Ductile Deformation Rocks Along the Palu-Koro Fault Zone, Central Sulawesi, Indonesia

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Abstract. The Palu-Koro fault is known as an active fault across metamorphic and plutonic rocks in the Central Sulawesi region. However, still difficult to find structural features and fault rocks along the fault line. Therefore, in this study, we have investigated the deformation characteristics that have been experienced by the rocks that exposed along the fault zone. The microstructure analysis method has been applied through detailed petrographic observations to identifying deformation from quartz recrystallization and porphyroblast characteristics. Based on the quartz recrystallization data, almost the dynamic recrystallization are found in the Palu-Koro fault zone such as grain boundary migration, subgrain rotation and bulging, the bulging recrystallization with undulose extinction that demonstrated recovery with elongate parent and subgrain of the Miocene-Pliocene rocks of Kambuno granitoid in the western and southern sections of the fault zone. In contrast, there are not many high-temperature deformations and low strain rates such as grain boundary migration, although it is known that Kambuno granitoid rocks come into contact with other rocks in this area after metamorphism. The deformation of the rocks around the fault zone has occurred at least in two-stage. The first stage (D1) is still closely related to metamorphism marked by parallel schistosity in metamorphic rocks, recrystallization of grain boundary migration in Wana and Gumbasa Metamorphic complexes, and Kambuno plutonic rocks. The second stage (D2) is characterized by quartz bulging recrystallization and alignment of schistosity was overprinting by *C'* shear band or S2 fold crenulation, inter-tectonic porphyroblasts. Both shear band and porphyroblasts are indicated that the sinistral and dextral sense of shear, the sinistral porphyroblasts is consistent with the Palu-Koro movements whereas dextral sense is may be related to other tectonic movements before the rocks are in the position in the shear zone.

1. Introduction

Palu and the surrounding area in the Central Sulawesi regions which has quite complex tectonic activity, due to the Palu area were cross cut by an active fault known as the Palu-Koro Fault which is a sinistral strike-slip fault, tectonically of the Palu-Koro an active fault was developed by three active plates namely the Eurasian, Indo-Australia, and Pacific-Philippines plates [1][2][3][4], the activity of the three plates causes the complexity of the geological structure in this region, also facilitated the exhumation and the outcropping of Trias-Jurarassic of the metamorphic rocks [1][2][3][4]. The tectonic and geodynamic process of the Palu-Koro fault line is a transtensional fault that indicating an extensional fault of the pull-apart basin in the middle part of the fault line and also it was cutting the basement rocks in the region. Pull-apart basin known as Palu Valley was filled with a variety of Neogen to Quaternary sedimentary rocks (figure 1). The fault section for the west is cut by Kambuno Granite rocks which are Miocene Pliocene aged and metamorphic rocks of the Wana Complex which are composed of Jurassic metamorphic rocks. The western and eastern segments are separated by the Palu valley, the eastern segment intersects the Jura-Trias gneissic of metamorphic rock which is a member of the Gumbasa Complex, the linear line narrows to the south or in this case the southern segment intersects composed by Kambuno Granite and the metamorphic rocks of Gumbasa complex [5][6].

