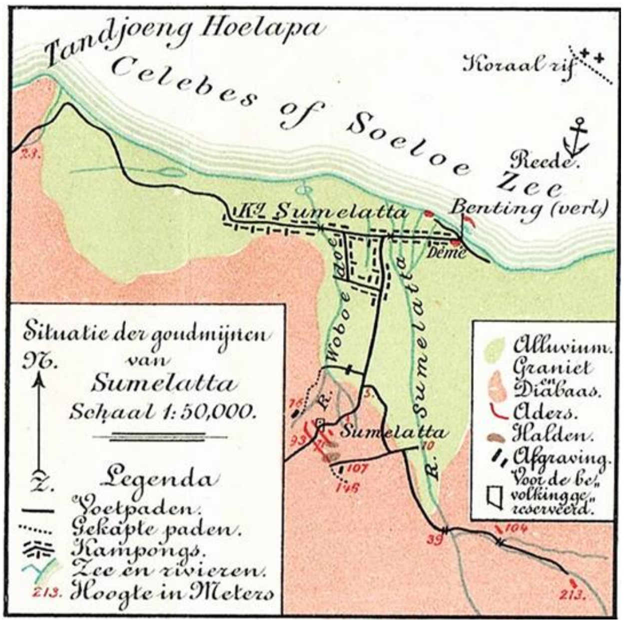


Figure 19. Map around Sumelatta (Sumalata) on the north coast of North Sulawesi, showing locations of gold-bearing veins in red lines in the area of granite and 'diabase' (= andesite) (pink; Van Schelle, 1889).

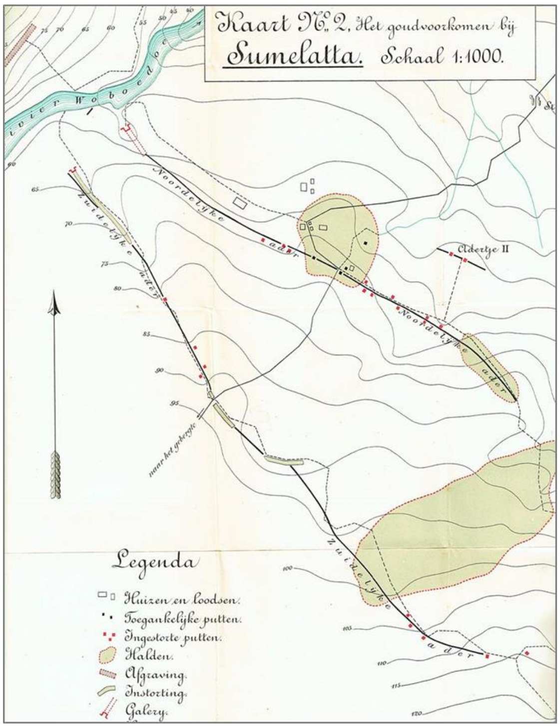


***Figure 20.** Part of a map of the native gold mining operations at Sumalata (Van Schelle, 1889). Exploitation was along two NW-SE trending quartz vein systems,*

owners at Sumalata). Parmentier accompanied Van Schelle during the North Sulawesi survey in 1886 and around 1897-1904 was Director of the Exploratie en Mijnbouw Maatschappij Gorontalo gold mining company.

North Sulawesi at that time was still geologically virtual terra incognita, and the gold prospectors mainly focused on areas around the many small native gold mines that were already been operational there before. There were no reliable topographic maps and it rugged, was heavily forested, volcanics-dominated terrain with very few roads or paths, and with a very limited Dutch colonial government presence.

Van Schelle reported on the native diggings, with shafts down to 14m deep, following quartz-bearing gold veins. They had been operational at least since 1813 or earlier, under the direction of local rajahs. However, by the time of Van Schelle's visit in 1886, the native mining operations were already mostly abandoned (Figures 19 and 20; Van Schelle, 1889). Van Schelle characterized the geology of North Sulawesi as a mix of granite, diorite, andesite and Late Tertiary clastic sediments and limestones.

IV.2. First European gold mining by entrepreneur Dr. Hermann Siber, 1890s

Swiss lawyer/planter/entrepreneur Dr. Hermann Siber became the first successful gold miner in (North) Sulawesi, after his tobacco plantations in NE Sumatra failed commercially. He came to North Sulawesi in 1891, possibly after reading the Van Schelle (1889) reports, which confirmed the presence of relatively widespread, small native gold diggings in the Sumalata and Gorontalo districts of North Sulawesi.

Siber was not a geologist, but he had a strategy to explore around older (mostly abandoned) native gold mines, then negotiate mining permits with the rajahs of the small kingdoms of North Sulawesi. Siber founded a series of gold mining companies and by the mid-1890s started mining operations at Bwool, Paleleh, Totok, Pagoeat and others. This then fueled the infamous, short-lived 'Sulawesi gold rush' around 1900, in which many small investors lost much of their money. Many of the North Sulawesi gold mines around 1900 were operated with English and Australian mining engineers.

Although the Siber-owned gold mines in North Sulawesi performed relatively well, they were probably only marginally economic and did not make Dr. Siber a wealthy man. He died of illness in Sukabumi in 1901, at age 41.

IV.3. The Sulawesi gold rush of the late 1890s

The initial successes and unrealistic estimates of gold reserves in North Sulawesi in the 1890s led to a speculation-driven 'gold rush' across the Netherlands Indies in the late 1890s. Truscott (1899) reported that 50 gold exploration companies formed in the Netherlands Indies between 1897 and 1898 (and many more would follow), mainly for small gold exploration ventures in Sumatra, Central Borneo and North Sulawesi. He noted that 'on the majority of properties nothing has been discovered'. By 1910 almost all of these speculative ventures had collapsed. For decades after that, small private investors were very reluctant to buy shares in new mining projects in the Netherlands Indies.

IV.4. Gold prospectivity evaluations for private entrepreneurs by visiting European academics (1898-1909)

Several highly regarded German and Dutch academic geologists were contracted by more serious private entrepreneurs for brief gold and coal evaluation surveys in Sulawesi, including H. Bucking (1898), F. Rinne (1898-1899), G. Molengraaff (1901) and J. Ahlburg (1909).

Prof. Hugo Bucking, SW and North Sulawesi (1898)

Prof F.C.B.H. Bucking from the University of Strasbourg in the Alsace (at that time part of Germany) visited the Netherlands Indies in 1898, as an advisor of the Amsterdam-based Mijnbouw- en Industrie Syndicaat of tobacco entrepreneur August Janssen. After advising on petroleum geological issues in NE Sumatra, Bucking visited SW and North Sulawesi in June-September 1898. He visited the active gold mines at Sumalatta and Paleleh, providing some good early insights into the geology of these parts. In July 1898 he climbed the Soputan volcano in North Sulawesi, after the Sarasin cousins had already done so in 1895 (and Rinne did the same in late 1898 or 1899 and Ahlburg in 1909).

Bucking's SW Sulawesi survey included various traverses in the hinterland of Pajangkene, presumably primarily for an evaluation of Eocene coal deposits, which he deemed to be 'of excellent quality'. Here he was the first to describe the (Bantimala) Cretaceous metamorphic basement complex with its mica-schist, glaucophane schist, etc., associated with serpentinites, and overlain by radiolarian cherts. Bucking (1899, 1904) also reported on the now well-known Miocene limestones of Maros, North of Makassar, and the underlying Eocene clastics with coal and overlying *Nummulites* limestones.

