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Tectonic control on dyke and sill intrusions of active tectonic margine, case study in Cilacap area, Central Java Indonesia

Asmoro Widagdo [1*], *Hari Wiki* Utama[2], *Gentur* Waluyo[1], *Indra* Permanajati[1], *Maulana Rizki* Aditama[3], and *FX Anjar* Trilaksono[4]

[1]Geological Engineering, Universitas Jenderal Soedirman, 53122, Central Java, Indonesia
[2]Geological Engineering, Universitas Jambi, 36361, Jambi, Indonesia
[3]Earth and Environmental Science Department, University of Manchester, Manchester, UK
[4]University of Pécs, Hungary

Abstract. Control of geological structures on the presence of dyke and sill intrusions in the Cilacap-Central Java area requires explanation. The research was conducted through a series of fieldwork. Field research is carried out by measuring geological structural elements such as rock layers, joints, faults and folds. Geological and cross-sectional maps provide information on the distribution of igneous rock intrusions in the study area. Fault analysis produces information on the stresses forming the geological structure in the study area. Thus the relationship between the distribution of igneous intrusion and the geological/tectonic structure that controls it can be known. The main stresses forming the structure in the study area are relatively in the north-south direction. This stress creates a fault trending west-east which then becomes a channel for dyke intrusion formation.

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* Corresponding author: asmoro.widagdo@unsoed.ac.id

1 Introduction

The research area is located on the southern side of the South Serayu Mountains, precisely in Kesugihan District, Cilacap Regency, Central Java. In this area, dyke and sill type intrusive igneous rocks are found that intrude the Halang Formation rocks [1]. Several basalt intrusive rock bodies are found in a west-east direction and are an important source of building materials [2] in this area. The presence of these intrusive rocks has attracted several researchers to reveal the genesis of their presence. [3] describes the presence of these intrusive rocks as part of the proximal volcanic facies of the Middle-Miocene-Late Miocene [4] in the underwater environment [5].

Fig. 1. Location of the research area is in the central part of Java Island.

The dyke intrusion in the study area is composed of igneous basalt [6] and [2] with a certain orientation. According to [7], the orientation of the dyke intrusion direction (vertical) may be concentrated in the maximum compressional (σ1) or intermediate compressional (σ2) direction of the regional main stress or it can also be in the direction of the weakest compressional stress (σ3). The direction of the strongest stress or 1 is usually horizontal in the contractionary tectonic area (in Figure 1 from the south of Java Island) which is characterized by the presence of a strike slip fault or trust fault that is not in the direction of the intrusion dyke (vertical). In areas with an extensional stress regime, σ1 is generally oriented vertically producing normal faults, perpendicular to σ3 but parallel to the vertical intrusion dyke [7].

The open sill is parallel to the smallest principal stress or σ3, the horizontal orientation of the sill indicates that σ3 is vertical, which is typical for areas of compressional tectonic stress [8] such as in the southern part of Java Island (Figure 1). The presence of sills is systematically related to lateral shortening by thrust faults or folds in the surrounding rock [9]. Thrust faults and folds are produced by the presence of a horizontal main stress, in the case that occurred on the island of Java this came from the thrust of the Indian Ocean Plate in the south [10, 11, 12] as shown in (Figure 1).

2 Method

Measurement of geological structure is carried out by measuring the orientation of the sedimentary rock layers (strike and dip), the orientation of intrusive rocks, the orientation of the joint/joint plane and the orientation of the fault plane. Analysis of geological maps and data on the orientation of the rock layers will result in the orientation of the main stress (σ1/strongest stress) of the constituents. Fault analysis will produce major stress orientations (σ1/strongest stress, 2/medium stress and 3/weakest stress).

The orientation of the main stresses forming various geological structures in the study area is then related to the distribution pattern and orientation of sill and dyke intrusive rocks. This will result in the distribution of sill and dyke intrusion distribution with tectonics that have worked on the formation of sill and dyke.

3 Results and Discussions

Sedimentary rocks in the study area are layers of sandstone and claystone which generally have a tuff composition. The Halang Formation is composed of alternating sandstone, claystone, marl, and tuff (Figure 2) with breccia insertions. This formation is estimated to be Middle Miocene-Early Pliocene (15-3.2 million years ago). The formation of the Halang Formation is influenced by turbid currents and underwater shearing. This formation was deposited as tubidite sediments [13] in the upper bathial zone (200-500 meters). Based on field observations, a thin layer of black claystone with a thickness of 0.75 meters was found in the center of this formation.

Fig. 2. Tuffy sandstone and tuffaceous claystone with dipping towards the south.

Fig. 3. Sill intrusive igneous rock dipping to the south found at the bottom of the Keleng river in the study area [14].