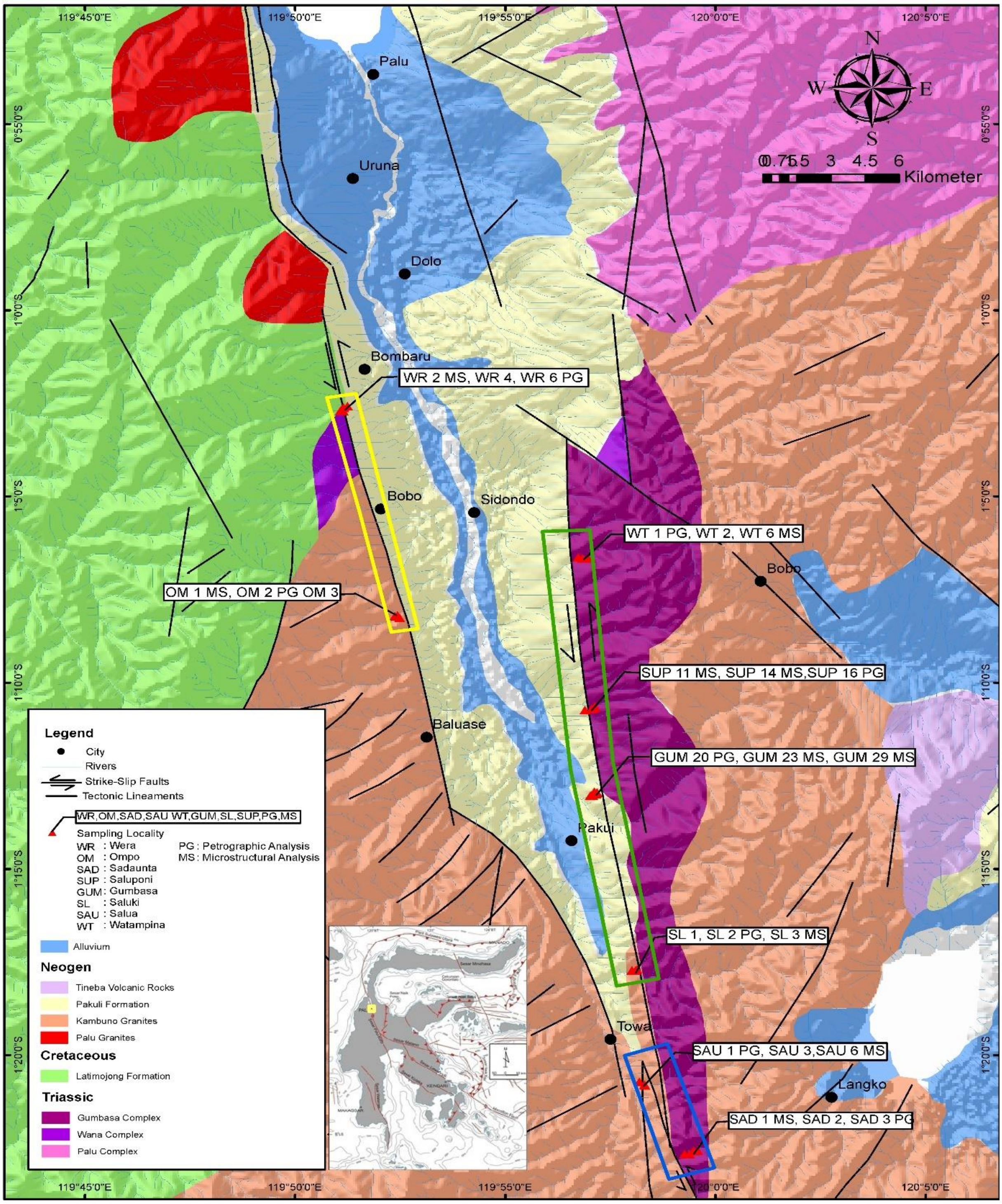

Figure 1. Geological map central part of Palu-Koro Fault zone showing sampling locality of the study area. The yellow line is the western segment, the green line is the eastern Segment and the blue line is the southern segment of the Koro Palu Fault, modified after [6].

Although the Palu-Koro fault is topographically showing a very perfect lineament trending from NW to SE (figure 1). However, along the Palu-Koro fault line is still difficult to obtain structural features and fault rock the fault zone such as fault rocks fault breccia and cataclastic in brittle zones and mylonite rocks in the ductile zone related fault zone, the non-coaxial ductile strain is not due to the Palu-Koro Fault indicating that its mid- or lower-crustal roots have not yet been exhumed [6]. The occurrence of a large earthquake on 28 September 2018 gave a slight symptom of brittle deformation with the alignment of rupture and fissures along with ± 180 km [7]. However, the brittle deformation has quickly eroded. Therefore, in this study, we have applied a microstructural approach to analyzing the deformation fabric by emphasizing the development of quartz mineral recrystallization and porphyroblasts characteristics to record deformation traces that have been experienced by metamorphic rocks in the Palu-Koro fault line.