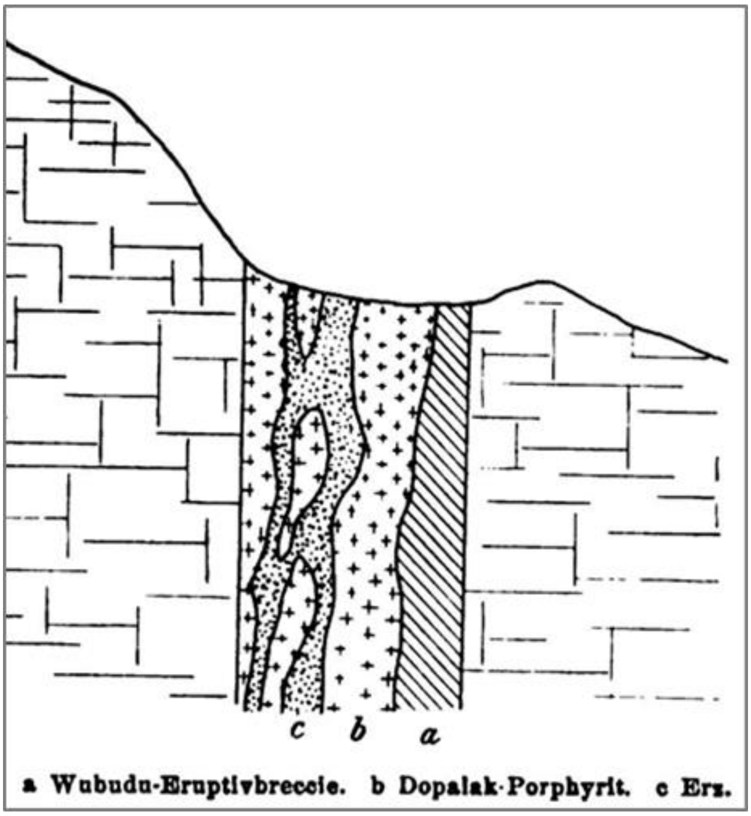


Figure 21. *Diagrammatic cross-section of a typical, vertical gold-bearing porphyrite intrusive into granitic rock and volcanic breccia, with gold-silver-lead-bearing sulphide ore (c), at Sumalata (interpreted as a fault zone; Molengraaff, 1902).*

Bucking also confirmed the presence of leucite-bearing basaltic rocks, first discovered in SW Sulawesi by Wichmann in 1888 (Wichmann, 1893). Bucking reported this rock from at the base of the Nummulites limestone, implying an Eocene age of the basalts, but 't Hoen and Ziegler (1917) considered it a much younger intrusion. In 1904 Bucking published an extensive paper on descriptions of rocks from Sulawesi sampled by Hoven, the Sarasins, Boehm and others.

Prof. F. Rinne (1898)

In the Fall of 1898 Prof. F. Rinne, Professor at the Technische Hochschule in Hannover, Germany, was commissioned by the Mijnbouw Maatschappij Oost Totok to conduct geological work in North Sulawesi, in the Minahasa (Kotabuna) and Gorontalo (Totok) districts. He published early petrographic descriptions of the volcanics-dominated rocks of the areas (Rinne, 1900).

Prof. G.A.F. Molengraaff (1901)

Seven years after his pioneering 1894 Central Borneo Expedition and while residing in South Africa (1896-1905) G.A.F. Molengraaff returned to the Netherlands Indies for a 4-month geological-mining survey near Sumalata at the North coast of North

Sulawesi, in June- December 1901. This was a consulting job for the Kwandang-Soemalata Mining Company, to evaluating gold-bearing veins. Like most industry work, this work remains mostly unpublished, except for a geological summary of the area in Molengraaff (1902; Figure 21)

J.H.W. Ahlburg (1909)

German geologist J. Ahlburg spent several months in Sulawesi in 1909, presumably on behalf of one of the gold mining companies, although the peak of the 'North Celebes gold rush' was over by then. Although his personal survey work covered only a limited area, Ahlburg did make a thorough effort of summarizing his and other geologists' work (Ahlburg, 1910, 1913) and even ventured into proposing a tectonic model of the island. Needless to say, his tectonic synthesis was somewhat premature, given the sporadic knowledge of the geology of Sulawesi at that time and its complexity.

V. PETROLEUM GEOLOGICAL SURVEYS

Many petroleum geologists conducted brief geological surveys across the Netherlands Indies, mainly as employees or contractors of the Koninklijke Olie (Royal Dutch; after the merger with Shell in 1907; subsequently operating as BPM), Their work tended to focus on Tertiary basinal areas ('follow the seeps'), but some also captured information on the geology of areas that were previously unexplored and proved to be non-prospective. Unfortunately, most of this oil company field geology work remains unpublished.

Early oil exploration in Sulawesi was unsuccessful. Several very shallow wells were drilled in the Lariang District of West Sulawesi (an area with oil and gas seeps) by the Exploratie Maatschappij Doda near Mamuju (Mandar) in 1898-1901, while the Bataafsche Petroleum Maatschappij (BPM/ Royal Dutch-Shell) conducted extensive geological field reconnaissance and prospect mapping in 1927-1938, in which surface anticlines were identified, but it is not clear if wells were drilled. No results of their surveys here were published. Several later rounds of oil exploration in West Sulawesi also did not lead to economic success.

Sulawesi geological surveys by mainly Swiss geologists of Royal Dutch/BPM included:

- M. Muhlberg (around 1902; probably in the SW or West Sulawesi area with oil seeps; unpublished);
- J. Wanner (1905) and H. Hirschi (1909) surveys of parts of the East Arm;
- W. Hotz (1912, NMMW survey of East Arm; mostly unpublished);
- E. Kundig and F. Weber (1927-1929; southern part of the East Arm);
- Von Loczy (1928; Tokala-Bungku traverse of the East Arm of Sulawesi);
- Horst von Bandat (1933-1935; Lariang/Pasangkayu/Mamuju Tertiary basinal areas in West Sulawesi).

First petroleum geological reconnaissance of the East Arm (1905-1912; Wanner, Hirschi, Hotz)

The East Arm of Sulawesi was long neglected by all travelers. Neither the Sarasins nor Abendanon bothered to include it in their expeditions. For some reason the little-known and structurally complex East Arm of Sulawesi attracted the interest of oil companies.

The first geological reconnaissance in the East Arm of Sulawesi was by German geologist Johannes Wanner, conducted a two-month geological survey in January-March 1905 on behalf of the Royal Dutch Petroleum Company ('Koninklijke') (Wanner 1910, 1914, 1919). This area had never been visited by Europeans, except perhaps by M. Koperberg during a 1903 survey in the west and by mineral prospector Reinier Verbeek (not the famous regional geologist Rogier Verbeek of Mijnwezen) during a little-known prospecting journey from Tangkian (Kintom) to Bunta a few months earlier (of which nothing was ever published).

J. Wanner mainly visited the SE side of the East Arm, along Peleng Straits, near Toeli, Nambo, etc. In and around the Central Mountains he described (1) ultrabasic rocks, (2) widespread Eocene limestones with *Alveolina*, *Discocyclina* and *Nummulites* (which he noted were reminescent of the *Alveolina* Limestone of Misool); (3) Early Miocene shallow water carbonates with *Lepidocyclina* and *Miogypsina*; (4) conglomerates of the Celebes Molasse (a name coined earlier by the Sarasin cousins), about 1200m thick, with sandy marls and limestone near its base containing latest Miocene-Pliocene planktonic and larger foraminifera (*Globorotalia tumida*, no lepidocyclinids), (5) Quaternary raised coral reef terraces up to 400m above sea level. Near Toeli, Wanner also described probably Jurassic-age 'Toeli Limestone', reminiscent of limestones Wanner had encountered on Buru Island. Along the North coast (Tomini Bay) Wanner found common gabbro and peridotite, with an oil seep in Babason creek. Wanner interpreted the gabbros as intrusions into Early Miocene limestone with *Spiroclypeus* and *Lepidocyclina* (Wanner, 1910), but these are now known as parts of the overthrust East Sulawesi ophiolite complex.

As a follow-up of Wanner's 1905 work in the eastern part, Swiss Royal Dutch geologist Hans Hirschi conducted a reconnaissance geological survey of the western part of the East Arm of Sulawesi in July-August 1909. Some of his results were summarized in a brief paper (Hirschi, 1913). Hirschi first trekked along the south coast of Tomini Bay from Todjo to Bongka and Tanjung Api. He then traversed the East Arm to the South, to Tomori Bay (the same route would be traversed by Abendanon in 1910), encountering peridotites, diabase breccias, and red radiolarites and shales. Closer to Tomori Bay he noted intensely folded Mesozoic limestones and peridotites.

In 1912 another Swiss geologist Walter Hotz visited the East Arm for the small

Dutch exploration company NMMW (which also employed L.M.R. Rutten), but his 1913 publication is quite brief and contains little news, except for his discovery of belemnites which proved the Mesozoic age of some sediments in the East Arm.

Second episode of East Arm geological surveys by BPM (1927-1929; Kundig, Von Loczy)

A second and more thorough episode of geological work by BPM in the East Arm of Sulawesi was in 1927-1929. Especially the works by Swiss geologist E. Kundig and Hungarian geologist L. von Loczy in East Sulawesi were thorough and exemplary.

Von Loczy reported on fieldwork in February-July 1928 in the Bongka River region of the western part of the Sulawesi East arm. 70% of area is covered by ophiolites (peridotite, serpentinite, gabbro), which he correctly interpreted as thrusted over folded Triassic- Lower Tertiary marine sediments (with local contact-metamorphism (Von Loczy, 1934). Von Loczy also significantly expanded the knowledge of the open marine Mesozoic stratigraphy here, which includes 300-500m of dense Late Triassic (Norian) limestones rich in Misolia, deep marine Late Jurassic belemnite limestone and white and red radiolarian-bearing Upper Jurassic-Cretaceous pelagic limestones. He also reported highly folded Late Eocene limestones with *Discocyclina* and *Pellatispira*, overlain by Miocene limestones. The youngest formation is the Celebes Molasse, 1200m thick, with Late Miocene *Lepidocyclina* limestone near its base.

