STRUCTURAL PATTERN AND STRESS SYSTEM EVOLUTION DURING NEOGENE - PLEISTOCENE TIMES IN THE CENTRAL PART OF THE NORTH ARM OF SULAWESI

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Abstract

The study area has been subjected to intense fracturing or brittle deformation resulting in five main trends of lineaments and faults, *i.e*. (1) the Group A (the Perantanaan Fault Group) with a mean of direction N95°E/ N275°E, (2) the Group B (the Gorontalo Fault Group) with a mean of direction N125°E/ N305°E, (3) the Group C (the Paleleh Fault Group) with a mean of direction 165°E /N335°E, (4) the Group D (the Randangan Fault Group) with a mean of direction N25°E/ N205°E and (5) the Group E (the Kuandang Fault Group) having a mean of trend of N55°E/ N235°E. The complexity of structural pattern in the study area has been interpreted to be due to stress system evolution during Neogene - Pleistocene. The changing stress system orientation has reactivated the preexisting faults of the five groups with different sense of movements from the older deformation.

The nearly E-W trending lineaments of Group A or the Perantanaan Fault Group coincide with trend of the long axis of ridges and valleys or depression areas which are covered by volcanic rocks, lake deposits, and alluvium of Quaternary age. This group of structures was presumably developed as reverse or thrust faults during Late Neogene which later on to have beem reactivated as normal faults due to extensional tectonics of the North Sulawesi area during Plesitocene.

The Gorontalo Fault, as a part of the Group B (the Gorontalo Fault Group), generally has been interpreted as dextral wrench fault. The present structural analysis suggests that this major fault was formerly developed as a dextral fault during Neogene, and later during Pleistocene it was reactivated in the sense of sinistral fault due to the changing of the stress system.

The Neogene stress orientation is supposed to be related to the subduction of the North Sulawesi Sea to the south, which during Pleistocene weakened as the Sangihe Subduction in the Mollucas Sea to the east commenced resulting in the change of field stress orientation.

Key words: Structural pattern, stress system, Neogene - Pleistocene, north arm of Sulawesi

S a r i

Daerah penelitian telah mengalami deformasi getas yang intensif, menghasilkan lima arah utama sesar dan kelurusan, yaitu: (1) Kelompok A (Kelompok Sesar Perantanaan) dengan arah rata-rata N95°E/ N275°E, (2) Kelompok B (Kelompok Sesar Gorontalo) dengan arah rata-rata N125°E/ N305°E, (3) Kelompok C (Kelompok Sesar Paleleh) dengan arah rata-rata N165°E/N335°E, (4) Kelompok D (Kelompok Sesar Randangan) dengan rata-rata arah N25°E/ N205°E dan dan (5) Kelompok E (Kelompok Sesar Kuandang) yang memiliki arah rata-rata N55°E/ N235°E. Kompleksitas pola struktur di daerah penelitian diduga disebabkan oleh adanya evolusi orientasi sistem tegasan sejak Neogen hingga Plistosen. Perubahan orientasi sistem tegasan ini telah mereaktifasi kelima kelompok sesar yang sudah ada dengan arah pergerakan yang berbeda dengan deformasi yang lebih tua.

Kelurusan yang berarah hampir barat – timur (Kelompok A atau Kelompok Sesar Perantanaan) merupakan kelompok struktur yang bertepatan dengan arah punggungan dan lembah atau daerah depresi yang ditutupi oleh endapan berumur Kuarter berupa batuan gunungapi, endapan danau , dan alluvium. Kelompok struktur ini diduga terbentuk sebagai sesar naik selama Neogen Akhir yang kemudian teraktifkan kembali menjadi sesar normal karena tektonik pada Plistosen.

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Sesar Gorontalo, sebagai bagian dari Kelompok B, umumnya ditafsirkan sebagai sesar mendatar dekstral. Sementara pada analisis ini menganggap sesar utama ini semula terbentuk sebagai sesar mendatar dekstral pada Neogen Akhir, dan kemudian teraktifkan kembali sebagai sesar mendatar sinistral selama Plistosen karena terjadinya perubahan orientasi sistem tegasan.

Sistem tegasan Neogene diduga berkaitan dengan tunjaman Sulwesi Utara, yang pada Plistosen melemah seiring dengan terjadinya tunjaman Sangihe di Laut Maluku di timur yang sekaligus merubah orientasi sistem tegasan di daerah ini.

Kata kunci: sistem tegasan, Plistosen – Holosen, lengan utara Sulawesi, teraktifkan kembali.