2. Method

Field and laboratory work and sample collection have been applied to the microstructural approached methods [8], in the field sampling method were performed the sampling orientation techniques by means marked a strike/dip on the plane the rocks. To obtain a representative sample, the locality of sample collection has been adapted to the situation of the Palu-Koro fault line with divided it into three segments and section survey area, each section followed the river across the fault line. in the western segment divided into 2 sections (WR and OM sample codes) each section was collected 3 samples, the eastern segment is divided into 4 sections (WT, SUP, GUM and SL sample codes) each section were collected 3 to 5 samples, in this area were collected 12 in total samples, at the southern segment is divided into 2 sections (SAU and SAD sample codes) each of sections was collected 3 samples (figure 1).

Further to laboratory work, to precisely observations and determination of fabric orientation and texture deformation, the rocks were cut parallel to lineation (XY plane) and parallel to foliation (XZ plane) and perpendicular to lineation and foliation of the rocks (YZ plane). A total of 32 thin sections have been made from 25 samples, the petrographic thin section was made with a thickness of 30 μm. Fabric determination and deformation texture were carried out using a polarizing transmitted light microscope.

3. Results and Discussions

3.1. Recrystallization

3.1.1. Bulging (BLG)

Bulging recrystallization is a process of local migration of a grain boundary into a neighboring grain with a higher dislocation density, eventually producing new crystals, recrystallization tend to be convex occurs along the edge of older grains, the deformation indicates strong formed at low temperatures high strain [8]. Although almost all rocks have shown bulging recrystallization, the western and southern segments where granitic rocks predominantly demonstrated the ideal recrystallization of the bulging (figure 2a, d, and e). Aggregation of quartz grains vary inequigranular to seriate-interlobate, both parent and subgrain elongate grain forms, there are indications of recovery in the parent grain characterized by undulose extinction, subgrain boundaries still be seen in optically. Low temperature and high strain rate on granitic rocks suggestion that rocks were deformed after magmatism in the fault zone, this supports the southern fault line is acting as the main fault of the Palu-Koro and continuing to the north through the western segment line, this mylonitic symptom is shown by the Kambuno granitic rocks such as in Ompo (OM) and Salua (SAU) sections (figure 1).

3.1.2. Subgrain Rotation (SGR)

Subgrain rotation is indicated by the presence of trace in the margins of the parent mineral which still be recognized but almost all of them are recrystallized into subgrains that spread parallel to schistosity, this process is due to changes or increases in temperature when deformation occurs [8]. Subgrain rotation in metamorphic rocks demonstrates aggregation of seriate-polygonal to seriate-interlobate grains and forms of parent grain and blocky to elongate subgrains. SGR recrystallization is present in the form of quartz arranged as a parallel matrix to oblique schistosity in metamorphic rocks such as sample SL 3 (figure 2c) and GUM 29 (figure 3a) in the eastern segment of SAU 1 (figure 2f) of the southern segment.