Separate chapters on paleontology of Von Loczy's samples included reports on Upper Jurassic- Lower Cretaceous radiolaria (Hojnos), foraminifera (Van der Vlerk) and Mesozoic macrofossils (Kutassy). Some of Von Loczy's conclusions were debated by Hetzel (1935), Oostingh (1935) and Tan Sin Hok (1935).

Last but not least, two important papers resulting from the late 1920s BPM work in East and Central Sulawesi are by Kundig (1932, 1956); The Kundig (1932) paper was an early attempt at petrographic characterization of the metamorphic basement rocks of Sulawesi, in which he recognized areas of gneiss, phyllite, glaucophane schist, etc.

Kundig (1956) is an elegant review of the BPM fieldwork in East and Central Sulawesi in 1929-1930 by Swiss geologists E. Kundig and F. Weber, which incorporated the earlier data from Wanner (1905), Koolhoven (1930), Brouwer (1934) and Von Loczy (1934). (Figure 22; for the Kundig geologic map of East Sulawesi, see the Van Gorsel & Subroto Tanjung Api paper; this volume).

All of the late-1920s geologists who worked in the East Arm and in eastern Central Sulawesi (Kundig, Von Loczy, Brouwer) arrived at the same interpretion of the structural style of the area: alpine foldbelt-style imbricated Mesozoic-Tertiary marine sediments, overthrust from the North and West by a large ultramafic sheet. This can now be understood as the

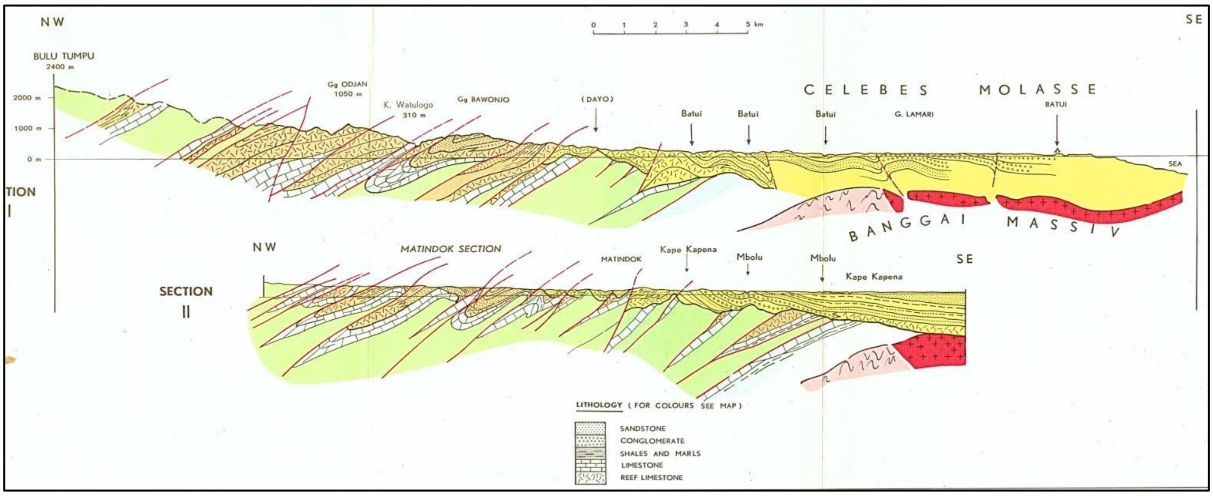


Figure 22. *Regional NW-SE cross-sections through the southern part of the East Arm of Sulawesi, based on BPM work in 1929-1930 (Kundig, 1956). It shows imbricated Jurassic-Cretaceous pelagic limestones (light blue) and Eocene-Middle Miocene limestones (tan) sediments (likely the sedimentary cover of the underthrusted part of the Banggai-Sula continental terrane). All rocks are unconformably overlain by Late Miocene-Pliocene post-orogenic 'Celebes Molasse' (yellow). In green is East Sulawesi Ophiolite, shown by Kundig as the oldest parts of the imbricated thrusts, but is more likely a separate overthrust sheet above the imbricated sediments*

scraped-off sediment cover of the Banggai-Sula plate ('Sula Spur') when it collided with (subducted under) Central Sulawesi.

VI. 'MODERN' TIMES (1970s-now)

Around 1930, interest in the geology and minerals of Sulawesi nearly completely collapsed, mainly due to the global economic recession. Although several important geological reports were still published in the 1930s until the 1950s, these were all based on pre-1930 fieldwork. No more field surveys were conducted in Sulawesi, with the exception of a few mineral evaluations by private companies and a relatively large evaluation program of nickel deposits in the Lake Matano area by the Billiton Maatschappij in 1940-1941 and in the late 1940s.

After a >40-year period of virtual dormancy, geological research and commercial exploration activities restarted in Sulawesi in the mid-1970s. Geological mapping by the Geological Survey of Indonesia was resumed mainly by Rab Sukamto and N. Ratman, who published several geological map sheets between 1975 and 1982, and later by T.O. Simandjuntak in the early 1990s. Other significant research by the Geological Survey in the 1990s was by Surono and others.

Minerals exploration by international mining companies was also resurrected in the 1970s, by Newmont, Rio Tinto, Kennecott, INCO, etc. The most prolific writer from the mining industry in Sulawesi since the 1980s was T. van Leeuwen. For more on mining activities in Sulawesi see Van Leeuwen & Pieters (2011, 2013). Oil and gas exploration since the 1970 resulted in only a small number of small fields, mainly in Tertiary carbonates.

Foreign academic teams also entered the area in the late 1970s, including the University of London under the direction of Dr. A.J. Barber who conducted a series of geological fieldwork projects across Sulawesi with Ph.D. students, resulting in a series of important theses in the 1980s- early-1990s (T. Simandjuntak, A. Guntoro, C. Parkinson, K. Hasan, M. Wilson, etc.). Later this work continued under the direction of Prof. Robert Hall.

Other significant academic groups active in Sulawesi were French (Villeneuve, Cornee, Bellon, etc.;with Indonesian doctorate students B. Priadi, I. Syafri and Y.S. Yuwono), Australian (M. Elburg, Surono, S. Soeka), and Japanese (K.Wakita and others; with Indonesian doctorate students A.Kadarusman, A. Jaya, A. Maulana, Munasri and others).

For a more complete listing of the many contributors to Sulawesi geology, see the Bibliography of the Geology of Indonesia, Ed. 7.1 (www.vangorselslist.com)

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Post-Earthquake groundwater potential analysis in Mamuju Regency, West Sulawesi

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ABSTRACT

The earthquakes that occurred in January 2021 at Mamuju, West Sulawesi not only caused damage to buildings but also destruction of water facilities. Thus, question is raised about the changes of groundwater quality in the area. This study aims to follow up this question by conducting the geoelectric measurement, pumping test, and water quality analysis. Based on the resistivity values of geoelectrical data, each area has aquifers in different stratigraphic layers of (1) calcareous sandstone of the Mamuju Formation, (2) lapilli rock of the Gunung Api Adang Formation, (3) breccia of the Gunung Api Adang Formation and (4) sandstone of the Alluvium deposit. These aquifers are mainly confined and were grouped into the shallow (less than 25m deep) and deep (more than 25m deep) aquifers. Water quality from the groundwater wells meet the criteria of Environmental Health Quality Standards, except for one well GL03-PLDA that has high Manganese content. Determined discharge values suggest that water resources are enough to support around 3916 people or 999 settlements in Mamuju District and about 11664 people or 2916 settlements in Simboro District.

Keywords: *groundwater, aquifer, geoelectric, water quality*

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INTRODUCTION

Water is one of the basic needs that affect life and humanity. However, freshwater accounts for only 1% of the total water on Earth. A good quality of fresh water is necessary for humans, animals, and plants in sustaining their lives. In Indonesia, the use of water is regulated by Indonesian Law (Undang Undang) No. 17 of 2019 which discusses water resources including groundwater, the soil and subsurface rocks layers.

Groundwater occupies the voids or pores between grains in the rock layers under saturated conditions. Groundwater analysis is needed to investigate the quality of freshwater. It is commonly done by drilling groundwater wells. Below the surface earthquakes can expose groundwater to pollution where open fractures can release fluids and alter streamflow from aquifers.

