Tectonic Geomorphic of Sulawesi Island and Its Implication for Future Large Earthquake
Catur Cahyaningsih$^{12}$, Yos Admojo$^2$
$^1$Department of Physical and Geological Sciences, University of Brunei Darussalam, Brunei Darussalam
$^2$ Geological Engineering Department, Faculty of Engineering, Universitas Islam Riau, Indonesia

*Corresponding Author: caturcahyaningsih@eng.ui.ac.id
Telp: 082284013121
Received: Dec 28, 2021; Accepted: Dec 31, 2021
DOI: 10.25299/jgeet.2021.6.4.8538

Abstract
This paper analyzes how resource of past and prospective great earthquake on the Central Sulawesi Arm, adhere on topography analysis from several space-based source. To answer the question, we analyze the tectonic geomorphic, stream pattern, exhumed fault, geological mapping and seismicity data. Detailed tectonic geomorphic studies in Sulawesi still lacking due to tectonic and fault obscure. For instance, Palu Koro Fault (PKF) was unpredictable, because the historical seismic records inevitably poorly documented and unrecognized fault strand, which was buried beneath abundant Quaternary alluvium subsequently obscured the fault trace. In other hand, the faults have been active during Quaternary must take into account because potentially faults during instrumental period must be re-evaluated in order to have awareness for large future large earthquake. Surprisingly, recent seismic activity of PKF generate super shear rupture a Mw 7.5 earthquake on 28th September 2018 with average slip 41 mm/year, which over the past two decade quiet from any seismic activity. The seismic potential for large fault is essential, since it has been silent during the instrumental period. Therefore, our motivation in this study to produce detail tectonic geomorphic map of the region in local scale, which is currently not available to prepare better knowledge and awareness for the large future earthquake. We have use Shuttle Radar Topography Mission (SRTM) with resolution ~30m, which run by ArcGis software to observed tectonic geomorphic evidence of fault system and supplement with structural, geological and bathymetric data’s as ware available to us. We relate this analysis with seismicity data from Centroid Moment Tensor Solution (CMT) to recognize the seismic source. Our results show the tectonic geomorphic of Central Sulawesi Arm due to nature extension of NW-SS left-lateral slip curving to NWW-ESE of Palu-Koro Fault (PKF), then transcript to N-S circular normal fault of Poso Fault (PF). The PF indicate replica of PKF curving, where has not been mapped previously. We have mapped 60 major onshore fault systems, 10 faults showed evidence maximal to rapid rate tectonic activity along instrumental periods. Based on our CMT analysis, Sulawesi Island is greatly dominated by oblique fault.

Keywords: Earthquake, Geomorphic, Central Sulawesi Arm, Palu-Koro Fault, Poso Fault

1. Introduction
The physical location and the shape of the Island of Sulawesi possibly reflect the active tectonics of the region because it is surrounded by the ~180° turn of the Sunda Megathrust and it is the only place that occupies central position of the curvature of the subduction zone (Hall & Wilson, 2000; Socquet et al., 2006). Therefore, it is one of the most important locations to navigate the overall tectonic architecture of the region, which until now remains largely unknown (Charlton, 2000; Hall, 2002; McCaffrey, 1989; Norvick, 1979). The caging of the Sunda plate within Australia, and the Philippines Sea plate and the complex nature of plate boundaries that demarcate the Sunda plate from Australia, Philippines Sea, and Pacific plates is one of the most interesting lithospheric tectonic plate's interactions in the world. The plate interactions have produced a wealth of information regarding the initiation, growth, and development of the region, and such information has not been fully mapped, particularly on the regionals, and local scales (Das, 2004; Pownall, 2018; Socquet et al., 2006; Watkinson et al., 2012). Historically, Sulawesi has complex tectonic consist of subduction, obduction and collision and forming some microplates (Hinschberger et al., 2005; Nugraha & Hall, 2018). This complex tectonics is constructed on to the geomorphic of the Island. Nevertheless, the seismic sources and the tectonic geomorphic of the region are poorly understood during the last two decade. The previous study has generally provided in the regional tectonic, seismic and geodetic data’s of the region. Consequently, through these data’s, this study has analyzed and
Presented the tectonic geomorphic of the region in detail. The tectonic geomorphism has supplemented with several evidence particularly the regional deformation is manifested on the geomorphology. Our tectonic geomorphic maps have integrated with seismicity, geology and submarine data of the region. These data’s conduct us to precisely interpret our onshore structural mapping and to attribute with appropriate offshore structure. This study is presenting evidence for Quaternary tectonic activity and re-evaluation of the seismic hazards of the faults in this region.

The earthquake disasters are expected at such locations where plates interact at varying velocities and in the past many moderate to large magnitude earthquakes have caused significant damage to life and property (Fang et al., 2019; Hall & Blundell, 1996; Kennett et al., 1995; Sieh, 2006; Simons et al., 2007; Subarya et al., 2006; Watkinson & Hall, 2019). The major active fault in Sulawesi is located in the central flank with type left-lateral strike slip fault known as The Palu-Koro Fault (PKF) (Daryono, 2019; Hall, & Watkinson, 2017). Geomorphic expression of Palu Koro Fault can be observed from western flank of Palu Valley until Masamba, North Luwu Regency with trend towards ~NNW-SSE and along 210 km (Patria & Putra, 2020). The relative motion of PKF is around 42 mm/year in between the North Sula Block and the Makassar Block (Socquet et al., 2006). The PKF and Matano Fault (MF) are connected at the southeast arm of Sulawesi; both of them show curving left-lateral strike slip movement from NNW-SSE turn to E-W. The PKF has generate the greatest seismic event and devastated earthquake in the Eastern Indonesia (Watkinson & Hall, 2016). The recent large earthquake event was ruptured by PKF on 28th of September 2018 with magnitude 7.5, left lateral offset 7 m, traverse Palu Valley and extend 180 km (Socquet et al., 2019, Bao et al., 2019). The earthquake event has produce tsunamis with 7 m high, probably connecting with landslide in submarine area (Putra et al., 2019). The earthquake hypocentre was detected at north of Palu City nearby Donggala Regency with shallow depth around 10-15km, which regarding Global Centroid Moment Tensor (GCMT) (Patria & Putra, 2020). Many studies have highlights the PKF but nature the PKF remains unknown whether pure left-lateral strike slip fault or extensional system. Therefore, the motivation of this work to investigate detail fault system in Sulawesi area to observed tectonic geomorphic evidence of fault system. Also we are using Centroid Moment Tensor Solution (CMT) to recognize the seismic source. Thus, we propose the nature possibility of PKF mechanism.

2. Tectonic Background

The geology and tectonic architecture of the Sulawesi Island has been discussed in a number of previous researchers. Here is summary analysis of the obtrusive points of the prior study (Advokaat et al., 2017; Anugrahadi et al., 2019; Katili, 1978; Natawidjaja et al., 2021; Natawidjaja & Daryono, 2016; Socquet et al., 2006; Wang et al., 2019; Watkinson & Hall, 2017; Hall, 2012b)

Sulawesi Island is composed of complex tectonic structures. The tectonic framework of Sulawesi involves three important plates movement: (1) The Eurasian Plate converging to southeast to Sunda Plate (2) The Australian Plate converging northward to the Timor Plate, and (3) The Pacific Plate converging westward to the Caroline and Philippine Sea Plate (Hall, 2012; Linthout et al., 1997). The three plates interaction triggers micro-plates movement through translation, rotation, and deformation (Linthout et al., 1997) (Fig 1).

In the north arm of Sulawesi, the Celebes Sea is being subducted beneath Sulawesi and forming North Sulawesi Trench (e.g. Hamilton, 1979; Silver et al., 1983a). The Philippine Sea Plate and Sunda Plate are accommodated by the overlying Sangihe and Halmahera Thrust and the Molucca Sea double subduction (e.g. Rangin et al., 1999; Hall, 2002; Beaudouin et al., 2003). Onshore of the north arm Sulawesi, there is active Gorontalo Fault. In the west arm of Sulawesi have rifting and divergent phase. Those tectonic activities have been opening Makassar Straits, fold belt, Majene Thrust Fault which are dipping towards west. Nevertheless, fold belt and Samarinda Thrust Fault are formed at East Kalimantan with dipping toward east. In the Central Sulawesi, the most significant structure is accommodated by left-lateral strike –slip movement of the Palu Koro Fault and continues to the Matano Fault in the southeast (Hinschberger et al., 2005). The Buton-Tukang Besi and Banggai-Sula in the eastern part of the island are two micro continental blocks, which having separated from the northern continental margin of Australia (Simandjuntak, 2012; Silver et al, 1983b; Simandjuntak, 1986). The investigation of Quaternary fault in Sulawesi is complicated due to lack of past earthquake record and few availability of paleoseismic data. Therefore, in this study will concern on nature of geomorphic salient faults and structure, also augmented with seismicity record.