Regional tectonic setting

The Sulawesi area and its surroundings can be divided into 4 main megatectonic provinces namely (1) the Western Sulawesi Magmatic Belt, (2) Central Sulawesi Metamorphic Belt, (3). Eastern Sulawesi Ophiolite Belt, and (4). Bangai-Sula and Buton Tukangbesi Platform (Figure 1). The formation of these geological provinces are related with collision between Sundaland as the easternmost part of the Eurasian continental plate and the microcontinents derived from the Australian continental plate.

The Western Sulawesi geological province form a volcano-plutonic belt which is physiographically comprises the south and north arms of Sulawesi. The south arm, which is dominated by volcanic and plutonic rocks of Miocene age or younger, is superimposed on the eastern margin of the Sundaland or the easternmost part of the Eurasian crustal plate (Katili, 1978; Silver *et al*, 1983). Meanwhile, the Central Sulawesi Metamorphic Belt is occupied by Pompangeo Schist and correlative units of blue schist metamorphic facies.

The Eastern Sulawesi Province covers the eastern and southeastern arms of Sulawesi. This geological province is characterized by the occurrence of the Late Cretaceous ophiolite belt. The ophiolite was obducted durimg Miocene (Smith and Silver, 1991).

The Banggai Sula Platform is an allochtonous continental terrain detached from the Australian Continent which is characterized by the occurrence of Paleozoic to Mesozoic metamorphic, sedimentary and intrusive rocks. The Tukangbesi Platform is also a microcontinent detached from the Australian continental plate.

The tectonic history of Sulawesi can be elaborated starting from the Early Cretaceous when the Eastern Sulawesi Province moved westward to follow a westward movement of a gentle subduction in the eastern part of the Western Sulawesi Province. The field evidence of the Early Cretaceous subduction are among others the Bantimala melange in South Sulawesi (Sukamto, 1975) and the Pompangeo Schist near Lake Poso representing a subduction metamorphism (Parkinson, 1991).

The second subduction event in Sulaswesi is marked by reactivation of the Cretaceous subduction zone during the Middle Oligocene as shown by the presence of ophiolite complex in the east arm. Based on the age of metamorphism, the subduction event took place in 28 – 31 ma (Kavalieris *et al*, 1992).

The third south dipping subduction zone resulted in formation of calc-alcaline magmatic rocks of Early Miocene age in the north arm .This subduction was subsequently followed by an arc and continent (Banggai-Sula and Buton – Tukangbesi Platforms) collision causing a clockwise rotation of the north arm, back-thrusting, and inception of subduction along the North Sulawesi Trench (Kavalieris *et al*, 1992).

During the late of Middle Miocene to Pliocene, molasse sediments were deposited unconformably over all geological provinces in Sulawesi. At the same time, granitoid plutons occurred in the Western Sulawesi Province. During Plio – Pleistocene all over Sulawesi area was deformed. The tectonic activity still continues up to now as indicated by the active thrust – fold belts in the south arm, i.e. the Majene Fold Belt and Kalosi Fold Belt (Coffield *et al*, 1993; Bergman *et al*, 1996, Bachri and Baharuddin, 2001), and the formation of uplifted Quaternary reefs in all Sulawesi geological provinces.