The earthquakes that occurred on 14, 15 and 16 January 2021 in Mamuju, West Sulawesi not only caused damage to buildings but also destruction of water facilities. Thus, questions were raised about disruption of aquifers caused by earthquakes and its effect on drinking water quality. This study attempts to address these questions by conducting geoelectric measurement, pumping test and water quality analysis in Mamuju and Simboro Districts (Figure 1).

REGIONAL GEOLOGY

Regional Tectonics

Sulawesi is situated at the triple junction between the Eurasian, Australian and Philippine Sea plates.

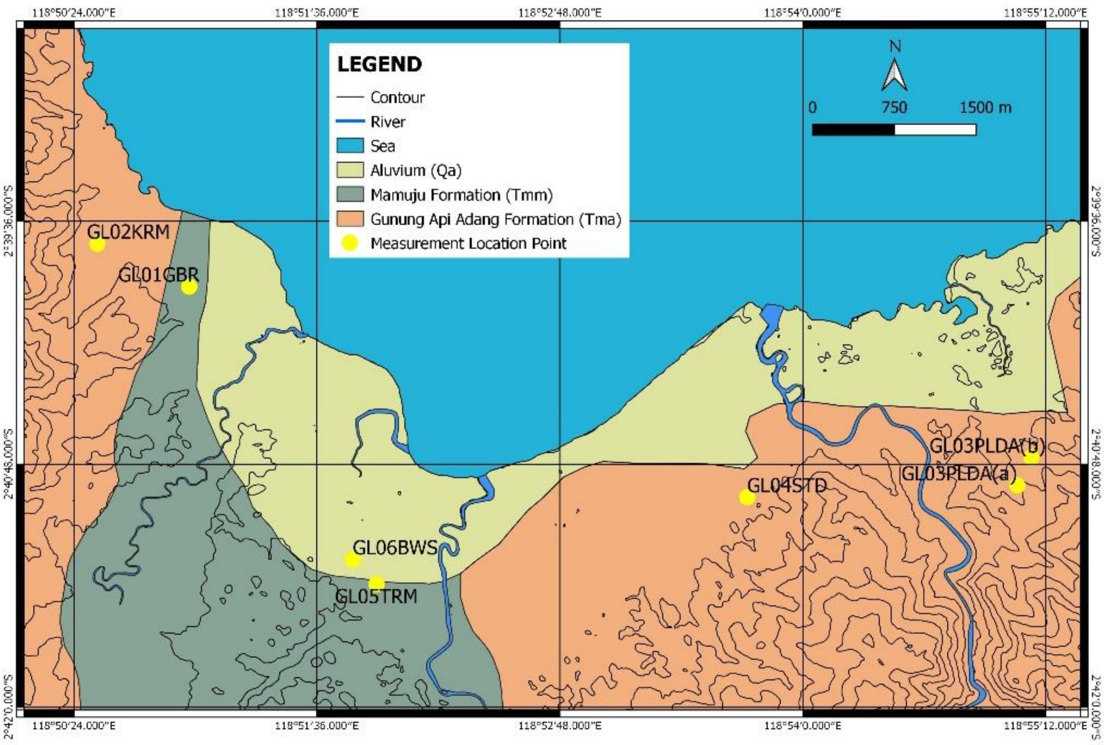

Figure 1: *Map showing the study area and site locations (yellow dots).*

This complex geology was often interpreted as a simple convergent arc-ophiolite-continent tectonic configuration resulting from a single arc-continent collision (e.g. Hamilton, 1979; Silver et al., 1983). West Sulawesi was affected firstly by Palaeogene extension which eventually led to the formation of the Makassar Straits. Secondly, it was influenced by Neogene contraction and lift due to the Sula Spur collision in the Early Miocene (Hamilton, 1979; Bergman et al., 1996; Calvert and Hall, 2007). The Early Miocene collision of the Sula Spur microcontinent (Klompé, 1954) and the North Arm volcanic arc (Hall, 2002) was followed by extensional fragmentation of the Sula Spur microcontinent because of Banda subduction rollback (Honthaas et al., 1998; Spakman and Hall, 2010; Hall, 2012; Hennig et al., 2016; Zhang et al., 2020; Nugraha et al., 2022).

Regional Stratigraphy

The stratigraphy at the Mamuju Regency consists of (1) Adang Volcano Rock Formation, (2) Mamuju Formation, and (3) Quaternary Alluvium (Figure 1; Ratman and Atmawinata, 1993; Armstrong, 2012). (1) Adang Volcano Rock Formation (Tma; Late Miocene) is composed of mainly leucite and breccia basalt lava rocks with a wide distribution. (2) Mamuju Formation (Tmm; Late Miocene) consists of rock calcareous sand, tuffaceous marl, sandy limestone with tuff insertion, and marl. (3) Alluvium (Qa; Holocene) is the youngest deposit and is composed of sediments on rivers, beaches, and mountains.

METHODS

Geoelectric

Resistivity in the geoelectric method is used to determine rock electrical properties by conducting an electrode current into the ground. The rock resistivity value is influenced by several factors including water content, rock porosity, and solubility of salt. 1D Geoelectric data acquisition were measured from 7 locations and were processed using IP2WIN software (Figure 2).

Pumping Test

Two types of pumping test that were used in this study are:

a. *Well Test*

Well test was used to determine potential well type capacity (Qs) by subdividing pumping discharge (Q) with water level subsidence (S). The capacity of the well type (Qs) can be expressed by the equation (Bisri, 2012):

$$Qs = \frac{Q}{S} \quad (1)$$

where:
Qs = Well type capacity (m^2/day)
Q = Pumping discharge (m^3/day)
S = Water level drop (m)

b. *Aquifer Test*

Aquifer test was carried out to determine the capacity of the layer to carry water (aquifer), the transmissivity value of the aquifer (T),

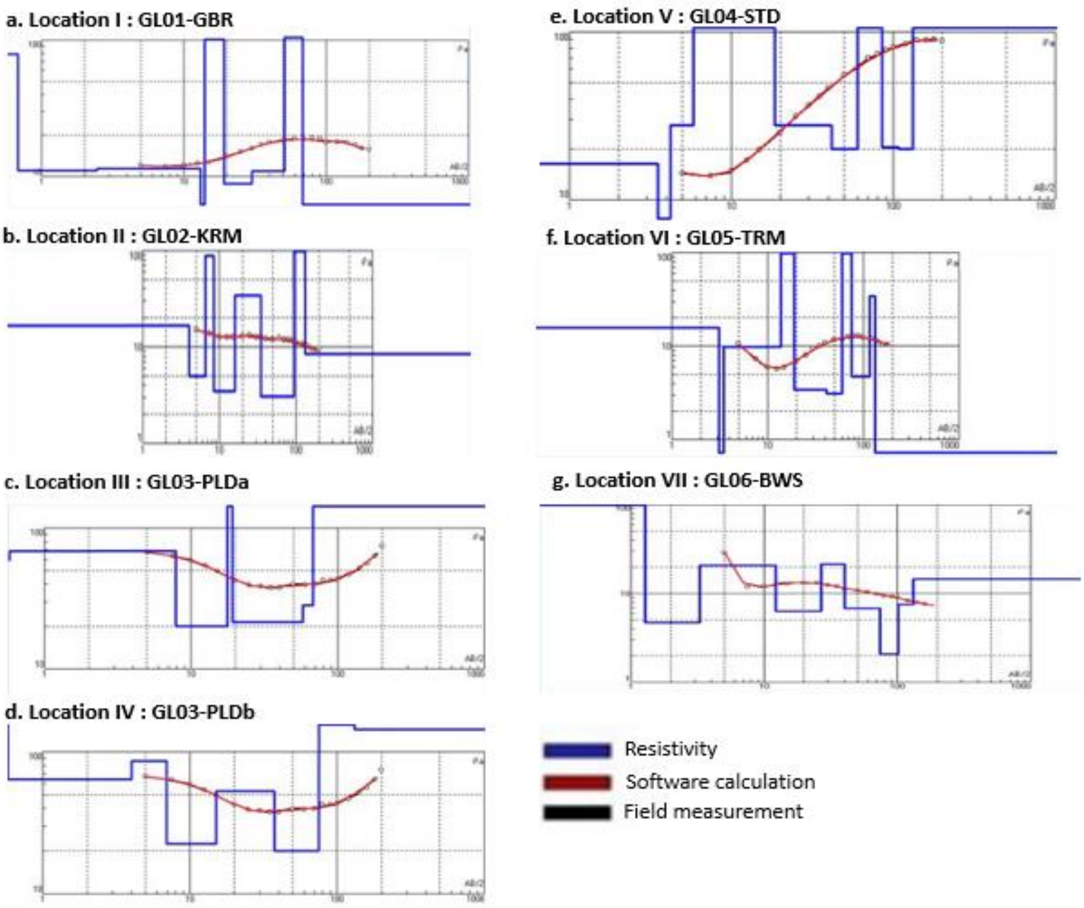

Figure 2: *Graphic display of geoelectric processing results in each well location*

and the coefficient value water flow (K). Aquifer tests are subdivided into:

- Constant Rate Test

  Constant rate test is a continuous pumping test with a fixed discharge in several wells.