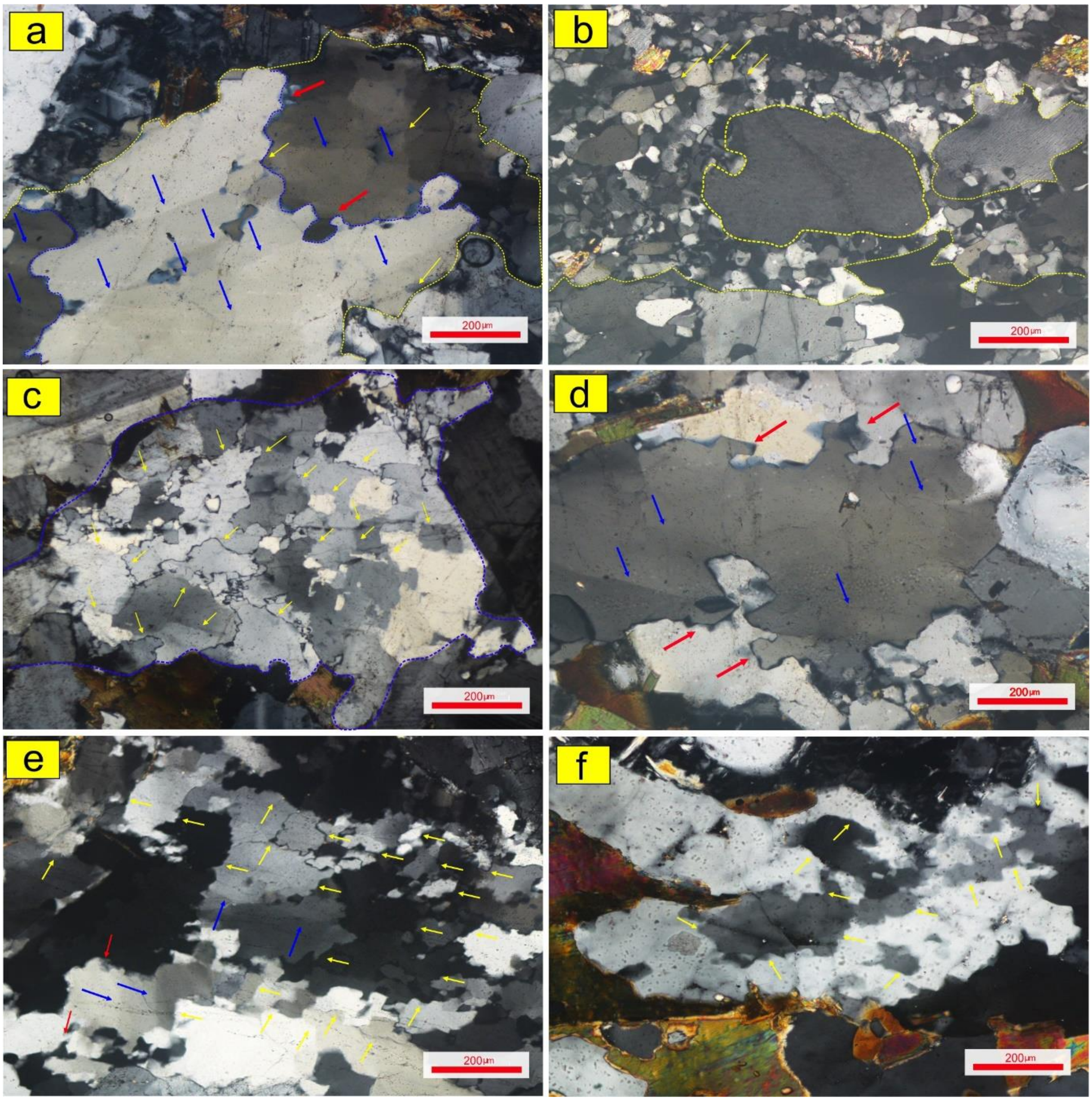

Figure 2. Representatives photomicrograph of quartz recrystallization (a) BLG recrystallization with undulose extinction showing elongate parent grain and subgrain, quartz-muscovite schist of Kambuno Granite (OM 1, YZ plane), (b) GBM recrystallization in the garnet-muscovite schist of Gumbasa Complex (SAD 1, XZ plane), (c) SGR recrystallization in the quartz-muscovite schist of Kambuno Granite (SL 3, XZ plane), (d) BLG recrystallization with undulose extinction with elongate subgrain, quartz-muscovite schist of Gumbasa Complex (SUP 11, YZ plane), (e) BLG recrystallization with undulose extinction showing elongate subgrain, quartz-muscovite schist of Kambuno Granite (SAU 6, XZ plane), (f) SGR recrystallization in the quartz-muscovite schist of Kambuno Granite (SAU 1, XZ plane). The dashed blue line is the parent grains boundary, the yellow arrow is subgrain boundary, the red arrow is undulose extinction, the blue arrow is bulgin, all of the figures under cross-polarized light.