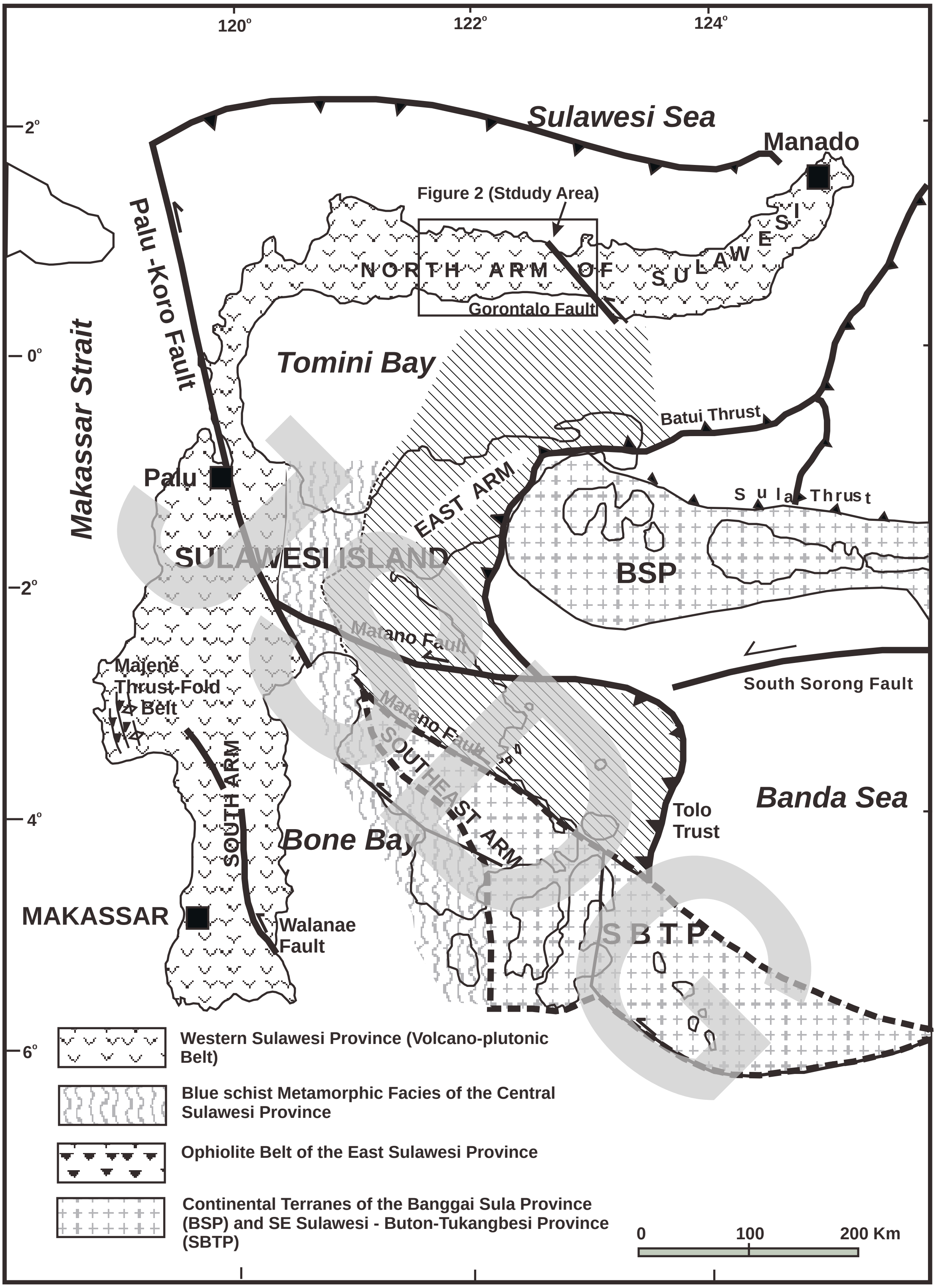


Figure 1. Tectonic setting of Sulawesi and adjacent area, compiled after Sukamto (1975),Helmers et al.(1990),Parkinson (1991),Smith & Silver (1991); Bachri and Baharuddin, 2001).

Lineament analysis

The lineaments and faults analyzed in this study area are extracted from the existing geological maps of 1:250,000 scale (Figure 2) published by the Indonesian Geological Research and Development Center (GRDC), now the Centre of Geological Survey, the Geological Agency. These maps include the Tilamuta Sheet (Bachri *et al*, 1994) and Kotamobagu Sheet (Bachri and Apandi, 1997). The structures present in these maps are based on SLAR image and aerial photographs interpretation and field geological mapping.

A 10 degree interval classification is applied in the present study area. As a consequence of this classification, the long curvilinear lineaments will be split up into segments according to their subdivision in 10 interval classes. This classification has provided 5 prominent trends of lineaments or faults , i.e. the Group A, B, C, D and E (Figures 3A,B). This grouping is simpler and easier to interpret based on their pattern as well as by comparing to the known structures existing on published geological maps. In this case, the relationships between the stress orientation and the types of fault refer to the theory of Moody & Hill (in 1956).

Group A (the Perantanaan Fault Group)

This group of structures is very prominent and has a mean of direction N 95°E/ N275oE, with a relatively narrow interval of direction. The total length and fracture frequency of this class are higher than the other classes. The lineaments are generally well pronounced forming long lineaments up to 35 km long. This lineament or fault group is represented by several major faults, such as the Perantanaan Fault, the Telongkabila Fault, the Tetembu Fault Fault which are obviously seen on SLAR image. This group of lineaments has been interpreted controversially, whether as thrust or normal faults (Trail *et al*, 1974).

The Perantanaan Fault Group is considered to be perpendicular to the largest principal stress S_1 during the Neogene, and therefore it can be supposed to be a thrust fault group. The occurrence of thrust faults in this direction is not prominent in the field. Some relatively small thrusts can be observed to the north of Tombuililato Village, east of the study area (Bachri *et al*, 1997).