- Recovery Test

  This test is used to test the recovery from a soil's water level soil at the time, before and after pumping.

Water Quality Analysis

Water quality assessment is carried out at the laboratory of West Sulawesi Provincial Health Office and includes analyses of physical and chemical parameters.

RESULTS & INTERPRETATION

Geoelectric

Geoelectric measurements were conducted from 7 locations in the Mamuju area (Figure 1) and are summarized in Table 1 and Figure 2. The maximum penetration depth is 133.33 meters with error values ranging between 0.508 % and 0.924%. There are up to 10 lithological layers that were observed based on its resistivity value of Palacky (1988). These lithologies can be grouped into Aquitar, Aquiqlud, Aquifug, and Aquifer systems. Aquifer is a non- or less consolidated layer or formation with saturated water conditions that can store and pass water. Aquiqlud is a layer or formation in geological units in saturated water conditions that can store water but cannot pass water because of its very low hydraulic conductivity value (impermeable). Aquitar is a layer or formation in which can store and release water under certain conditions (semi-impermeable layer). It has a small hydraulic conductivity value so that the water flow moves slowly but still has a possibility to flow water. Aquifug is a layer or formation that cannot store and pass water. The water that is not absorbed on the surface becomes surface flow.

In general, we classified the aquifer depth into: (1) shallow aquifers which are free aquifers with depth less than 25m from ground level; and (2) deep aquifers which are semi-depressed and depressed aquifers with depths more than 25m below ground level (Table 1).

Lithostratigraphic Correlation

A 2D stratigraphic correlation was made from five geoelectrical measurement logs (Figure 3) to show the distribution of different lithologies and aquifer types. Figure 3 shows correlated aquifers for GL01-GBR, GL05-TRM, GL04-STD, and GL03PLDA(a) wells.

The shallow aquifer layer has a maximum depth of 19.2 meters below Ground Level (m GL) and is observed in the GL01-GBR, GL05-TRM, GL04-STD, and GL03PLDA(a) wells. This layer is pinching out to the west and includes breccia and limestone of the Gunung Api Adang and Mamuju formations respectively.

The deeper aquifer layer has the minimum depth of 51.93 m GL and is generally located 30m below the shallow aquifer. This aquifer is lithologically similar to the shallow

Table 1. Aquifer depth at each geoelectric measurement well locations (m GL)

No	Name	Location	Aquifer Type Shallow aquifer (<25m GL)	 Deep aquifer (>25m GL)
1	GL01 GBR	Governor Office of West Sulawesi	13.97 m – 19.16 m	51.06 m – 68.40 m
2	GL02 KRM	TNI KOREM 142 TATAG, Mamuju, W. Sulawesi	6.54 m – 8.446 m	94.05 m – 132.6 m
3	GL03 PLDA(a)	POLDA (Regional Police Headquarter) of W. Sulawesi	17.63 m – 19.20 m	67.78 m – 105.9 m
4	GL03 PLDA(b)	Helipad, POLDA of West Sulawesi	-	75.70 m – 100.0 m
5	GL04 STD	Manakarra Stadium, Mamuju, West Sulawesi	5.803 m – 18.47 m	60.33 m – 85.47 m
6	GL05 TRM	Mamuju Bus Station, West Sulawesi	13.71 m – 19.10 m	60.04 m – 74.66 m
7	GL06 BWS	Office of BWS III, Mamuju, West Sulawesi	3.265 m – 12.28 m	26.93 m – 40.02 m

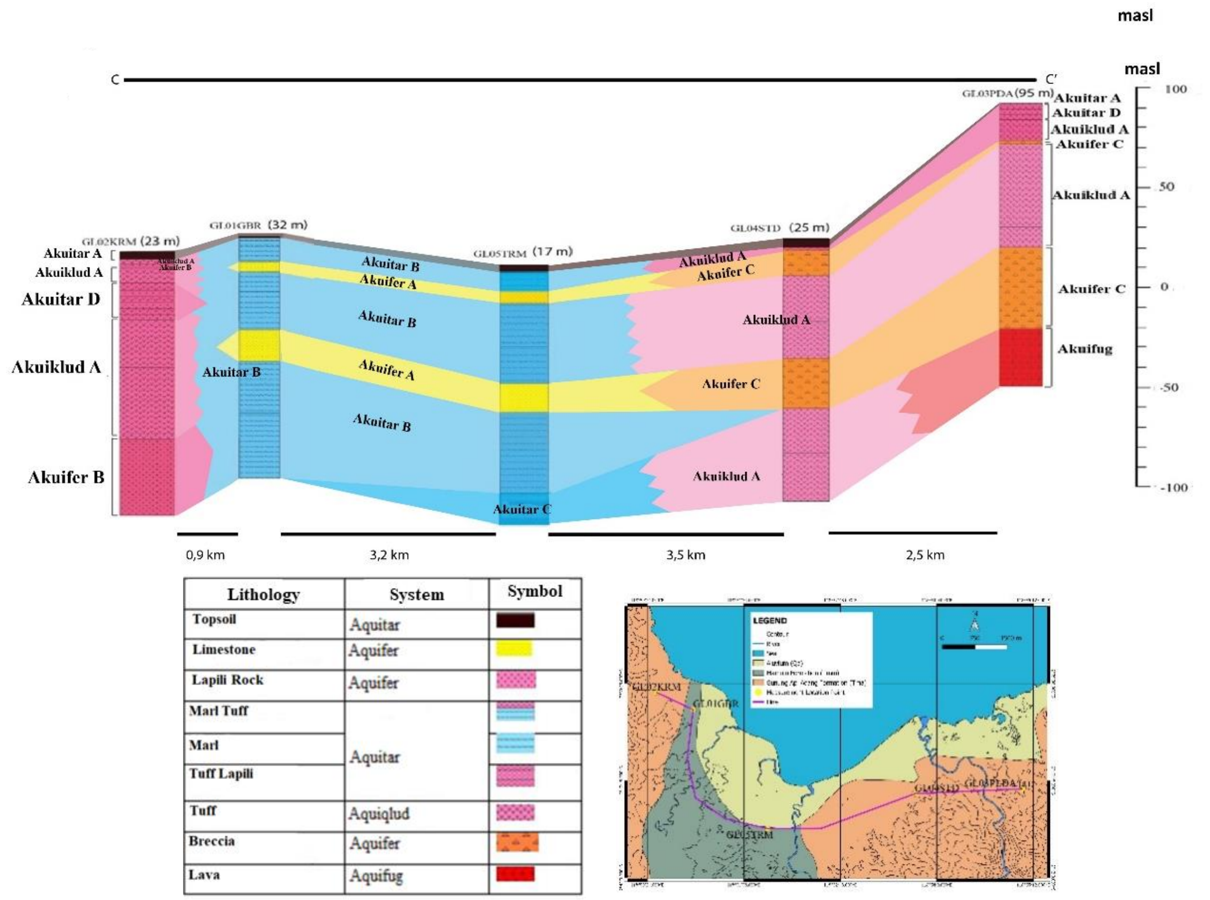

Figure 3: *2D stratigraphic correlation across the well locations where geoelectric measurements took place.*

unit and is pinching out to the west too.

Pumping Test

Pumping tests were carried out in five locations to determine the discharge (Q), water level drop (Sw) and specific capacity (QS) as shown in Table 2. Ground water level subsidence (s) and time (t) of the well pumping test well is summarized in Figure 4. Semi-log plot on Figure 4 shows a linear relationship at the end of the pumping test that indicates confined aquifers.

The values of water level subsidence were used to calculate transmissivity following the Jacob's method (Kruseman dan de Rider, 2000). Transmissivity ranges from 21,095.5 to 101.3 m^2/day and is higher within the carbonate aquifer in GL01GBR and GL02-KRM wells (Table 3).

Groundwater Potential

Groundwater potential at the study area was determined based on slope level, geomorphic lineament, drainage system, overburden, and aquifer thicknesses for the shallow (Figure 5) and deep aquifers (Figure 6).