Based on geological condition, Sulawesi Island can be divided into four provinces (Hamilton, 1973; Katili, 1978); which are the North Sulawesi Magmatic Arc, the West Sulawesi Plutono-Volcanic Arc, the Central Sulawesi Metomorphic Belt, the East Sulawesi Ophiolite and the Microcontinental fragment of Banggai-Sula and Tukang Besi-Buton (Fig 2). The West Sulawesi Plutono – volcanic arc comprises the north, central and south Sulawesi arm. Southern region compose of the Eocene to upper Miocene carbonate, which were deposited on shallow marine shelves close to deep marine Malassar Straits basin through rifting during the Eocene (Hall & Wilson, 2000; Hall et al., 2009). The Central Sulawesi Metamorphic Belt consists of Pompangeo Complex and Ophiolitic Melange (Hamilton, 1973; Parkinson, 1998b). This belt has existed on the eastern margin of Sundaland before-
Fig 1. The map shows complex tectonic structures of South East Asia. The white line is study area.

Fig 2. The map shows simplified geological setting of Sulawesi have modified after (Hall & Wilson, 2000)
Cenozoic which contains micro-continental fragments. The East Sulawesi Ophiolitic Belt is formed by two different compositions; the ophiolite and pelagic sedimentary rocks (Mubroto et al., 1994). It had been thrust over the continental terranes during the Late Oligocene-Middle Miocene, which subsequently proceeded with the Sulawesi Molasse was unconformably deposited on top (Harris, 2004). The East Sulawesi is estimated from Mid Oceanic Ridge origin, within the Pacific plate. On the other hand, the continental terranes were originated from the northern margin of the Australian continent (Monnier et al., 1995). The basic geology information is important and will combine with tectonic geomorphic in order to define seismic source zones, maximum earthquake magnitude and determine quaternary deposit of Sulawesi Island.

Topographic expression of deformation in Sulawesi is well expressed, which almost completely mountainous and poorly extensive lowland. Mountainous topography is predominantly at the northern flank of Sulawesi, which is extend to Talaul and Sangihe Island. Also, at the central flank extent until Banggai and Sula Island. During early Miocene between East Sulawesi and Bird’s Head microcontinent have collided and formed the ophiolitic forearc. Therefore, ophiolite of East Sulawesi is the key of the suture. Thrusting was active in SE Sulawesi because ongoing convergence since the early Miocene. For the most part of Sulawesi was not emersion until the late Miocene or later and the present high mountains rose at west Sulawesi in the Pliocene (Hall & Wilson, 2000).

In the central Sulawesi, the most prominent active left-lateral strike slip of Palu-Koro Fault has a slip rate of approximately 42 mm/year. The PKF accommodates between the North Sula and Makassar Block movement, and continues towards the Matano Fault with slip rate 20 mm/year (Scocquet et al., 2006). The PKF is the most significant structure because of its proximity to Palu City, which has a population number around 340000. The cross basin fault system is nearby to the city, which has a high potential of seismicity risk, shallow focus, supershear earthquake, and liquefaction (Fang et al., 2019; Ulrich et al., 2019). The cross-basin strike slip fault system as an alternative, which is probably covering by fluval deposits and lack of geomorphic features, accommodates the lateral slip drawback. The PKF is unpredictable due to its largely unknown seismic history. The basic tectonic framework of Sulawesi will therefore be important in making sense of the tectonic activity in this region in order to anticipate high probabilities and potential future strong earthquakes on Sulawesi Island.

3. Methodology

Sulawesi is host to several active fault systems, which need to be mapped. In this study will assign the active deformation, which is reflected from geomorphology, topography and geology of the region. The geomorphological mapping is a preliminary method for providing lithospheric plate interaction that relies on geomorphic expression of tectonic topography (Carbonel et al., 2019). Some distinguishing geomorphic expressions such as topographic breaks, young river terrace, deflected stream, valley, canyon, triangular facet, ridge axis have been examined in order to understand the evidence of deformation (Rao et al., 2017). Moreover, geomorphic expression is a robust tool to define potential earthquakes in the obscured area where Quaternary sediment has buried the rupture beneath the surface. Thus, we have worked to map all the active tectonic features, using freely available satellite data such as a ~30 m Shuttle Radar Topography Mission (SRTM) and Google maps. This study is focused with assessing Quaternary fault activity particularly during Pleistocene and Holocene.

The initial step in the mapping of geological structures on satellite images to trace the faults by carefully examining the tectonic geomorphic evidence, which principal method to investigate subsurface structure and geometry (Parkinson, 1998a; Shyu et al., 2005). Detail geological structure observation to preserve the evidence of rupture such as displacement, scarp, fold, and deflected landform have traced on the maps. The accuracy of fault trace is shown by appropriate symbols, where solid lines are accurate fault, whilst dashed lines are indefinite or inferred fault. We have relied on the geomorphic manifestation of active structure, certainly we have forfeit some notable features, which are not observable on the available resolution of the data have used.

Rule of V has been applied in order to predict and understand the intersection between sedimentary beds and faults, especially on the surface location which poorly exposure of strata or dip. The fault dip direction indicates the direction toward the fault, also can determine downthrown and up-thrown side, relative age and type of fault. The relative older rock will always be on the up-thrown block (Kiratzi, 2014).

We have supplemented the geomorphic analysis with seismic, bathymetric, structure and geology as was available to us. However, we do not claim to produce comprehensive description of the Sulawesi Island, which will definitely need decade of supplementary work. The seismic data have collected from the available Centroid Moment Tensor (CMT) solutions or known beach balls. The CMT is robust tools to determine the type of fault under investigation in the region (Lister et al., 2018; Okal & Reymond, 2003). We have used the CMT solution in order to characterize and interpret the deformation domain (Ryan et al., 2009). The open source structural geology software Faultkin 8 (Marrett & Allmendinger, 1990) have generated some structural parameters (dip, strike and rake) from the CMT data in order to interpret the potential moment tensor solution on the mapped faults. The Aki-Richard format has used to specify the sense of slip with the right-hand rule (Kligel et al., 2006). Goal of this study to provide comprehensive view of the active tectonic of the island and the earthquake hazard potential of the seismic sources in the region.
Field survey have conducted two years after Palu earthquake event in October 2020 until July 2021. We have mapped surface rupture, ground fissure, offset and landslide. The field data and the SRTM images are combined to comprehend sense of slip movement entire Sulawesi Island.

4. Results
4.1 Tectonic Geomorphic
Tectonic geomorphic mapping in this research is obtained by carefully tracing the deflected stream, ridge axis, topographic break, triangular facet and fault scarp. Aim of tectonic geomorphic mapping is to differentiate between old and tectonically active structures and this is mainly based on the geomorphic expression of landforms where Holocene sediments are broken or uplifted. Tectonic geomorphic maps have been constructed through overlain seismological, geological and structural maps. This research on tectonic geomorphology explains some prominent areas including Palu Valley, Poso, Poso, Mamuju, Majene, Poh Head, Sorowako, Kolaka, and Manado.