In reality, the Perantanaan Fault Group also coincides with the direction of ridges and big valleys or graben/ half graben in the north arm of Sulawesi. Three examples of the graben area are the Lake LimbotoValley, the Bone Valley and the Pinogu Valley in the eastern part of the study area. These valleys are covered by relatively young sediments and volcanics such as the Quaternary lake deposits and the Plio-Pleistocene Pinogu Volcanics. This phenomenon may suggest that probably the lineaments of Group A are closely related to the occurrence of the almost E-W elongated valleys which are presumably representing extensional structures developing in the Late Pleistocene - Holocene time. The extensional tectonics may have triggered reactivation of volcanism after the Neogene collision, as indicated by the occurrence of the major almost E-W oriented lineaments passing through two big cauldrons in the Kotamobagu area and in Tondano (Kavalieris *et al*, 1992). Hence, it can be interpreted that the thrust faults, which were generated by a compressional tectonics in Neogene times, have been reactivated by post collision extensional tectonics and rotation of the North Arm of Sulawesi. due to post collision rifting, forming extensional structures, such as normal faults and depression areas in Plio-Pleistocene times.

Group B (the Gorontalo Fault Group)

These lineaments or faults have a relatively wide range of direction, with a mean direction of N125°E/ N305°E. The most prominent representation of this group are the Gorontalo Fault passing through the Gorontalo Bay, and the Bodi – Utilemba Fault in the western part of the study area. Systematic shear joints are well developed in the Gorontalo Bay area, in the Bone Diorite. On the basis of the shear joints orientation, the sense of movement of the major lineament can be deduced as a right lateral fault or dextral wrench fault (Figure 4). The dextral displacement is also obviously displayed by the shape of the Gorontalo Bay. On contrary, a sinistral displacement is also suggested by off set of Quaternary limestone occurred along the fault zone. This fault is interpreted to be a major dextral wrench fault developed during the previous deformation period (Late Neogene or older) which was later on reactivated to be a sinistral wrench fault during the younger deformation period

(Pleistocene – Holocene). The sinistral displacement is supposed to be much smaller than that of the previous dextral wrench movement, so that the present morphology of the Gorontalo Bay still , as if, suggests a dextral sense of movement.

Group C (the Paleleh Fault Group)

This group of lineaments also has a relatively wide interval of direction (see Figure 3A), with a mean direction of N155°E/N335°E. The most prominent representation of this group are the Paleleh and the Bulokidoka Faults. The faults were formerly developed as normal - dextral faults during the Late Neogene or older, which was subsequently in the later deformation period (Pleistocene) reactivated to be thrust - sinistral faults.

Group D (the Randangan Fault Group)

This trend of lineament and faults has a mean direction of N25°E/ N205°E. The total length and frequency are relatively small in comparison to the other groups. The Randangan Fault is a representation of this group. This fault group has been interpreted to be normal - sinistral faults during the older deformation (Late Neogene) and was reactivated to be thrust - dextral faults during the younger deformation (Pleistocene).

Group E (the Kuandang Fault Group)

This group of structures is also not so prominent as the Groups A, B or C. The Kuandang and Olie Faults are the most important representation of this group. This fault group has a mean of direction N55°E/ N235°E. During the Late Neogene this group was developed as sinistral wrench fault, whilst in the later deformation this group was reactivated to be dextral faults. The associating lineaments making a small angel to this group are interpreted to have a combined lateral and vertical movement. Explanation of its relationships to the stress system orientation is given in the next chapter.

Stress system orientation

The study area has been subjected to major strike-slip deformation as indicated by the occurrence of the Gorontalo Fault and other associating shear fractures. The Late Neogene structures in the north arm of Sulawesi are presumed to be related to the subduction in the North Sulawesi Sea. In order to analyze the relationships between the Gorontalo Faults and the other smaller strike-slip faults, ellipse strain model of Harding *et al.* (1973) has been applied. On the basis of orientation of the Gorontalo Fault Group) and the associating shear fractures, the largest principal stress s1 during the Late Neogene was directed at N5oE/ N185oE, whereas the smallest principal stress s_3 was oriented at direction of N95°E/ 275°E (Fifure 6A). This stress system has generated synthetic dextral faults of the Gorontalo Fault Group. The Perantanaan Fault Group which is almost nearly perpendicular to the s_1 is supposed to be mainly having vertical (thrust) movement. The Gorontalo Fault Group (Gorontalo Fault, Bodi-Utilemba Fault, *etc*) has been interpreted to be a group of dextral wrench faults of the first order.