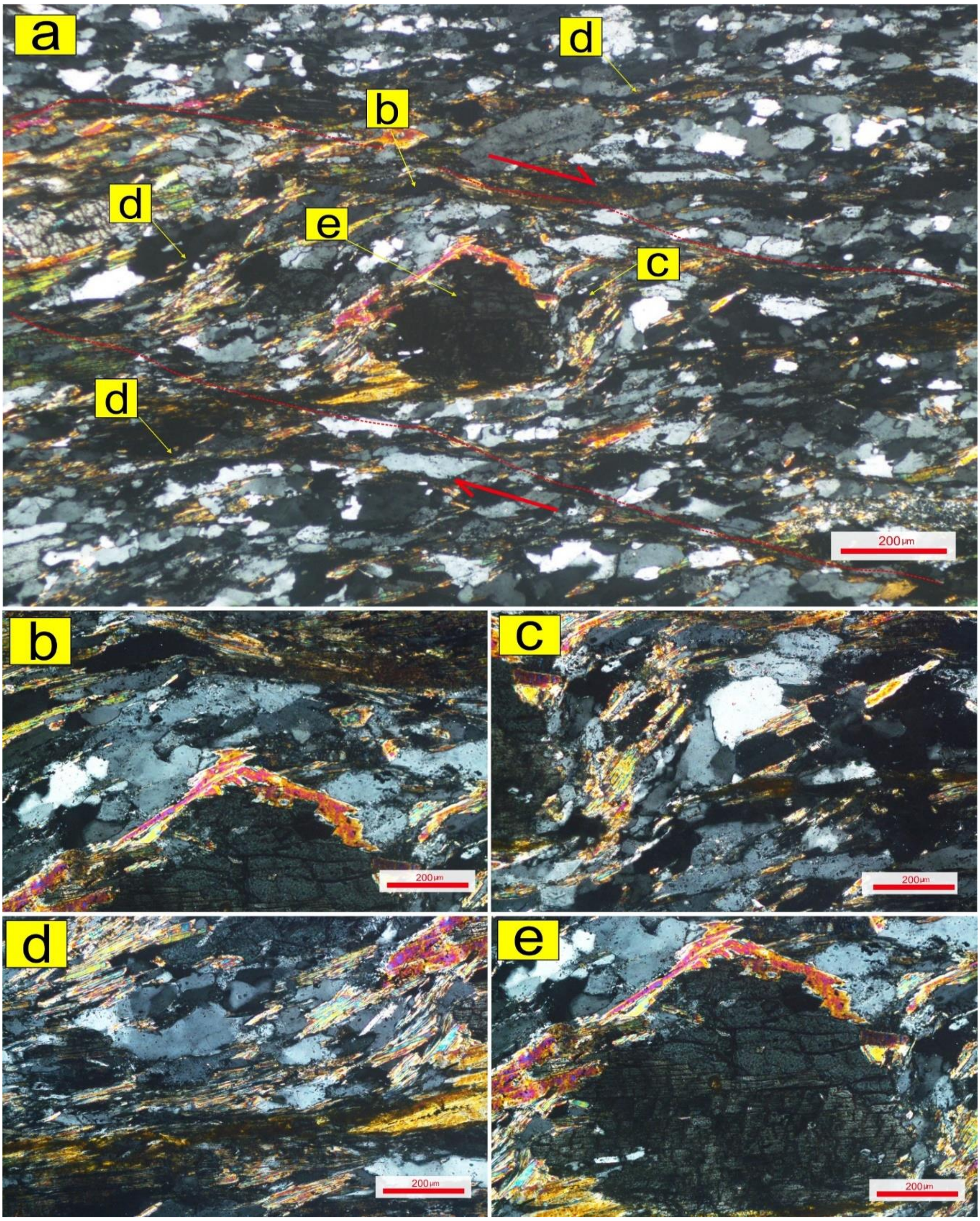

Figure 3. (a) Garnet porphyroblast showing indicated inter-tectonic of quartz schist of Gumbasa Complex, dashed red line is S2 fold crenulation or *C'* shear bands transection with the main schistosity, dextral sense of shear, (b) Strain cap contain quartz array with SGR recrystallization, (c) Strain shadow contains quartz curve arrays with inequigranular-polygonal aggregate, (d) Internal foliation is shown view quartz arrange with SGR recrystallization (d) External foliation array with SGR recrystallization, (e) Internal foliation in garnet porphyroblast with a view quartz inclusion arranged (GUM 29, XZ plane). All of the photos were taken by cross-polarized light.