Palu Valley
The Palu Valley has the glance of regional topography indicating the Central valley is drowned, whilst the west and east are uplifted. Prominent geomorphology of Palu shows a rugged mountainous range and some basin. The highest peak mountain at western is around 2200 m above sea level, whilst the eastern part is lower than western approximately 1600 m above sea level. Palu Valley is crossed by Palu Koro Fault (PKF). The PKF is initiated from SW corner of the Celebes Sea (Watkinson & Hall, 2017) along 265 km offshore, then straddled along Palu Valley throughout 75 km and formed distinctive geomorphology. The geomorphic expression of Palu-Koro active fault contrast along the strike, which traverses as discontinues traces and pierces through some Holocene to Recent alluvial fan deposits. PKF is not easily distinguish the topographic break and fault trace, but linear fault can observe in the western flank of Palu Valley. We have mapped geomorphic evidence of deflected stream shows the left lateral movement, which moves relative to the southeast and the offsets around 0.8 km and 1.8 km. We have identified triangular facets existing in granite and granodiorite and dipping toward -ENE in the western flank, whereas in eastern flank triangular facet is prominent towards -NW. Broad eastward-tilted subtle young alluvium in the central flank at Palu Valley circumscribe the west and east flank steep-sided of mountainous ranges. In eastern flank, two rhomboidal valleys trending WNW-ESE and NNW-SSE at northern and southern respectively. Toward to the south flank, Palu Valley becomes narrower than central flank and dramatically accumulated young alluvial not clearly seen. South flank Palu Valley shifted from the subtle valley to be a relay ramp flanked by two prominent mountainous range. Wineglass canyon is developing in the western flank, which indicates the tectonic subsidence or uplift rate is faster than erosion. Moreover, in the western flank young alluvial fans have been truncating old alluvium, both of alluvial fans have been filling the feeder channel and east flow debris movement. Along the Palu Valley, has meander stream channel the trend NNW-SSE (Fig 3).

In western flank, we have mapped prominent left-lateral slip movement of PKF with trend NNW-SSE, the dip towards ENE, dip-slip movement and very segmented. We have mapped PKF onshore along 22.17 km from north Makassar Strait until Buyu Balease Mountain close to Bone Basin. Probably PKF starts from NW of Makassar Strait offshore and traverses along 220 km, it cross Palu Valley to North Luwu Regency (Patria & Putra, 2020). The PKF was interpreting southeast continuation to the Matano Fault (Socquet et al., 2006), but where PKF ceased still being debated. There are four main segments from north to south include Tanimbaya, Donggala, Palu and Saluki segments, which separated by large bend and step over (Natawidjaja et al., 2021). Linear fault scarp is clearly seen in the western flank, although partially buried by alluvial fan deposits during the instrumental period. Left lateral strike-slip and normal fault has crossed the sidewall along 30 km. In the field, there are several landslide, waterfall and hot spring which relate with PKF movement. Strain of PKF and normal fault have driven a 10 km landslide around Matanitali Hill. The toe of landslide towards the east and the debris fill the Palu River as a feeder channel. The other landslides are around Dolo, Mantikole, Rogo, Baluase and Pakuli Region. The Massive landslide associate with liquefaction have occurred at Balaroa, the scarp around 1.5 km from the fault trace, 1 km length and width 0.5 km. The Balaroa liquefaction scarp have thick alluvium fan and steeper at the western flank with elevation around 55 m and gradually subdue to the toe approximately below than 5 m at the eastern flank. This phenomenon cause debris, soil material and building from the western flank flowing northeast down and slump to the eastern flank. Several places at the western flank include Beku, Baru, and Bolapapu Villages often hit by flash flood contain rock fall, alluvium and debris, which have accumulated from the instrumental period. Those materials fill the between ridge and the river channel and during heavy rainfall flowing down easily, then swept away lower area have resident houses and plantations at the eastern flank. The landslide, liquefaction and flash flood events, remind us of the importance of mapping alluvium, particularly at the area of prone an earthquake and followed by other geo-hazards. There are three waterfall include Wera, Jono and Mantikole Waterfall, they have slickensides on the outcrop with strike almost NNW, average dip 52°, and easterly downward around 1-7 cm. The slickensides suggest oblique fault evidence of left-lateral strike slip composite with normal fault component. We have mapped surface rupture along 45 km at Palu Valley. We have observe surface ruptures and ground fissures on the road, fence, building and paddy field area which show any offset or displacement. Most of surface ruptures show trend 310° to 340°, dipping 65° to 80° with left lateral strike slip movement. The ground fissures almost show the trend NNW and dipping to ENE with vertical displacement and fracture approximately 10 to 65 cm.
Surface rupture play important role to understand sense of slip of PKF because the displacement can observe in the field only, where the rupture not clearly seen on SRTM images. The high temperature hot spring exist at Pulu and Mantikole Region few meter from the fault scarp. We suggest the hot spring exist because deep fracture along NNW-SSE of PKF movement with the characteristic no smelly of sulphur, taste less, steamy and have clear water. The geomorphic features have mentioned above so well-expressed and surfaces, which indicate they are youthful.

In the eastern flank, the fault scarp was cut by a normal fault with trend almost N-S, dipping towards west, along 45 km, gentler, non-linear and highly eroded than western flank. Triangular facets have formed plenty with dipping NNW and normal fault striking SW-NE at Lasoani Hill. In the southeast two asymmetric rhomboidal valleys were forming, which are Sapu Valley and Lindu Valley. Those valleys suggest formed by releasing bend and normal fault movement.

In the southern flank, Pulu Valley close to Pakuli Town dramatically becomes narrower than the central flank, due to local restraining and releasing bend of PKF. We have observed extensional horstail splay, a basin bounding, and a pull-apart basin was forming, it is manifest from releasing bend of PKF. Likewise, gentle narrow push up ridges were established between those narrow basins in consequence restraining the bend of PKF. Geomorphic features in the southern flank were established, indicating PKF is a non-linear fault. We have taken some photos and measurement regarding evidences of left-lateral strike-slip fault, liquefaction, flash flood, triangular facet, sand blow, waterfall, hot spring and fold structure, which have triggered by Palu-Koro Fault movement during fieldwork (Fig 4).

The CMT Solution is sparse particularly at the western flank of Palu Valley. We suggest earthquake on NNW-SSE striking left lateral strike slip faults, with motion, either on NNE-SSW dipping fault planes. The fault dip is increasing gradually 11° towards to south. The fault dip approximately 50° around Dolo Region. Further to the south is steeper than the north around 61° close to Baluase Region. The strike direction of PKF turn a bit to NW at Bone, which is called as PKF Kulawi segment. Regarding the latest deadliest earthquake event on 28 September 2018, the biggest magnitude was recorded Mw 7.5 around Donggala City. The left lateral strike slip fault of PKF play important role to trigger active movement with average slip 4.1 cm/year.

We sum up; PKF is the prominent left-lateral movement to cross Palu Valley. The geomorphic expression along PKF is clearly seen. The releasing and restraining bend indicate PKF is a non-linear fault.

Poso

The most salient geomorphic expression in Poso shows striking valleys and ridge, due to upthrown (horst) and downthrown (graben) block development. Poso has lower topography than the west and east arm of Sulawesi. Owing to the tangible topography, Poso looks like a constraint between the west and east arm of Sulawesi Island. The highest topography in Poso reaches 2000 meter in the western flank, whereas the-
Fig 3. (Top) The un-interpreted and interpreted tectonic geomorphology of Palu Valley, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with an estimated centroid moment tensor solution.
Fig. 4 Field photos shows a) Palu Bridge IV before earthquake b) left-lateral offset at Palu Bridge after 2018 earthquake c) satellite image of Balara residential area before liquefaction d) the residential area have sunk because liquefaction after 2018 earthquake e) The 8m vertical displacement on the road close to house A at Balaraa Palu City f) The 4.2m left-lateral offset on the drainage at Kangkung st., Palu City g) The 5m left-lateral offset on the road at Kawatua, Sigi Regency h) Debris accumulation because PKF movement have transported by flash flood on March 2021 and hit some properties at Marawola Sigi Regency i) the triangular facet have formed by fault movement at Poboya, East Palu with ESE dipping direction j) Hot sand blows with temperature 65°C at Tompobubus Village, South Kulawi k) PKF movement have formed Maima waterfall and hot spring at South Kulawi l,m) uninterpreted and interpreted outcrop shows fold and angular unconformity at Tuwa Village, Sigi Regency.
highest elevation in the eastern flank at Pompaneo Mountain is approximately 2500 meter above sea level. The Poso Valley has notably apertur e lake NNW-SSE direction known as Lake Poso, with length and width geometries around 34 km and 15 km respectively. The lake control by the N-S normal fault with dipping towards east and rake 65°, which circular expression. We have map clear circular expression, which show the N-S normal movement start curving like scissor type fault along 90 km. At the same time the movement accommodate space and opening the Poso Lake with distinctive shape, which is broad at the northern part and narrow at the southern part. The shape only can happen where the fault is curving. Based on topographic profile A-B clearly shows big jump of half graben around 1350 m (Fig 8). The N-S normal fault indicate transcription of PKF curvature, where the PKF start curving from NNW-SSE turn to WSE-ESE, therefore the N-S normal fault is formed. The normal fault in this region is called as Poso Fault. Anticline with crestal expression have mapped, it is due to dip of opposite foliations of metamorphic rock with direction WNW and ESE in the western fl ank. Other than that, relay ramps are clearly seen, which are gradually raised between the low-lying area and ridge in the western flank. We have mapped triangular facets with dip direction ENE on the fault scarp, almost obscured by young alluvium at Poso Valley. Quaternary alluvium in the southern flank of Poso Valley shows northwestward-tilted parallel with Lake Poso direction.