The stress system during the Pleistocene resulted in a strain ellipse as depicted in Figure 6B. This deformation period is dominated by extensional tectonics as indicated by the occurrence of several major normal faults and grabens (depresion area) directed at more or less N95°E/N275°E. The depression areas are found in the eastern – central part of the study area, *i.e*. the Lake Limboto depression area (inside the study area), the Bone Valley and the Pinogu Valley (outside the study area). On the basis on the orientation of the major structures developed during Pleistocene, the largest principal stress 1 is thought to be directed at N275°E/ N95°E, whereas the smallest stress s_3 was oriented at N5°E / N185°E. This stress orientation is supposed to be related to the Sangihe Subduction to the east of the north arm of Sulawesi. During this period, the Perantanaan Fault Group was reactivated to be normal faults forming graben or depression areas, whilst the Gorontalo Fault Group was reactivaded to be sinistral faults.

Concluding remarks

An anti-clockwise rotation of stress system orientation occurred during Late Neogene – Pleistocene times in the north arm of Sulawesi. The changes of the stress system orientation have generated difference senses of movement to the fault systems in the study area.

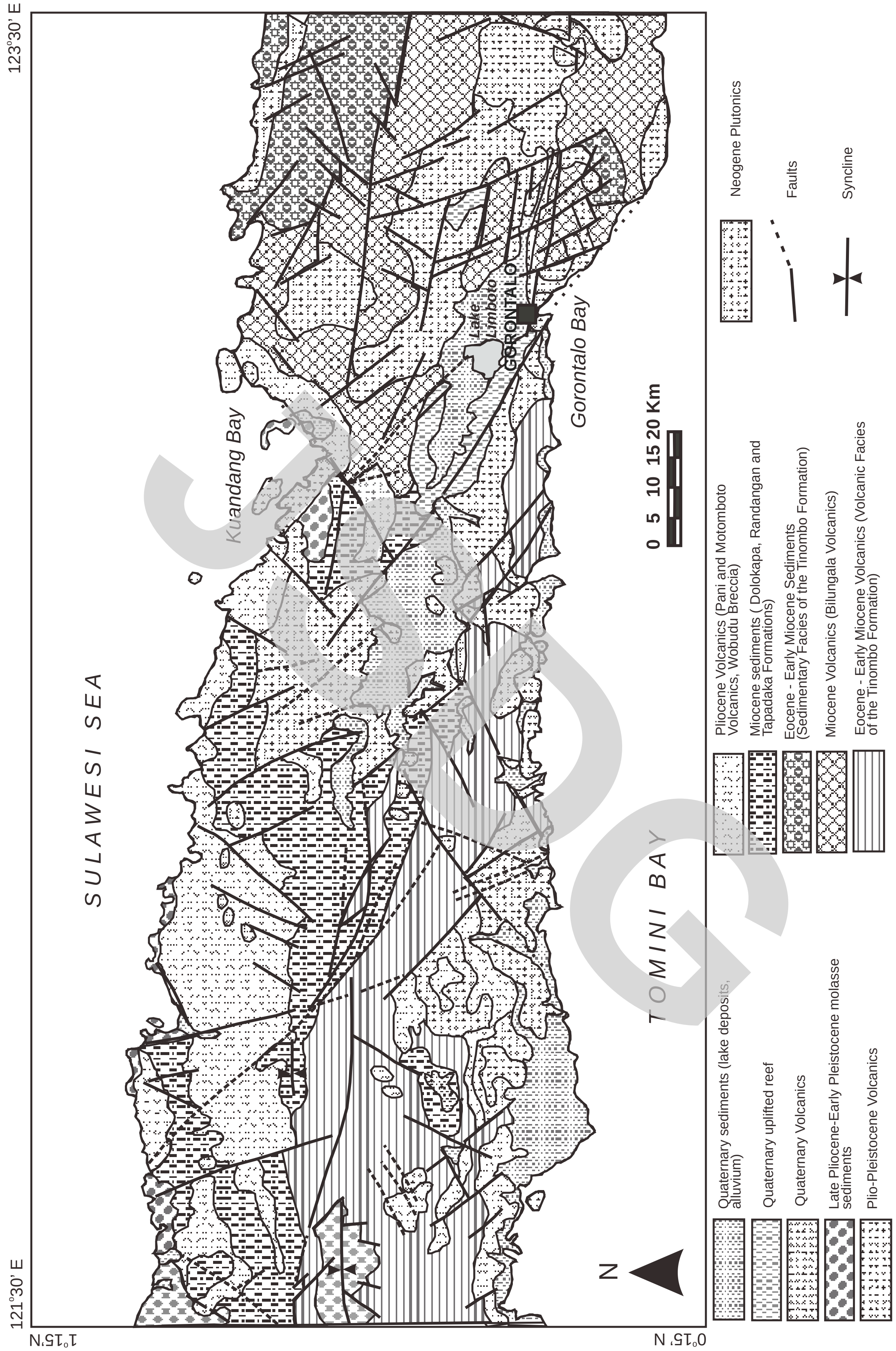


Figure 2. Geological map of the central part of the north arm of Sulawsi, simplified after Bachri et al (1993) and Apandi & Bachri (1997).