Groundwater potential is generally lower in the area with a higher slope.

Table 2. Values of pumping discharge (Q), water level drop (Sw) and specific capacity (Qs)

No	Well Code	Q (m^3/s)	SW Optimum (m)	Qs (m^2/s)
1	GL01GBR	0.3	13.0 m	0.02
2	GL02- KRM	7.5	3.0 m	2.50
3	GL03-PLDA (a)	1.0	2.5 m	0.40
4	GL04- 0STD	2.7	6.5 m	0.40
5	GL05-TRM	3.0	6.0 m	0.50

Table 3. Values of residual drawdown difference (S), transmissivity (T) and interpreted groundwater potential

Well Code	S	T (m^2/day)	Groundwater Potential (Domestic)
GL01GBR	4.7	101.3	Very Well
GL02-KRM	1.4	84,358.9	Very Well
GL03-PLDA (a)	1.5	10,547.7	Very Well
GL04-0STD	3.0	14,239.4	Very Well
GL05-TRM	2.25	21,095.5	Very Well

The weighting was calculated by dividing the level of the slope and the degree of slope. The study area is dominated by a weight value of 2 to 5 (from orange to green, Figures 5 and 6). To sum up, only GL03PLD is located on the higher slope.

Groundwater potential is usually higher in the area with straight geomorphic lineaments. The weight value of 1 is marked in green and indicates that there is no straightness. The value of 2 is marked with red and suggests the presence of straight geomorphic lineaments (Figures 5 and 6).

Drainage system was used to differentiate between the main and branch of a river. Groundwater potential will be higher for the main river flow that is indicated by pink, whereas blue indicates a branch of a river (Figures 5 and 6).

Overburden thickness affects the ability of layers to pass and store water. Overburden thickness from geoelectrical resistivity analysis is also divided into shallow (Figure 5) and deep aquifers (Figure 6). Ground water potential will be higher in the higher value of overburden thickness. The weight value of 1 has less than 6m overburden thickness (shown by white). The weight value of 2 has overburden thickness between 6m and 25m (red). The weight value of 3 has more than 25m overburden thickness (dark red).

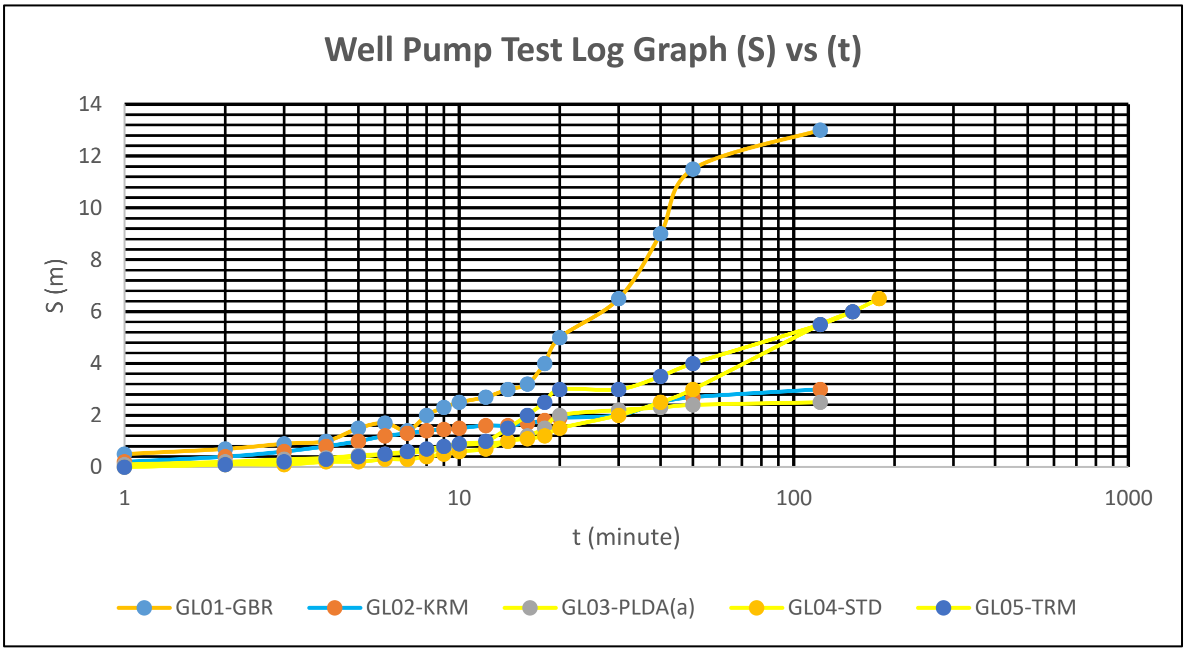

Figure 4: *Well pump test log graph*

Aquifer thickness determines the ability of the layer to pass water which groundwater potential will be higher in a thicker aquifer. The thickness of the shallow aquifer with a value of a weight of 1 indicates that the thickness of the aquifer is less than 6m (white). The weight value of 2 indicates ranges of aquifer thickness between 6m and 15m (light blue). The weight value 3 indicates a thickness between 16m to 25m (dark blue; Figure 5). The thickness for deep aquifers with a weight value of 2 indicates a thickness aquifer between 6m and 15m (light blue; Figure 6), a weight value of 3 which indicated by an area with dark blue has a thickness between 16m and 25m.

Water Quality Analysis

Assessment of water quality were measured from 5 wells in the study area (Table 4). Based on Water Quality Reference of the Minister of Health Regulation No 32 of 2017 regarding concerning Environmental Health Quality Standards and as contained in water for Sanitary Hygiene Purposes. Sanitary personal needs include bathing and brushing teeth, as well as for washing food, tableware, and clothing, and raw water for drinking water

There are 4 wells that meet all the requirements, they are GL-01GBR, GL-02KRM, GL-04STD and GL-05TRM (Table 5). Water quality assessment is carried out at the laboratory of West Sulawesi Provincial Health Office. From 5 measured wells, only well GL03-PLDA(a) chemical parameter that does not meet the requirements is Manganese with a yield of 1.33 mg/L. In PERMENKES No. 32 of 2017 the maximum value for Manganese is set at 0.5 mg/L. However, high Manganese (Mn) content can be reduced by using the method oxidation or can use the filtration method with filter media.