In western flank, we have mapped of an upthrown block with initial normal fault movement with trend NNW-SSE dipping toward ENE in the southern part. The normal fault has flexural bend counterclockwise rotated to the northern part. Subsequently, N-S normal fault shifted trend and dipping toward E, then cut youthful fold. The Fold has developed due to rollover anticline. The horst block has rested on the Mesozoic foliated metamorphic rock, this condition possibly creating fold or anticline. Further the western part, the NNW-SSE left-lateral strike slip fault is cutting the N-S normal fault. Together these two fault systems accommodate NS shortening along Tokorondo, Bomba and Mangkoetana region, also the NS opening and descending of Tomini and Bone Basin.

In the central flank, normal fault has mapped NW-SE trend dipping towards NE. This fault has been defined from the clear triangular facet in the south, but in the central fault trace almost buried by east-northwestward-tilted Quaternary alluvium. The extension of a normal fault has created the depression basin of Lake of Poso, which rests on graben (downthrown) block (14a). Furthermore, triangle depression of Pada Valley has formed between two movements (Fig 14b): left-lateral strike slip curving at the western flank and normal fault movement of Poso Fault at the eastern flank which has replicated of Palu-Koro Fault (Fig 5). The young alluvium in the south of Poso Valley Northnorthwestward-tilted parallel with Lake Poso, it indicates Lake Poso has been rotating by flexural bend normal fault during the instrumental period. The ridge axis is dominantly parallel to the normal fault NW-SE trend.

In the eastern flank has a gentle ridge lying on the Mesozoic metamorphic rock with foliation trend NNW-SSE in northern. We find evidence normal movement of Lore Fault on the sedimentary outcrop with striking North-South and dipping towards east at Bomba Region (Fig 14c). Whilst in southern has Mesozoic meta-limestone ridge gradually sink to southeastward-tilted with SW-NE strike and NW dip of bedding. The sink is constructed Fumana Valley and Mori Valleys (Fig 6).

The CMT solution is lack at Poso, we have relied on geomorphic expression at western flank to assign strike and dip of fault. We suggest earthquake on –NNW-SSE striking normal faults, with motion, either on NNE-SSW dipping fault planes approximately 70°. The total length of rupture approximately 234 km, which divide into two segments: along 107 km onshore and extend to 127 km NE of Gulf Tomini. We suggest motion of Poso Fault (PF) rotate clockwise, possibly replica of PKF. The biggest earthquake was recorded Mw 6.2 with depth 38 km and the epicenter approximately 82 km SSW of Poso on 7 June 1968. Based on our calculation PF have potential trigger earthquake around Mw 7.4, which bigger than past earthquake have occurred during instrumental period. Therefore, the potential magnitude earthquake from our calculation need to consider for large future earthquake. Due to lack of CMT solution at this region, need to map in detail and going for fieldwork, in order to get fault dip, offset, and sense of slip for better understanding. The normal movement of Poso Fault develop easterward downward of pull-apart basin (Poso Lake) at onshore and Tomini Basin at offshore with average slip 2.1 cm/year. High resolution multibeam bathymetry is needed in order to understand length and motion of PF, particularly across NE of Gulf Tomini.

We sum up geomorphological features such as horst, graben, depression basin, and anticline at Poso Valley driven by extensional of a normal fault system. The young geomorphic surface concentrates in the central flank, its responses to the extensional collapse of the graben block and extension of NNW-SSE of PKF. The rotation clockwise of PF, possibly correspond with PKF Kulaawi segment rotation at the western portion. The 1350 m big jump indicate half graben at the western flank. The NNW-SSE curving of PKF turn to WSE-ESE shows the N-S normal movement of Poso Fault.
Fig 5. (Top) The un-interpreted and interpreted tectonic geomorphology of Poso Valley at the western flank, using -30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with estimated centroid moment tensor solution.
Fig. 6 (Top) The un-interpreted and interpreted tectonic geomorphology of Poso Valley at the eastern flank, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with estimated centroid moment tensor solution.
Mamuju

The notable geomorphic feature in Mamuju is mountainous highland in the western and eastern flanks. The highest topography around 3000 m at Kinatang Ridge. Restraining bends are exist in the central flank where the fault curves or steps along NE-SW left-lateral strike slip of Mamuju Fault (MF) and branching in the southern flank. We have mapped geomorphic evidence of deflected stream shows offset along 1 km at Karana River, which is represent left lateral strike slip fault of MF. We have mapped uplift or pop-up topography shows orientation NE-SW, which show anticline same orientation uplift topography in the central flank. Sag basin is formed where following orientation of MF. Triangular facets are present NNE-SSW direction. Ridges axis at Mamuju area show W-E dominated. Meandering stream growth at Eocene sedimentary rock particularly along MF, but in northern flank control by dendritic stream. Gentle coastal is dominated along western flank, which Quaternary deposit shows NW tilted.

In the central flank, we have mapped prominent left-lateral slip movement of MF with trend NE-SW and the dip towards SE. We found 1 km left lateral offset, which indicate MF has movement the left-lateral slip (Fig 14d). The MF has two branches with direction parallel almost NE-SW. The branches establish uplift or pop-up morphology because local transpression of restraining bend. The MF within the pop-up morphology is very steep dipping around 80° with elevation around 1 km lying on Miocene volcanics at Hinua Ridge (Fig 7). In contrary, towards the south become gentler than north around 45°; which indicate the MF control by dip-slip component. The NNW-SSE striking with average length 5 km and the dip toward WSW exist due curve and branch of Mamasa Fault (MSF), subsequently formed local restraining bend in this region. Crowding of crustal material by the NE-SW left-lateral strike slip movement into the fault bend produce uplift and crustal thickening by the 5 km local thrust faulting adjacent to the transpressional fault zone (principal displacement zone) of the active strike-slip fault. In vice versa, transtensional zones or releasing bends presence where the fault bends or step gradually turn to the SW. Local transtension produce in crustal thinning and the 13 km elongated Bonehau Basin formation by subsidence adjacent to the Principal Displacement Zone (PDZ). The NE-SW anticline suggest the maximum compressive stress NW-SE direction which perpendicular with MSF direction. The NE-SW meandering river with average sinuous 500 m, which indicate the river control by the NE-SW left-lateral slip of MSF. We interpret the local stress orientation field undergoes a -50° rotation and -25° about a horizontal and vertical axis respectively. The orientation occurs over a shortening with length 35 km and wide 5 km.

In the western flank, triangular facets have formed around 7 sets with SW dipping lying on Oligocene volcanic rocks at Sondoang Regency. The triangular facets are obscured by erosion which control by the WNW-ESE normal fault. This fault accommodate space and sediment to the -NW through Beru-Beru River, then formed symmetric alluvial fan. The western flank preserve triangular facet (Fig 14h), fault scarp, Quaternary deposit and river terraces, which are evidence for youthfulness and the vibrant of the faults and folds. The geomorphic of this region preserve fresh landforms with less erosion on the surfaces, although the Sulawesi Island has heavy rainfall, high temperatures and humidity throughout the year, which the erosion rates should be higher. The expected the erosion rates is high but the young geomorphic features still preserved along frontal of MF.

In the northern flank, the NE-SW left-lateral strike slip movement along 30 km formed ridge axis parallel with the fault system. Meander and dendritic river establish in this region. The meander river has maximum sinuous around 10 km. In the eastern flank, the W-E ridges axis are dominated lying on Miocene granite.