3.1.3. Grain Boundary Migration (GBM)
The texture of grain boundary migration recrystallization is characterized by new subgrains due to the influence of slowly moving minerals which is more controlled by temperature than strains when rock deformation occurs so that it shows less grain orientation parallel to the schistosity this process is called grain boundary migration in high-temperature condition [8]. GBM recrystallization type in this area is characterized by recovery deformation in the form of aggregate seriate-polygonal such as sample SAD 1 (figure 2b). GBM characteristics are not commonly found either metamorphic rocks or plutonic rocks in fault lines, and it is unique that the effect of high temperatures causes by intrusion from Kambuno Granite to metamorphic rocks of Gumbasa Complex and others rocks are not significantly present.

3.2. Porphyroblast
Porphyroblasts are relatively large single crystals, which grow on metamorphic rocks embedded in fine-grained matrices [8]. Petrographically, the appearance of porphyroblast type can explain the deformation phase that occurs in a rock, in terms of the relationship between the deformation time and the growth of porphyroblasts [8]. The development of porphyroblasts is shown by metamorphic rocks in the eastern segment. In the Gumbasa river section which is generally composed by gneiss Complex Gumbasa (figure 1), predominantly the type of inter-tectonic porphyroblast in the garnet-muscovite schist, characterized by garnet porphyroblast which is embedded in the quartz Gumbasa Complex (figure 3, 4), muscovite and quartz external schistosity is parallel and partially oblique to porphyroblasts with indications of left rotation although occasionally only cracks are likely to influence brittle deformation when exhumation rocks, developing type *C'* shear band or S2 fold crenulation, internal foliation is indicated by alignment of quartz inclusions and also oblique to external schistosity, strain shadows are filled with pull equant quartz minerals and are slightly elongated across the porphyroblasts, the strain cap building very tightly above porphyroblasts.

The sinistral sense of the shear pattern of the porphyroblasts rotational corresponds to the relatively sinistral direction of the Palu-Koro fault movement, although occasionally some samples are found to a dextral sense of shear (figure 4). Phorphyroblasts in this segment is generally influenced by matrix folding, even though internal foliation is relatively straight forward. The presence of moderate type *C'* shear band dextral sense crenulation normal to foliation (figure 3) suggested that more than one deformation stage or multiple phase deformations that have been activated in the Palu-Koro shear zone, type *C'* shear band usually forms on strongly foliated and mica-rich mylonites [8].