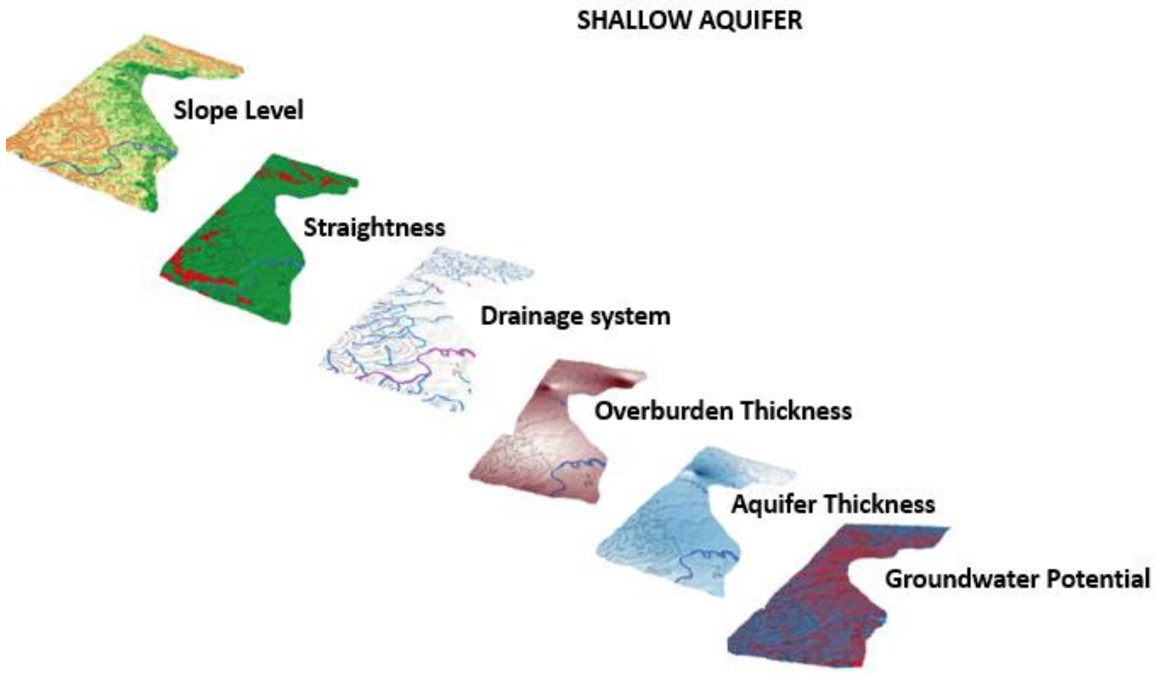

Figure 5: *Integrated groundwater potential parameters for the shallow aquifer*

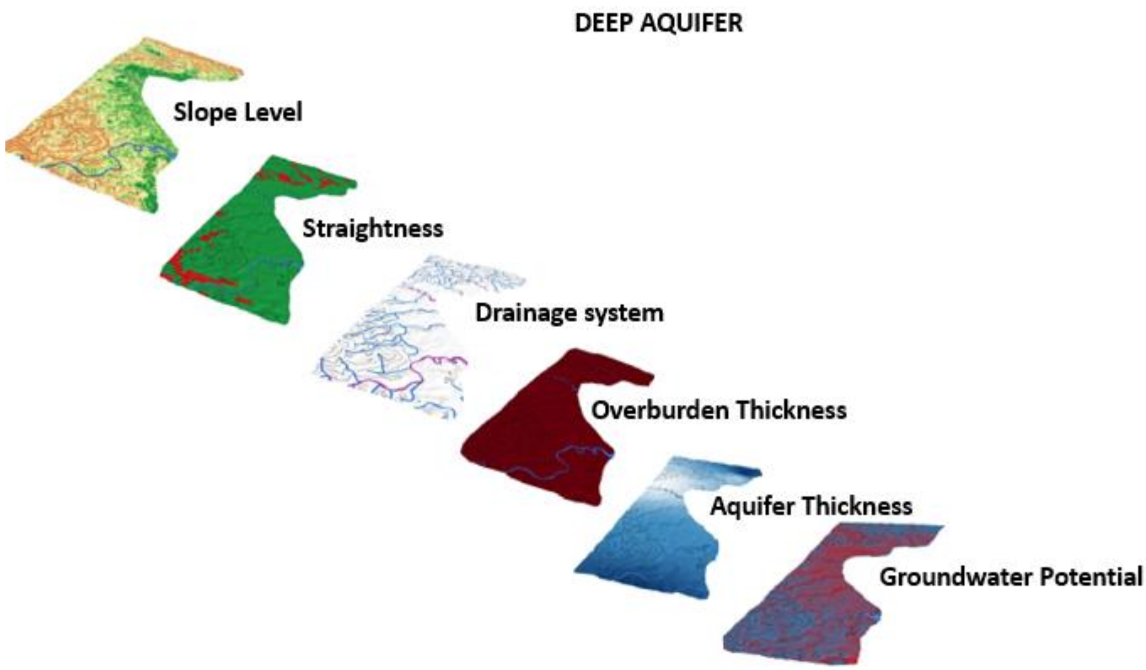

Figure 6: *Integrated groundwater potential parameters for the deep aquifer*

Table 4. The results of water quality analysis

No	Parameter	Result				
		Well-01GBR	**Well-02KRM**	**Well-03PLD(a)**	**Well 04-STD**	**Well GL-05TRM**
A	**Physical properties**					
1	Smell	No Smell	No Smell	No Smell	No Smell	No Smell
2	Flavour	No Flavour	No Flavour	No Flavour	No Flavour	No Flavour
3	Color	No Color	No Color	No Color	No Color	No Color
4	Temperature (°C)	21/22	21/22	21/22	21/22	21/22
5	TDS	57 mg/L	57 mg/L	131 mg/L	71 mg/L	89 mg/L
	Result	**Qualify**	**Qualify**	**Qualify**	**Qualify**	**Qualify**
B	**Chemical properties**					
1	PH	7.1	7.1	7.7	8.0	7.5
2	Chloride (Cl)	6.0 mg/L	6.0 mg/L	6.8 mg/L	5.4 mg/L	7.8 mg/L
3	Iron (Fe)	0.05 mg/L	0.05 mg/L	-	-	0.05 mg/L
4	Ammonium (NH_4)	-	-	-	-	-
5	Manganese (Mn)	0.28 mg/L	0.28 mg/L	1.33 mg/L	0.25 mg/L	-
6	$CaCO_3$	250 mg/L	250 mg/L	138 mg/L	330 mg/L	377 mg/L
7	Nitrite (NO_2-N)	-	-	-	-	-
8	Nitrate (NO_3-N)	-	-	-	-	-
	Result	**Qualify**	**Qualify**	**Not Qualify**	**Qualify**	**Qualify**

Table 5. Summary of the population and settlement coverage

No	Districts	Well Code	Well Debit (L/s)	Debit Availability (L/day)	Water Needs (L/people/day)	Assumption of 1 Family (people/house)	Amount Coverage (people)	Residential Coverage (House)
1	Simboro	GL-01GBR	0.3	25920	80	4	324	270
2		GL-02KRM	7.5	648000	80	4	8100	729
3		GL-05TRM	3	252900	80	4	3240	810
						TOTAL	**11664**	**2916**
4	Mamuju	GL-03PLD(a)	1	86400	80	4	1080	270
5		GL-04 STD	4	233280	80	4	2916	729
						TOTAL	**3996**	**999**

DISCUSSION

Water resources, Population & Settlement

GL01-GBR and GL02-KRM wells are situated in Mamuju District with population of around 3996 people and 999 settlements (Central of Statistics of Mamuju Regency, 2020; Table 6). GL04-STD and GL05-TRM wells in Simboro District to cover around 11664 people and 2916 settlements.

The overlay between the groundwater potential parameters shows the area of medium to good water potential in the shallow aquifer at (Figure 7) and good to very good groundwater potential at (Figure 8) deep aquifer. The coverage area of shallow aquifer (Figure 7) and deep aquifer (Figure 8) for GL01-GBR