The CMT solution is sparse at Mamuju, we have relied on geomorphic expression at the western flank to assign strike and dip of fault. We suggest earthquake on ~N-S striking left lateral strike slip faults, with motion, either on E-W dipping fault planes approximately 75°. The length of rupture along 170 km, which initiate from Bonehau Valley and extend until Majene Region, then possibly ceased few kilometer at SE Makassar Strait. Detail multibeam bathymetry is needed to figure the location of left lateral strike slip of Mamuju Fault break. The fault dip is gradually decreasing towards to south. The biggest past earthquake events were recorded on 23 February 1969, 08 January 1984, 24 February 1985 and 14 January 2021 with Mw 7.0, Mw 7.0, Mw 5.9 and Mw 6.2 respectively. Regarding to our calculation, MF and MSF have potential bigger earthquake for the future approximately Mw 7.8. Due to recent earthquake events on January 2021, several building such as West Sulawesi governor office, public hospital, grand mosque, hotel, school, hyper-mart and resident houses have damaged (Fig 14f, 14g, 14h). Also, almost 80 percent housing at Uluamanda and Kabiraan Villages have damage and road access close by massive landslide (Fig 14e, 14j, 14k). This phenomenon, bear in mind to construct earthquake resilient building for the future in order to reduce seismicity risk. The left lateral strike-slip of MF and MSF are significant active movement with average slip 4.1 cm/year and 3.7 cm/year respectively.
Fig. 7 (Top) The un-interpreted and interpreted tectonic geomorphology of Mamuju, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with an estimated centroid moment tensor solution.
We conclude geomorphological features such restraining bend, pop-up morphology, and anticline driven by double restraining bend of MJF and MSF at this region, which is possibly impeding earthquake rupture. Whereas the sag basin has produced by transtension. Obvious morphology have produced by transtension and extension which clearly indicate MJF and MSF remain active until now. The deformation have encouraged erosion and accommodate space. Tectonically, West Sulawesi arm is located around fold and thrust belt, also east-west spreading of Makassar straits. Therefore, the earthquake activity is common in this region. The Makassar Strait thrust fault at western portion is divided into three segment, which are Central, Mamuju and Bomba segments. There are three main fault at west Sulawesi arm include MJF, MSF and Paternosfer Fault (PrF). The PrF at the east of Makassar straits possibly have contribution for future earthquake events. In this study, the PrF has not map yet because located at the offshore and could not well observed using the SRTM image, but we will highlight the PrF for further study.

Mamasa
The most salient geomorphic expression in Mamasa region is sharp restraining bend in the central flank. The NE-SW left-lateral strike slip of Mamuju Fault (MJF) shows curvature or sharp bend along 110 km, consequently produce the NWW-SSE local thrust fault along 4 km in the central and northern flank. The sharp bend of MJF is rotating 240° from the vertical axis. Pop-up or uplift morphology shows the highest topography around 1600 m at Aralle Ridge. Triangular facets exist in the northern and southern flank, which dipping toward NE and W respectively (Fig 14 m). Parallel stream distribute in the western flank, where lying on Miocene volcanic. Whilst in the eastern flank rectangular streams are dominated on Pliocene granite. Ridge crest offset along 300 m in the western flank indicate left-lateral strike slip movement (Fig 8).

In the central flank, huge jump of the NE-SW gentle restraining bend from MJF exist with dipping very steep at northern flank around 70° and decreasing at the southern flank around 40° towards SE, which indicate the dip-slip left lateral slip is dominated in this region. The ridge axis direction almost N-S. The NWW-SSE local thrust with dipping toward WSW around 80° due to transpression of MJF along 4 km. We sum up this region control by transpression and local extension where impede earthquake rupture.

Banggai
The most prominent geomorphic feature of Sulawesi’s east arm is a mountainous highland that spread from west to north. Our geomorphological mapping shows the highest peak mountains in the northern part around 1500 m above sea level and wide range approximately 12 km. We have mapped this mountain as an anticline plunging to the southwest. As well as, in the western part represent the mountainous range with highest crest, wide and length 1400 m, 50 km, and 105 km respectively, it majority built from Tertiary limestone of Salodik Formation in northern and Poh Formation in the southern part. Narrow southwestward-tilted surfaces demarcate the steepest parts of its central flank, highly eroded and deposited along Ranga-Ranga Bay. Similarly in the western part, Quaternary sediment accumulated at Poh Valley, which indicates the clockwise steepest and narrow valley. Wineglass canyon southwest stream cut down the Cretaceous Mafic Complex. We have mapped the relay ramp between Mesozoic Mafic Complex and Tertiary limestone close to Simpangan City. We have found a deflected stream with offset displacement around 0.6 km and it classified the right slip movement. Northeast of Poh’s head, we observed the landslide towards SSW (Fig 9).

In the north topographic expression prominent remarkable mountain, it has an uneroded surface and consists of Mesozoic igneous and metamorphic complexes. While, highly eroded young alluvium composed Holocene – Oligocene Kintom Formation and Poh Formation, northward-tilted surface, it deposited along the northern of Poh’s head. The young alluvium is dragged at Padang City by the topographic offset of left-lateral slip, it is deflected to the northeast-tilted surface of alluvium. Similarly, at the eastern part, young alluvium accumulated at Pangkalaseang Bay due to right-lateral slip movement to accommodate narrow space. Likewise, at the westward, the intersection of three faults, they are Balantak Fault, Poh Fault and inferred Pagimana Fault is created linear topographic offset and accommodated narrow space, which is filled by Quaternary alluvium at Poh Valley. At the same time, those three faults have driven transpression and shortening to be Bualemo anticline. The east of Bualemo anticline is subsidence as a landslide southwest movement, in consequence of Balantak Fault in the southern part and strike-slip fault at the northern. Wineglass canyon indicates the recent uplift in this region. The sluggish stream has mapped in the eastern part with displacement right-lateral slip around 0.6 km, which classified Balantak Fault as a dextral fault with trend WNW-SEE. Moreover, the crest line is clear, developed, sharp and slightly asymmetrical.

In the central shows linear fault scarp and steep-sided wall driven by the right-lateral slip of Balantak Fault traverse along 49 km from Poh Bay in the west and Balantak town in the west, probably extend more or less 250 km away to the Mollucca Sea offshore (Watkinson & Hall, 2017). The Batui Thrust Fault made a bend and intersect with Balantak Fault have constructed a relay ramp at Simpangan City, also the topographic expression abruptly drowned and subdued at Ranga-Ranga Bay due to basin-bounding of both faults developed. Also, young alluvium has accumulated and eroded in this region, which implies very recent activity.

In the west geomorphic expression shows mountain range, which build upon Mesozoic Mafic Complex at northern and Tertiary to Quaternary layering limestone of Salodik Formation and Poh—
Fig 8. (Top) The un-interpreted and interpreted tectonic geomorphology of Majene, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with an estimated centroid moment tensor solution.
Fig. 9. (Top) The un-interpreted and interpreted tectonic geomorphology of Bangai region, using ∼30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with an estimated centroid moment tensor solution.
Formation (Fig 140). Layering limestone has striking WSW-ENE and moderate dip around 40 degrees. Two prominent faults, those are thrust fault (Batui Thrust Fault) cut the southern flank and right-lateral fault (Poh Fault) crop the northern flank. Batui Thrust Fault has crossed through 115 km from Matindok Town until Simpangan City with striking SW-NE and made a sharp bend, then the strike shifted to WNW-ESE along 26 km. Deformation of Batui Thrust Fault has established the sinkhole in the southern flank.

In the southeast layering hill from Tertiary limestones of Salodik Formation is protruding with a peak roughly 600 m above sea level, the wide and length approximately 19 and 25 km successively. The layering of limestones has strike westward and gentle dipping northward. At the southern flank young sediment is northward tilted parallel with dipping. Sirom Fault has been shortening the layering of limestone with trend W-E and dipping towards north along 26 km. In the eastward flank, the topography is dipping to the east due to the releasing bend of Balantak Thrust Fault.

The CMT solution is quite representative at Luwuk region. There are earthquake sources at onshore and offshore. We suggest the earthquake source from offshore -SW-NE striking left lateral strike-slip fault, with motion either on NW-SE with very steep dipping fault planes approximately 87°. Whereas, onshore -N-W striking thrust fault, with motion either on E-W dipping fault plane. The fault dip is gradually increasing further east of Molucca Sea and southeast of Poh’s head. The -SW-NE striking strike-slip fault interpret as a continuation -E-W left lateral strike slip of North Sorong Fault at the western portion. While, -N-W striking thrust fault correspond with West Molucca Thrust continuation at the southern portion. Tectonic activity at the east Sulawesi is very complex, so need further study to know the earthquake source and sense of slip using high resolution multibeam bathymetry and tomography along Molucca Sea. The ~30 m SRTM image is not enough to figure out the continuation of North Sorong Fault at the western portion and their impact for seismic activity, particularly at Banggai Region. The biggest past earthquake events were recorded on 7 May 1982, 2 December 1959 and 4 May 2000 with Mw 7.6, Mw 6.4 and Mw 5.7 successively. There are two major faults the Belantak Fault (BF) and Batui Thrust Fault (BTF) at this region. We suggest BF and BTF have potential trigger earthquake approximately Mw 7.1 and Mw 7.4, which reasonable with past earthquake events have occurred at this region. The average slip of BF and BTF around 1.7 cm/year and 2 cm/year are significant active tectonic movement. The past earthquake on May 2000 has triggered tsunami at Luwuk and Peleng Island with run up varied from 1.8 to 2.4m (Hirashi & Harada, 2000).