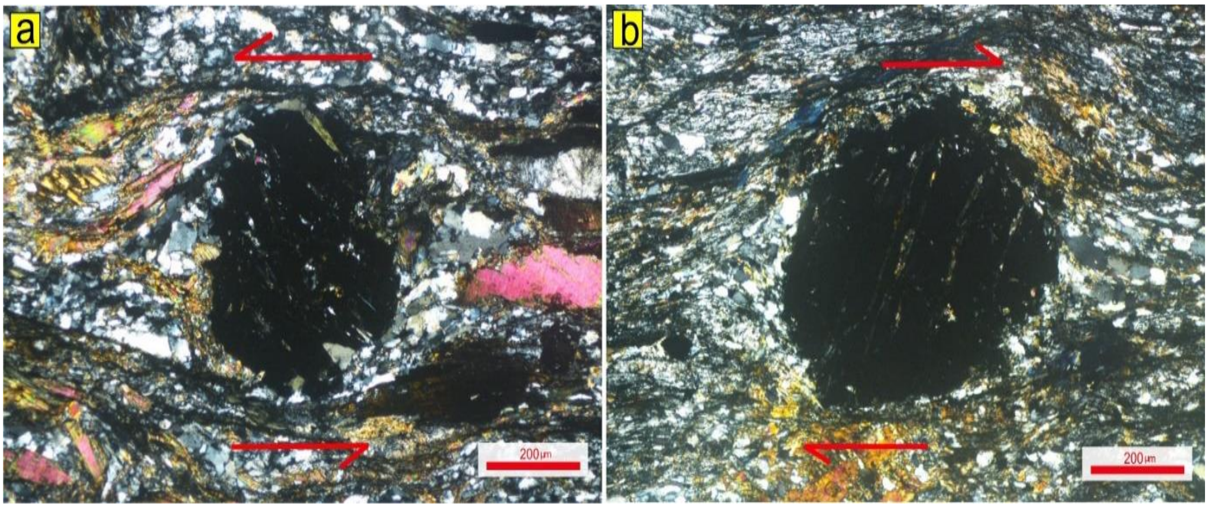

Figure 4. Representative inter-tectonic porphyroblasts, internal foliation of garnet porphyroblasts shown straight quart inclusion and oblique to the external foliation, garnet-muscovite schist of Gumbasa Complex ((a) showing a sinistral sense of shear (SUP 14, XZ plane), (b) showing a dextral sense of shear (SUP 16 XZ plane), cross-polarized light.

3.3. Deformation Stage

In determining the stages of deformation in the study area several aspects have been considered such as schistosity/crenulation, recrystallization, and the degree of deformation of the porphyroblasts characteristics. The first stage (D1) begins post metamorphism grain boundary migration and subgrain rotation which is a quartz recrystallization process that occurs at high-temperature, ie the type of quartz deformation formed at temperatures with a formation temperature range of 400°C-500°C [8]. Schistosity is generally parallel, whereas the type of porphyroblasts cannot be determined which is likely a pre-tectonic deformation (table 1).

The second stage of deformation (D2) is characterized by generally recrystallization in the form of bulging recrystallization that mainly in the western dan southern segments, a process of metamorphism which gradually decreases in temperature in the range of 200˚C-400˚C [8], has developed a second schistosity marked by S2 fold crenulation of *C′* shear bands that predominately shown in Gumbasa metamorphic rocks. After the second stage deformation, it is possible to continue with retrograde to the greenschist facies zone or brittle deformation in the Palu-Koro fault zone. The second deformation occurs simultaneously or after retrograde and continued to brittle deformation in the Palu-Koro fault zone, but indications of exhumation are still difficult to determine.

Tabel 1. Summary of deformation stage of the rocks in the study area

Deformation Components	Deformation 1	Deformation 2
• Schistosity/Crenulation	• Parallel schistosity	• C' shear band normal to the foliation, S2 fold crenulation
• Rekristalisasi	• Moderate Subgrain Rotation	• Low temperature bulging
• Porphyroblast	• No porphyroblasts are found	• Porphyroblast with the Garnet core is oriented obliquely to schistosity
• Deformation level	• Pre-tectonic	• Inter-tectonic

4. Conclusion

Novel insights derived from our microstructural observation of ductile deformation of Palu-Koro fault zone in the Central of Sulawesi can be summarized in the following points:

- Based on the quartz mineral recrystallization data, almost all types of dynamic recrystallization are found in the Palu-Koro fault zone such as grain boundary migration, subgrain rotation and bulging that describe hight to low temperature, but what's interesting is the bulging with undulose extinction recovery with elongate subgrain is demonstrated. in the Kambuno granitoid Miocene-Pliocene rocks in the western and southern sections of the Palu-Koro fault. In contrast, there are not many high-temperature deformations and low strain rates such as grain boundary migration, although it is known that Kambuno granitoid rocks come into contact with all other rocks in this area.
- After metamorphism, the rocks in this region have been experienced in two deformation phases where the first stage (D1) is still closely related to metamorphism marked by parallel schistosity in metamorphic rocks, recrystallization of grain boundary migration in Wana metamorphic rocks and Gumbasa Complex and Kambuno plutonic rocks, pre-tectonic deformation is no longer seen by rocks. The second stage (D2) is characterized by the formation of quartz recrystallization types in the form of bulging and alignment of schistosity overprint minerals to *C'* shear band or S2 fold crenulation with the sinistral and dextral sense of shear, inter-tectonic porphyroblasts. Both shear band and porphyroblasts are indicated that the sinistral and dextral sense of shear, the sinistral porphyroblasts is consistent with the Palu-Koro movements whereas dextral sense is may be related to other tectonic movements before the rocks are in the position in the shear zone.

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