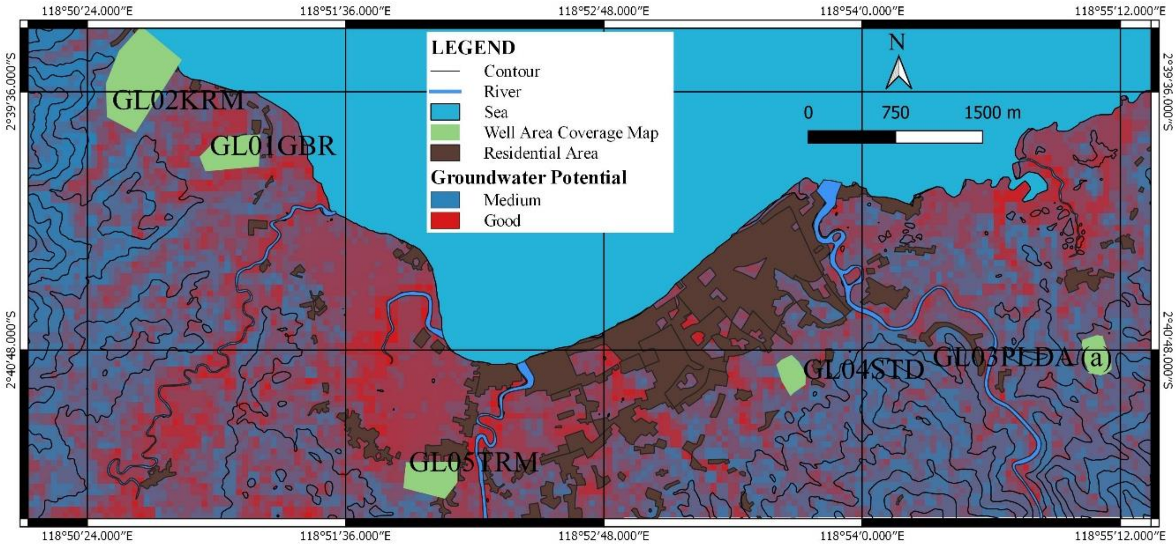

Figure 7: *Groundwater potential map of the shallow aquifer*

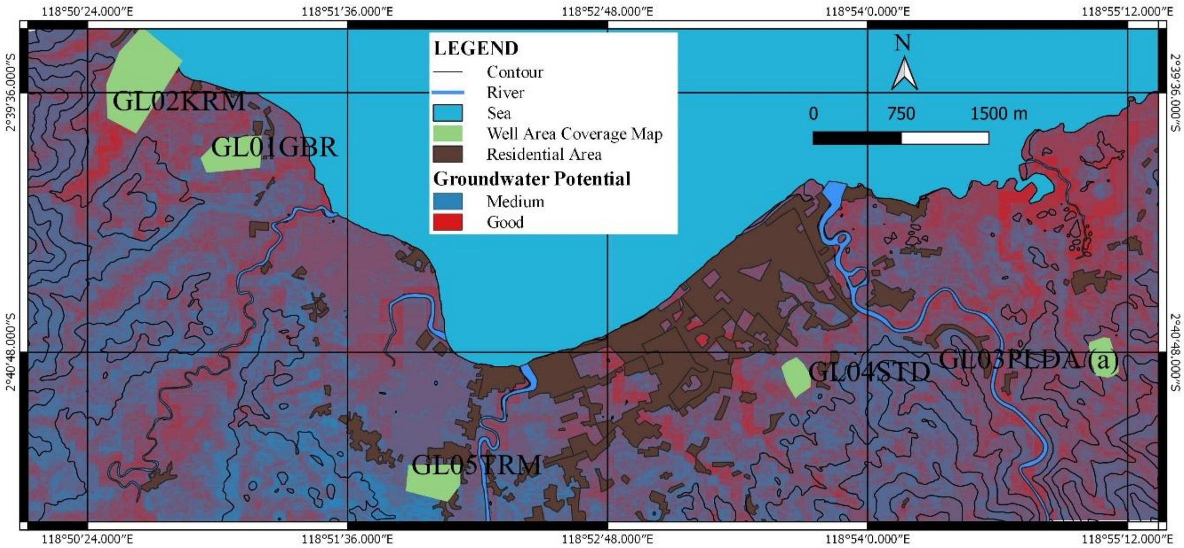

Figure 8: *Groundwater potential map of the deep aquifer*

well is about 130 m^2 and can provide water needs for 324 people/day or 81 houses. The coverage area for GL 02-KRM well is about 1320 m^2 and can provide water needs for 8100 people/day or 2025 houses. The coverage area for GL 03-PLDA (a) well is about 67 m^2 can provide water needs for 1080 people/day or 270 houses. The coverage area for GL 04-STD well is about 445 m^2 and can provide water needs for 2916 people/day or 729 houses. The coverage area for GL 05-TRM well is about 618 m^2 can provide water needs for 3240 people/day or 810 houses.

Water Distribution

The shared water flow direction and well distribution system from the water tank to the water storage container via distribution pipes are suggested based on:

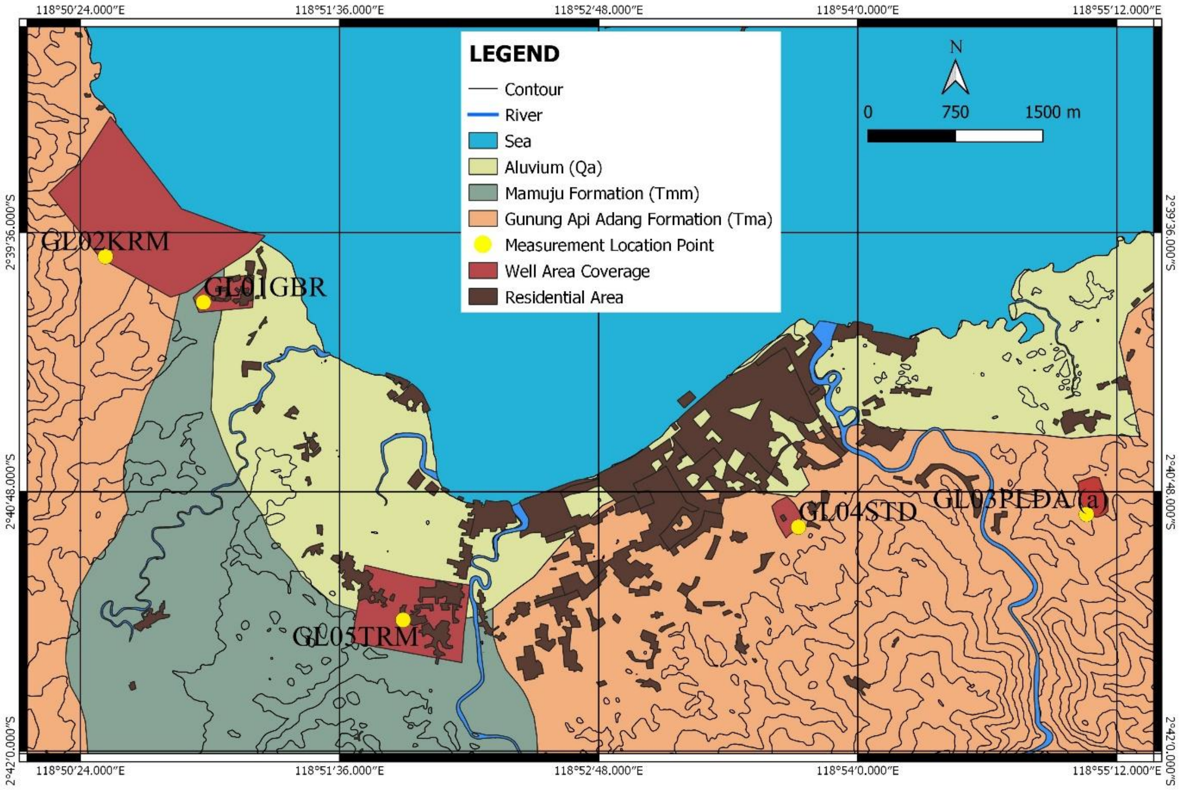

Figure 9: *An integrated map showing well coverage and residential areas on top of the geological map of the study area.*

a. Well distribution direction:

- Wells GL01-GBR, GL02-KRM, GL03-PLDA(a) and GL05-TRM have NE-SW direction

- Well GL04STD has SW-NE direction.

b. Well flow distribution system (Figure 10):

- Wells GL03-PLDA(a) and GL04STD can take advantage of gravity because the area has a slope elevation that can provide water pressure to make water flow.

- Wells GL01-GBR, GL02-KRM, and GL05-TRM can use a pumping distribution system because the area has a low elevation so that the pressure needs to be pushed to make the water flow.

CONCLUSIONS

a. Based on the resistivity values of geoelectrical data, the lithologies of the aquifer (Figure 9) are:

- Limestone and sandstone of the Mamuju Formation in wells GL01-GBR and GL05-TRM. Lapili rocks of the Gunung Api Adang Formation at well GL02-KRM.

- Breccia of the Gunung Api Adang Formation at wells GL03- PLDA(a), GL03- PLDA(b) and GL04-STD.

- Sandstone is located of the Alluvium Deposit in well GL06-BWS.

b. Aquifer type (shallow aquifer & deep aquifer)

- GL01-GBR; the depth of the shallow aquifer ranges from 13.97m to 19.16m and the depth of the deep aquifer ranges from 51.06m to 68.4m.

- GL02-KRM; the depth of the shallow aquifer ranges from 6.54m to 8.44m and the depth of the deep aquifer ranges from 94.05m to 132.6m.

- GL03PLDA(a); the depth of the shallow aquifer ranges from 17.63m to 19.2m and depth of the deep aquifer ranges from 67.78m to 105.9m.

- GL03PLDA(b) only has shallow aquifer that ranges from 75.57m to 100m.

- GL04-STD; the depth of the shallow aquifer ranges from 5.803m to 18.47m and deep aquifer has depth ranges from 60.33m to 85.47m.

- GL05-TRM; the depth of the shallow aquifer ranges from 13.71m to 19.1m and the depth of the deep aquifer ranges from 60.04m to 74.66m.

- GL06-BWS; the depth of the shallow aquifer ranges from 3.26m to 12.28m and the depth of the deep aquifer ranges from 26.93m to 40.02m.

c. Aquifer Types:

- Confined aquifer based on pump test data processing.

- Based on the depth of geoelectric drilling, it is divided into shallow aquifer with a depth of < 25m and deep aquifer > 25m.

d. Water Quality Analysis

- Wells GL01-GBR, GL02-KRM, GL04-STD and GL05-TRM meet the physical and chemical parameters as water for the requirements of the Minister of Health Regulation No 32 of 2017 concerning Environmental Health Quality Standards and as contained in water for Sanitary Hygiene Purposes.

- The water quality in well GL03-PLDA(a) meets the requirements of physical parameters but does not meet requirements of chemical parameters. The chemical parameter that does not meet the requirements is Manganese with a yield of 1.33 mg/L. In PERMENKES No. 32 of 2017 for Mangan the maximum value that is set at 0.5 mg/L Manganese (Mn).

e. Coverage of population who get groundwater potential:

- Wells GL01-GBR and GL02- KRM in Mamuju District can support around 3996 inhabitants or 999 settlements.

- Wells GL03-PLDA(a), GL04-STD and GL05-TRM in Simboro District can support around 11664 inhabitants or 2916 settlements.

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