We sum up geomorphic evidence and geological evidence shows Poh’s head have built during several deformations with Batui Thrust Fault started and uplifted the Tertiary limestone to the surface lies on the Mesozoic mafic complex. Afterward, transsioning had occurred in Poh’s head driven right-lateral slip of Balantak Fault and drag the Batui Thrust Fault from trend WSW-ENE to sharp bend trend to WNW-ESE.

Sorowako

The most prominent geomorphic feature at Sorowako has 3 major contiguous lakes between high mountains. The names of lakes are Lake Matano, Lake Towuti, and Lake Mahalona. The asymmetrical rhombohedra basin was established in the western flank, while in the southwest broad basin close to the bay, which lies at boundary central and southeast arm of Sulawesi. The highest peak is within 110 km-long-range rise more than 1.3 km above sea level on the Veerbeek Mountain, built from Eocene-Miocene igneous Ultrabasic rocks. Triangular facet NE dipping is developed in Pansu Valley, whilst in Lake Towuti dipping towards NW. We have mapped a deflected stream with offset left lateral displacement around 3.7 km and 2.5 km. Pop-up topography and termination splay are found in eastern flank. Ululire bay was produced in eastern flank of a narrow alluvial fan protruding to Southeast toward the Banda Sea.

In Western flank, particularly in Pansu Valley shows lengthwise asymmetrical rhombohedral basin, it was manifest from the extension of sinistral Matano Fault with trend NW-SE and normal fault. The basin lies on Cretaceous Limestone and Eocene-Miocene igneous ultrabasic rock at NW-SE and SE respectively. Triangular facet dipping to NE, formed by the erosion of fault-bounded mountain ranges, is arguably one of the most prominent geomorphic features on active normal fault scarps in southeastward of Pansu Valley/Landangi Valley (Fig 10, 14p). The Bonebone Valley along Tomini Gulf is broadly developed due to basin bounding segment of some fault including left lateral slip of Palu Koro Fault, Matano Fault, and Lawanopo Fault, also a normal fault of Poso Fault.

In the central flank, Lake Matano shows ellipse lengthwise shape (Fig14q), which driven by the oblique extension of left-lateral slip of Matano Fault (MF). The Matano Lake lies between the Cretaceous-Eocene Ultrabasic complex and Cretaceous-Paleocene crystalline limestone of Matano Formation. The depth of Matano Lake is around 590m, which is the deepest lake at Southeast Asia. The depth of the Matano Lake indicate Matano Fault is exhumed in this region. Lake Mahalona is the smallest lake in the Malili region. It is separated from Lake Matano by a narrow wedge at northwestward and also Lake Towuti by a slender ridge at southward. Lake Mahalona was formed by transension of MF, the formation of this lake indicates MF is a non-linear fault trace. Matano fault was accommodating space and filled by Quaternary alluvium southwestward-tilted at Eastern of Lake Mahalona. Lake Towuti is the largest lake in the Malili region with asymmetrical triangle shape. Lake Towuti is formed by three faults, they are a left-lateral slip of Matano Fault with trend NW-SW and Lawanopo Fault with trend NNW-SEE, also curvilinear normal fault at southward with trend NE-SW. The interior of Lake Towuti has two sections of wedge, which are formed intersect between Matano Fault and Lawanopo Fault, then the wedge-
Fig 10. (Top) The un-interpreted and interpreted tectonic geomorphology of Majene, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with an estimated centroid moment tensor solution.
between those faults intersection was broken by deformation. Alluvial fan in the northwest of Lake Towuti is prograding to southeastward of the lake.

In eastern flank, the sluggish stream has mapped with displacement left lateral slip around 3.7 km and 2.5 km, which indicates Matano Fault is a sinistral fault with trend NW-SE. The pop-up topography indicates Matano Fault is a non-linear fault. The Matano Fault is a non-linear fault, it accommodates space a narrow alluvial fan at Ululere bay, which is prograding to Southeast toward the Banda Sea (Fig 11).

The CMT solution is concentrated at Southeast end of Matano Fault (MF). We highlight the strike of earthquake from CMT solution is not representative with geomorphic expression along the MF. We suggest the earthquake striking –WNW-ESE left lateral strike-slip fault, with motion either NNE-SSW dipping fault plane. The dip is gradually steeper toward ESE, but return a bit gentler towards ESE of Banda Sea. The MF is initiated from Rampi Region to Morowali Regency along 202 km and possibly continue to NW of Banda Sea along 160 km. Historically, two shallow earthquakes have occurred in the past with Mw 6.1 and 6.0 at 28 km SE of Matano Lake and 15 km SE of Morowali Region respectively, with an earthquake depth less than 20 km beneath the surface. Those past earthquakes event have moment magnitude lower than our calculation approximately Mw 7.6. Based on this situation, our calculations need to be considered with possibility will occur larger earthquake for the future and will doing re-evaluation.

We sum up geomorphological features Lake Matano, Lake Towuti and Lake Mahalona driven by transtension of a non-linear of Matano Fault and Lawanopo Fault.

Kolaka

The notable geomorphic feature in Kolaka City is mountainous highland in the west and subtle in the east. The highest peak within 85 km long range rises more than 3 km above sea level on the Mekongga Mountain, built from Paleozoic metamorphic rocks. Triangular facets are clearly seen in western flank with a dipping direction almost SW. Broad northeastward-tilted surfaces demarcate the steepest parts of western flank on Anggolawa Mountain, highly eroded and deposited along Kolaka valley until Kendari Bay with length 85 km. While in western flank, narrow bay in Baula Valley is shifted to southwestward-tilted surfaces with length and width 11 km and 8 km successively, it straddles the steep parts facing Bone Gulf. Two set wineglass canyons southwest and west stream down cut the Carboniferous metamorphic complex. Asymmetric and narrow valley was formed in the eastern of Kolaka City with length and width 12 km and 11 km respectively. Along Bone Bay coast and Kolaka city shows downthrown side, which indicates normal fault has been controlling with Quaternary sediment accumulated facing southwest (Fig 12).

In the western flank topographic expression prominent remarkable mountain, it has an uneroded surface and consists of Carboniferous metamorphic complexes. Highly eroded young alluvium composed Holocene – Recent sediment, southwestward and westward-tilted along Bone coastal and Kolaka City. The Kolaka Susua Fault (KSF) with trend NW-SE and dipping to SW, is created linear topographic offset and accommodated narrow space, which show abruptly steep side wall and low-lying plain filled by Quaternary alluvium along Bone Bay Coastal and Kolaka City (Fig 14r). The narrow bay may be related to basin bounding extensional structures accommodating subsidence in the bay. KSF was a drag and end in Baula Valley and accommodated a narrow space as a narrow bay, which was filled by alluvium. KSF show clear triangular facet towards southwest dipping. Wineglass canyon is developing with a deeply incised stream, which indicates the tectonic subsidence or uplift rate is faster than erosion.

In eastern flank shows subtle topographic expression prominent with irregular hills in the valley. The irregular hills are built from Triassic Meluhi Formation, which consist of metasediment. Asymmetrical valley was forming in the eastern of Kolaka City due to extensional structures accommodating local subsidence in Konaweha Valley (14s).

The CMT solution is concentrated at Kolaka region. We suggest the earthquake –ESE-WNW striking normal fault, with motion either SSW or NNE dipping fault plane. The dip is gradually diminish toward SE of Kolaka. The Kolaka Fault (Kf) is the main fault, which trigger earthquake in this region. The geomorphic expression shows Kf is initiated from NW Susua until Lambandia (SE Kolaka) along 141 km. Subsequently, Kf is rotated anticlockwise and obscured by Quaternary alluvium until Toroboelo (South Konawe) approximately 71 km and possibly extend southeastward to NW Banda Sea along 290 km. Several past earthquake have occurred on 25 November 1964, 4 November 2006, and 11 July 2011 with Mw 6.0, Mw 5.2 and Mw 5.5 respectively. Those past earthquakes event have moment magnitude lower than our calculation approximately Mw 7.8. Based on this situation, our calculations need to be considered with possibility will occur future large earthquake event.