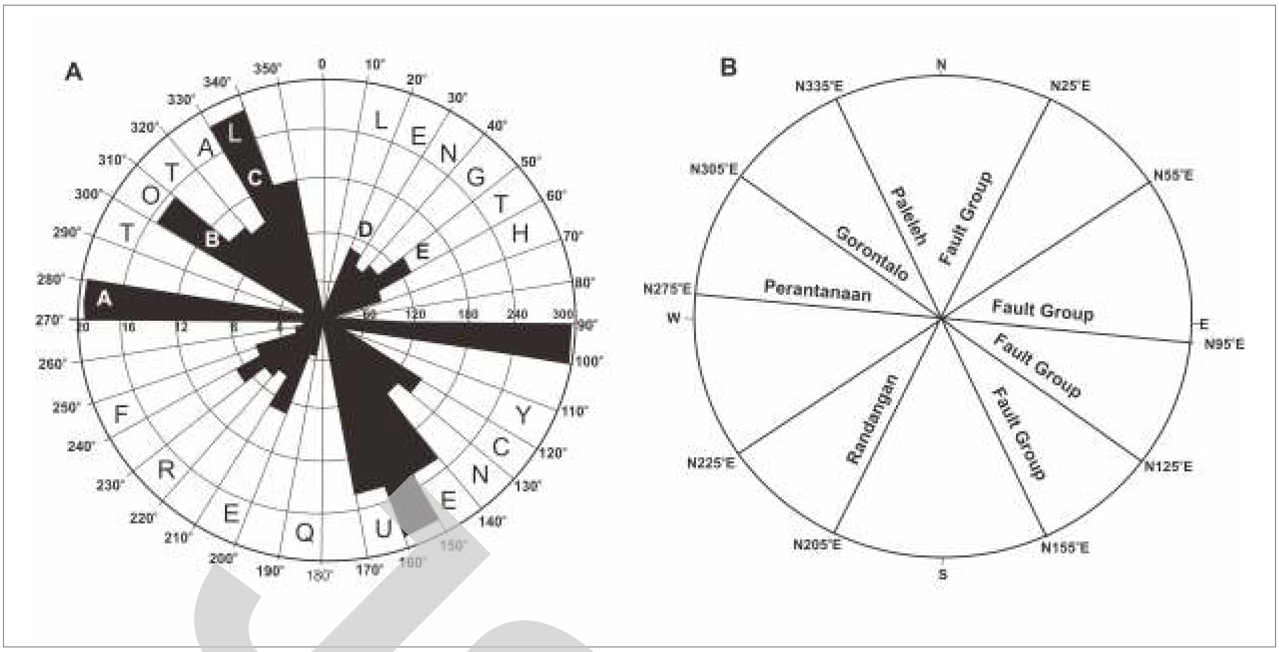
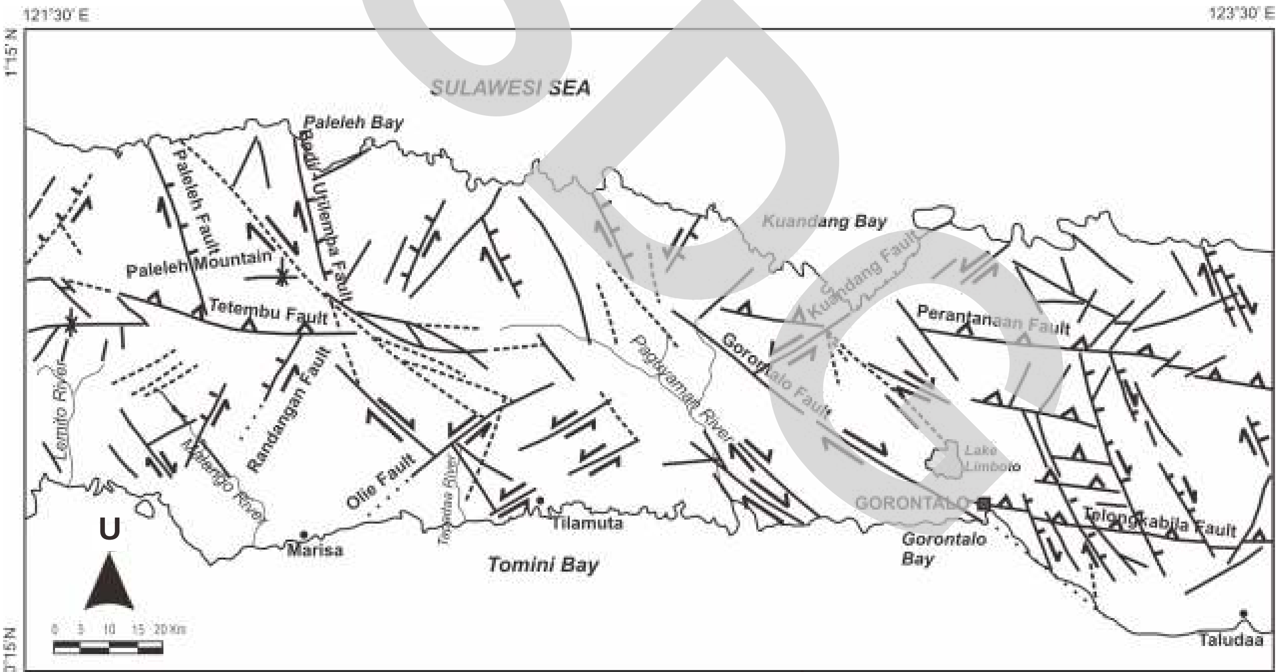


Figure 3 A. Length and frequency rose diagram of the lineaments or faults of the study area based on an 10° interval classification B: Mean of trends for the



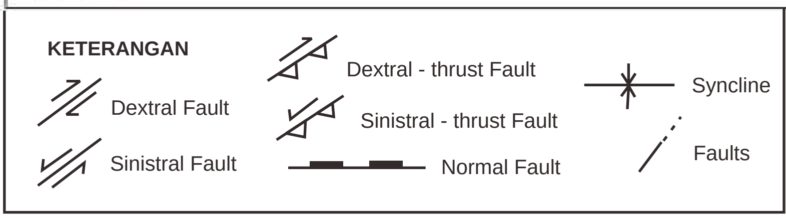
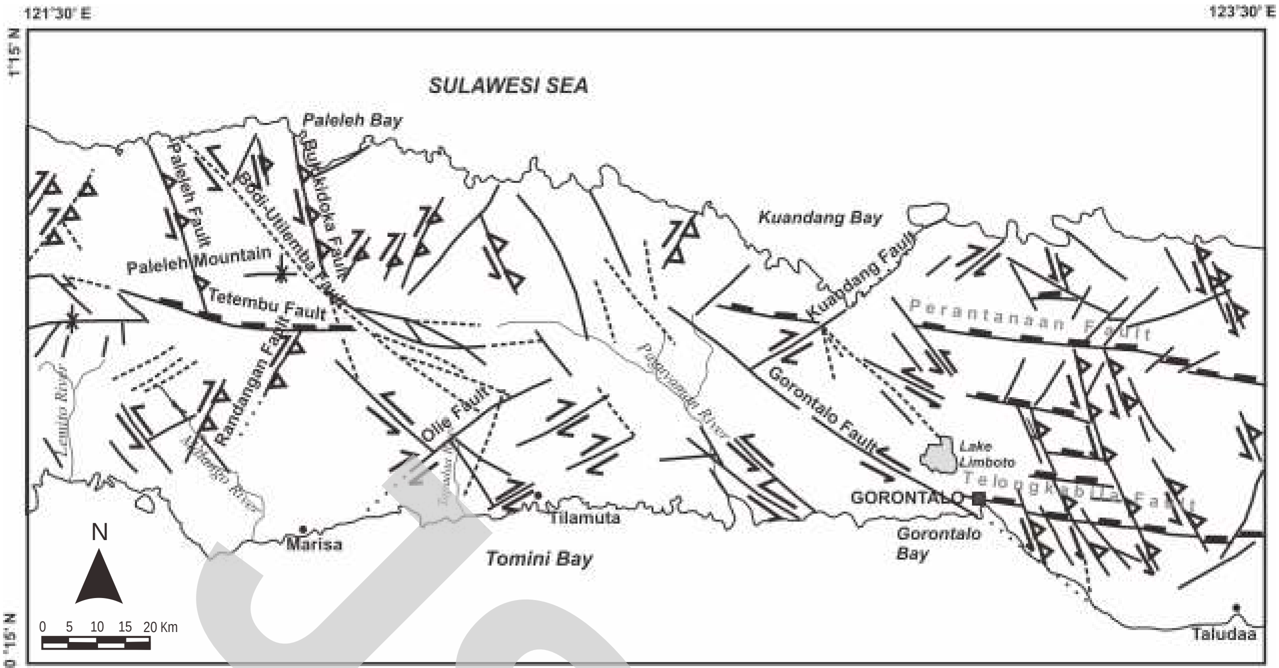


Figure 4. Structural map during Late Neogene. Structures extracted and modified after Bachri *et al.* (1993) and Apandi & Bachri (1997).