We sum up geomorphological features such as fault scarp, triangular facet and wine glass canyon in Kolaka City driven by normal movement of Kolaka Fault. The young geomorphic feature is concentrated in the eastern and central flank, may be related to extensional collapse of graben block, but the fault is inferred in this region.

Manado

The most conspicuous geomorphic feature in Manado is the mountainous highland run from the northeast until southeast flank. The highest peak is around 2000 meters above sea level in the southeast flank at Mount Klabat. Whereas, in the southwest flank subtle distinction. Bedrock mapping shows the-
Fig 12. (Top) The un-interpreted and interpreted tectonic geomorphology of Kolaka, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with estimated centroid moment tensor solution.
Fig 13. (Top) The un-interpreted and interpreted tectonic geomorphology of Manado, using ~30 m resolution shuttle radar topography mission. (Bottom) 3D view of the region that shows active faults and potential earthquake with an estimated centroid moment tensor solution.
Fig. 14. Field photos shows a) horst, graben and Poso Lake have formed by Poso Fault at Padamarari Village b) narrow triangle Pada Valley have formed by south segment of PKF and Poso Fault c) outcrop shows normal movement of Lore Fault with dipping towards east d) surface rupture at Mamuju main road have formed by the 2021 earthquake because Mamuju Fault movement e) landslides have triggered by the 2021 earthquake between Mamuju and Majene main road f,g) Mitra Hospital Mamuju building before and after the 2021 earthquake h,i) The West Sulawesi Governor office before and after the 2021 earthquake j,k) Houses and public health centre have collapsed because the 2021 earthquake at Ulimanda Village, West Sulawesi l) triangular facet have formed by Balantak Fault close to Siuknyo Beach, Luwuk m) Hilly structure and triangular facet have formed by Mamaju Fault at Ulimanda Village, Majene n) triangular facet and hilly structure have formed by Mamasa Fault at Kalukku Village o) Poh Formation have uplifted and same position with Salodik Formation because Batui Thrust Fault at Teletubbies Hill, Luwuk, Banggi p,q) Landangi Valley, hilly structure, Matano Lake have formed by Matano Fault r,s) Hilly structure and Konaweha Valley have formed by Kolaka Susua Fault t) Tondano Lake and hilly structure have formed by Tondano Fault u) Mountain structure and valley have formed by Airmadidi Fault at Airmadidi Village, North Sulawesi.
mountainous at southeast flank is younger than the northeast and northwest flank.

Our geomorphological mapping in western flank shows the old volcanoes, which have a low-relief section of the mountain. It is rising 800 m above sea level at Mount Pinilil. Mount Pinilil shows a half-round caldera with a diameter of 2.8 km northward and half eroded at southward, the height is around 650 km. Another old volcano is Warisa Volcano. The Warisa Volcano shows full caldera with diameter and elevation approximately 5 km and 600 m respectively. Fault system dipping towards the northwest, traverse between Mount Pinilil and Mount Warisa for distance ~25 km along dies out volcanoes (Fig 13).

In eastern flank shows three young volcanoes, they are Mount Klabant, Mount Tangkoko, and Mount Batuangus. Mount Klabant is the highest peak around 2000 meters above sea level, has not caldera, which indicates a young volcano and no more eruption. Whilst, Mount Tangkoko and Mount Batuangus are older than Mount Klabant, which show caldera and lava flow has crystallized to be basalt and andesite along NE costal of this region.

The CMT solution is sparse at Manado Region. We suggest the earthquake ~NNE-SSW striking left lateral strike-slip fault, with motion either ESE or WNW dipping fault plane. The Likupang Fault (LgF) and Airmadidi Fault are main fault (Fig 14u), which trigger earthquake at Manado Region. The LgF is initiated from Tabenu until Likupang region along 20 km, and possibly extend to northeastward of SE Celebes Sea along 22 km. The north arm Sulawesi onshore predominantly shows east-west direction, but gradually change northeastward from Kotamobagu, Tondano until Manado Region (Fig 14t). Possibly the situation due to pull of double subduction of Sangihe-Siau thrust fault at the eastern portion. Several past earthquake have occurred on 22 January 1980, 05 June 2006 and 1 August 1988 with Mw 5.3, Mw 5.2 and Mw 5.0. Those earthquake events were deep exclude on January 1980 at shallow depth. The past earthquakes event have moment magnitude lower than our calculation approximately Mw 6.6. Which indicate our calculations need to be considered, which possibility occur future large earthquake. To sum up, Manado has young and old volcanoes which separate by fault movement.

5. Discussion

Sulawesi is complex because it is actively moving and triggering earthquakes which accommodate by active fault system. In order to understand nature and significance of the active fault system, this research produces tectonic geomorphic together with the seismological data. Based on tectonic condition, eastern of Sulawesi is very complex. The eastern portion located along the north edge of the Australian Plate, where the plate margin play a role to transtensional and transpressional tectonics associated with oblique convergence between the Australia and Pacific Plates. The tectonic complex is built unique geomorphology expression and seismic activity from Banggai-Sula until Belantak Region. We suggest the eastern portion is simultaneously encountering extrusion, collision and rotation due to oblique convergence in the regional scale. In the east arm of Sulawesi, the biggest rupture potential is triggering by Batui Thrust Fault (BTF). Our geomorphic shows Belantak Fault (BF) has trend ~SE-NW with dipping to ~SW and crossed the BTF around Simpangan City formed geomorphic is drowned in southern and mountainous in the northern part. This interpretation is arguing from previous researchers, which mentioned the BF trend is ENE. Purely steep thrust fault (BTF) and right-lateral slip (BF) accommodated space and formed a Quaternary basin in southwestern part and also geomorphic evidence upthrown and downthrown close to Simpangan City. We have found a deflected stream with an offset around 0.6 km, the short-offset clearly indicates thrust fault dominantly and composite with dextral movement has occurred in this regime. The Sorong Fault at the eastern portion has extended and controlled the geomorphology feature in this region also.

The northeast portion of Sulawesi is located between the southwest edge of Philippine Sea Plate and west edge of Caroline Sea Plate, where the plate margin is subjected to transpresional tectonics associated with subduction. The subduction of Maluku Sea Plate extends from north to southeast of Manado. The Maluku Plate is subducting westward under the Sangihe-Siau arc. This complexity is built active volcanoes, northeastward rotation of Manado, opening of Gorontalo Basin and Tomini Basin, and deep earthquake in this region. While, the north portion of Sulawesi is corresponded by southward Celebes Sea Subduction. The Celebes Sea subduction at the western portion is activating several strike slip fault include Palu-Koro Fault, and Gorontalo Fault. The western portion of Sulawesi is located along eastern flank of Makassar Strait. The Caroline Plate has pulled Australia Plate and vice versa, because of the activity have pushed Sunda Block, opened the Makassar Strait and Bone Basin, and dislocated between Borneo and Sulawesi Island. The tectonic activities have initiated the ongoing transtension include Paternosfer Fault, Walanae Fault, and strike-slip fault in the western flank of Borneo. The ongoing transtension is extended to southward, then developed structural detail until northwest of Lombok offshore, west Flores Fault and Makassar Strait Thrust Fault.

In central arm of Sulawesi, ruptures segment are highly concentrated along Palu Valley until Poso City, whereas in Kolondale region is less concentrated. The geomorphic evidence shows linear fault scarp in the western flank of Palu Valley and deflected stream, which are driven by PKF. MF has produce tangible geomorphic evidence on the offshore like V-shaped toward Banda Arc and termination splay, which clearly indicate an active rupture in this region. The thrust composite with right lateral slip from Belantak region has transtensioning through Gulf Tomini until Donggala City. Transtension in this region indicates from the geomorphology of the end Belantak region narrow and busted, while Donggala City tighter and slightly rotated in a clockwise movement. Transtension
in this region produce extension from strike-slip fault and normal fault. The Poso Fault (PF) with the N-S normal fault curving has produced hanging wall until Tomini and Bone Gulf. The entire region of central and east Sulawesi region identically part of continent. The partial continent under the ocean due to two extension of PKF from the western part and Sorong Fault (SF) from the eastern portion. The NNW-SSE left-lateral slip of PKF which traverse from west of Celebes Sea, then curving to the NW-SE and extend until west of Banda Sea. The E-W left-lateral slip movement of SF cut through Ceram Sea and until Taliabu Island, then control geomorphology at the east arm Sulawesi. The SF and PKF connected which driven by extension, therefore have produced pull-apart basin at Banda Sea with geometry of length 400 km and wide 350 km.

In the southeast arm of Sulawesi, the notable lakes geomorphology consist of Mahalona Basin, Matano Basin and Pansu Basin have formed by three faults; Matano Fault (sinistral), Lawanopo Fault (sinistral), and Lawa Fault (normal fault). These three faults were producing releasing bend, pop up basin and termination splay, which indicate active rupture in this regime. In SW Arm of Sulawesi found less rupture segment. The Walanae Fault (WF) only the one major rupture is identified. The Walanae Fault (WF) has extended through Selayar Island in the southern part, which is formed narrow, disrupted fill sediment and elongated island. The ruptures generate highest potential earthquake in this regime has obscured by Quaternary alluvium. Also, the WF has traverse along South Sulawesi province, where it has biggest population for entire Sulawesi Island.

The PKF is a major sinistral fault in Sulawesi Island and triggering other rupture surrounding. This research shows evidences left-lateral strike slip displacement on the footwall along 150 km and the dips NE to E on the Sulawesi Island, whilst in the offshore show along 350 km a prominent discontinuity that runs parallel to the strike of PKF where located around 120 km border shallow sea from the Island on the east and demarcates a clear boundary between the shallow sea and the deep sea basin. Pull-apart basin has developed on the PKF in deep basin in between shallow oceanic basin; clearly indicate tectonic history in this region open recently. The nature extension of NNW-SSE the PKF then turns to WNW-SE continuation of MF is clear indicator that this region is undergoing oblique compression that possibly originates from the current North Sulawesi subduction directed N-S forces and associated with the active extension of E-W left-lateral slip of Sorong Fault from the west portion. The presence of normal fault cut by the PKF, NW dipping triangular facets, highly eroded mountain in the eastern flank of Palu Valley possibly indicates relative age of normal fault older than PKF. We propose two possibilities of tectonic mechanism models. First model shows the ENE-WSW normal faults have formed early and cut by PKF. The relative age faulting is determined by the cross-cutting relationship, where the normal fault is older than NNW-SSE left-lateral slip of PKF. Second model shows normal fault and PKF formed together. First model is making sense because offset of normal fault in the eastern flank can be observed in the western flank of Palu Valley, which obscured by opening of the Palu Valley and Quaternary deposit in the central flank (Fig 15). Thus, this research suggests nature of curving of the PKF shows oblique fault (left-lateral strike slip fault composite with normal fault) has relatively younger than the normal fault.

The seismic parameters suggest the fault systems in Sulawesi Island could host a number of > Mw 7. Based on CMT catalogue of earthquake with Mw > 7 in this region, suggests a total of 15 past large earthquake events over the last century, which includes the devastating earthquakes of 1941 and 2018. The large earthquake ruptures are dominantly strike-slip and clustered on north and central arm of Sulawesi Region. These have occurred potentially along well-defined structures include the two major strike slip fault, which are Gorontalo Fault and Palu-Koro Fault. There were two large earthquake at offshore around Mw 8.1 and Mw 7.9, which located 91 km southwest of Gorontalo region and Toli-Toli region (181 km north of Palu) respectively, and have occurred on 21 December 1939 and 1 January 1996. Whilst, onshore have occurred two large earthquake with Mw 7.5 and 7.4, which located 72 km north of Palu and 37 km northwest of Gorontalo on 28 September 2018 and 8 November 1941 respectively. Those past events, prove the the fault is capable generating large earthquake events. We conclude, the most of onshore and offshore faults of the Sulawesi region have been storing strain, rather than releasing it, over the past 80 years. The Palu-Koro Fault and Gorontalo Fault contribution to seismic hazard of North and Central Arm Sulawesi should not be underestimate, particularly given its proximity to large towns such as Palu and Gorontalo City, and poorly known seismic history as well.

5. Conclusion

Our data provide tectonic geomorphic evidence and seismicity in Sulawesi Island, which focus on Quaternary fault activity during Pleistocene and Holocene. However, this analysis could not cover all details entire Sulawesi Island, we only took several representative location.

PKF is a major left-lateral strike slip fault in Sulawesi Island and triggers other rupture surrounding. The fault scarp is developing in the western flank of Palu Valley, which indicate PKF produce neotectonic geomorphic feature, naturally oblique fault (NNW-SSE of left-lateral strike slip fault composite with normal fault and relatively younger than WSW-ENE normal fault in the east. The migration of PKF is going to eastward and opening the Palu Valley because curving NNW-SSE left-lateral strike slip turn to WNW-ESE have force and accommodate the space. The releasing and restraining bend indicate PKF is a non-linear fault.
The tectonic geomorphic features such as horst, graben, depression basin, and anticline have mapped around Poso Valley. We suggest the features driven by extension of a normal fault system of Poso Fault (PF). The young geomorphic surface concentrates in the central flank, it responds to the extensional collapse of the graben block. The 1350m big jump of half graben of PF possibly support downward movement of Tomini Basin at northern flank and Bone Basin at southern flank. We suggest the N-S normal movement of Poso Fault is transcription of the NW-SE curvature of PKF.

Based on our CMT data analysis, Sulawesi Island is greatly dominated by oblique fault. The strike slip fault and composite with normal fault is propagated along the central arm. The faults system consists of Palu-Koro Fault, Matano Fault, Poso Fault and Kolaka Fault. While, thrust dominantly and composite with strike slip fault is the second largest fault systems, which propagated along north, southwest and east arm, such as Gorontalo Fault, Mamuju Fault, Mamasa Fault, Walanae Fault and Batui Thrust Fault. The strike slip fault systems have mapped here on land confirmation that regional stresses in Sulawesi are oblique, where the left-lateral of PKF has formed later after WSW-ENE the normal fault of PF exist.

The possible future large earthquake around Mw 7.8 on Palu-Koro Fault. Historically, the large earthquake have recorded approximately 15 events in Sulawesi Island over the last century, which devastating earthquakes of 1968 (Mw 7.2, Donggala), 1966 (Mw 7.9, Toli-Toli), and 2018 (Mw 7.5, Palu), indicates central and north arm Sulawesi particularly around Palu to northward portion is active deformation area. Consequently, the active geomorphic clues demonstrated here suggest those earthquake historical events have ruptured the surface, which are now perpetuated as active fault scars. Further, untangle the earthquake chronology of Sulawesi is urgently needed paleo-seismological work and advance investigation. We suggest paleoseismic work is assigned within identified active surface rupture along Palu-Koro Fault, Poso Fault, Mamuju Fault, Mamasa Fault, Batui, Balantak Fault, Likupang Fault and Kolaka Fault. Detail multibeam bathymetry is needed along Makassar Strait, Gulf Tomini, western portion of Mollucca Sea and Banda Sea, and eastern portion of Celebes Sea to recognized geometry and fault break.
Acknowledgments

The evaluation of this manuscript from reviewers and editors is highly appreciated. Great appreciated to Afroz Ahmad Shah and Md. Aminul Islam for discussion and idea. Thanks to Rio Hamdani have contributed data collection in the field for almost a year. This research has fund from Universiti Brunei Darussalam Graduate Scholarship and Universitas Islam Riau.

References


Geology, 12(8), 973–986. https://doi.org/10.1016/0191-8141(90)90093-E


Watkinson, I. M., Hall, R., Cottam, M. A., Sevastjanova, I., Suggate, S., Gunawan, I., Pownall, J. M., Hennig, J., Ferdian, F., Gold, D., Zimmermann, S., Rudyawan, A., & Advocaat, E. (2012). New Insights Into the Geological Evolution of Eastern Indonesia From Recent Research Projects by the SE Asia Research Group, Berita Sedimentologi, 23(January 2012), 21–27. © 2016 Journal of Geoscience, Engineering, Environment and Technology. All rights reserved. This is an open access article distributed under the terms of the CC BY-SA License (http://creativecommons.org/licenses/by-sa/4.0/).