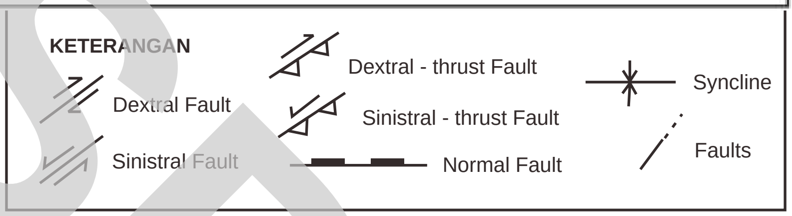
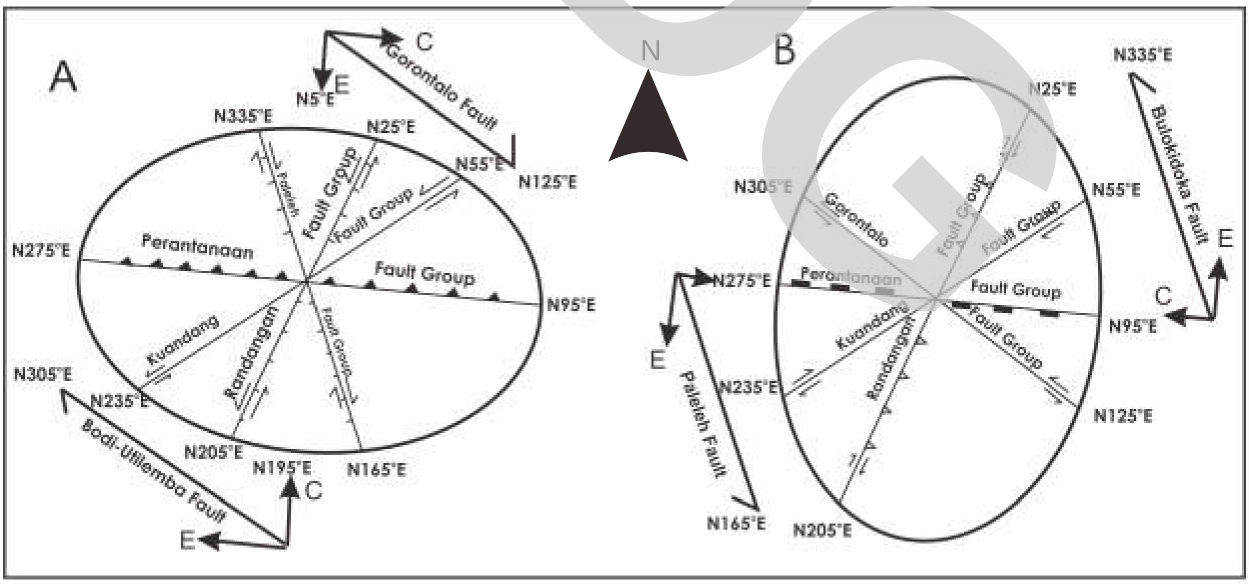


Figure 5. Structural map during Late Pliocene-Pleistocene. Structures extracted and modified after Bachri *et al* (1993) and Apandi & Bachri (1997).



The biggest fault recognized in the study area, *i.e*. the Gorontalo Fault, so far is identified as a dextral fault as seen from the displacement Gorontalo Bay. However, this fault has been actually reactivated to be as sinistral fault during the Pleistocene time. The displacement during the later deformation is smaller than that of the previous deformation, so that the older sense of displacement is still prominently seen.

The major lineaments oriented in N95°E/N275°E belonging to the Perantanaan Fault Group, which has been formerly controversially interpreted whether as thrust or normal faults, was previously developed as thrust faults during the Late Neogene, and later on it was reactivated as extensional structures during the Pleistocene. The occurrence of several major depression areas oriented nearly parallel to the North Sulawesi Arc suggests that during the Late Pleistocene time, the study area was mainly subjected to an extensional tectonics.

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