In Figure 4, a geological map of the Kesugihan area is presented, which is composed of intrusive basalt rock (Tpb) and Halang Formation rock (Tmph). Basalt intrusive rock is an igneous rock type with black colour (Figure 3), has an aphanitic texture, with anhedral to euhedral crystal forms. Composed of the minerals plagioclase, feldspar, hornblende, olivine, magnetite. These intrusive rocks are formed as dyke and sill intrusive rocks, aged Late Pliocene (3.2-1.8 million years ago).

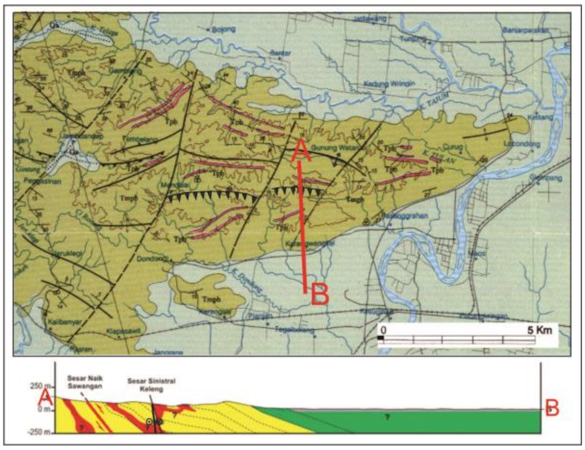

Fig. 4. The distribution of sills follows the strike line of the Halang Formation which forms an anticline.

The passage of dyke-forming magma along the crust and lithosphere is controlled by the arrangement of lithospheric crustal stress-fields and local stress-fields and fractures caused by normal faults, thrust faults and strike-slip faults [15]. The formation of dyke and sill (Tpb) in the study area is associated with faults and strain fractures that allow magma to flow and fill the existing space. Pre-existing tectonic geological structures such as faults and joints have contributed to the formation of dyke intrusions [16].

In a contractionary tectonic environment such as in the southern part of Java Island, magma migrates upward. Most of it freezes as the body of the intrusion. However, large, long-lived magma chambers with high production rates [17] allow sufficient magma to reach the surface under high mega-pressures against the major horizontal tectonic forces (σ1) of the subduction thrust of the Indian Ocean Plate to the south.

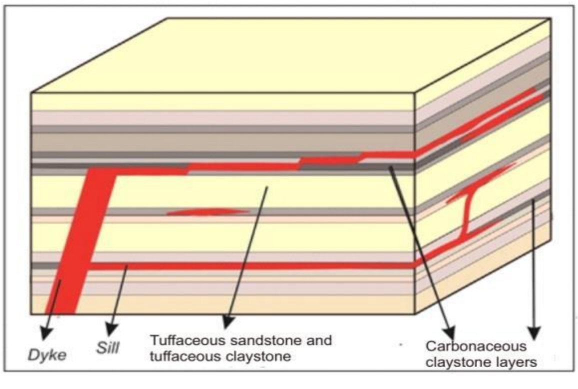

Fig. 5. Model of dyke and sill intrusion through the carbonaceous claystone in the study area.

The activity of magmatism is closely related to tectonic activities in the Late Pliocene (3.2-1.8 million years ago). As long as the tectonic activity of the area is still ongoing, it can cause reactivation of magmatism or volcanism activities. The existence of tectonic movements, the Late Pliocene volcano can show magmatism activity below the surface through the formation of dyke intrusions.

Classically, volcanism is associated with extensional tectonics, because this allows magma to move upward along vertical, perpendicular cracks with the weakest principal stress (σ3). This occurs only in divergent tectonic plates and in convergent tectonic areas such as in the south of Java Island, the tectonic control becomes different. Sometimes the question is how magma can move upward under conditions of pressure or stress with -σ2 (medium main stress) and -σ1 (maximum main stress) in the horizontal plane. This condition hinders movement along the vertical crack and magma will move horizontally in this case. Magma moves in a brittle crust along a vertical/subvertical plane that is perpendicular to -σ2, which is a thrust fault zone associated with -σ3 vertical. It is possible that magma may also move through local dilational areas associated with ramp and flat structures.

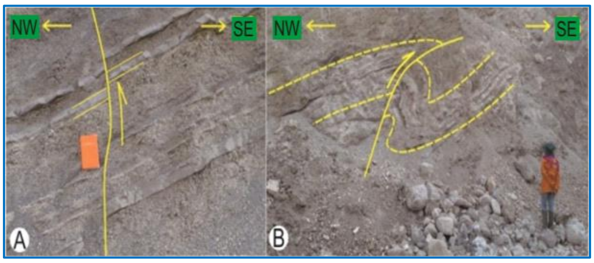

Fig. 6. Outcrop of thrust fault at coordinates 7.5819ºS and 109.1081ºE [14].

Magmatism activity in the subduction area will increase significantly with the occurrence of tectonic activity. The increase in dyke and sill-forming magmatism activity over a long period of time is due to relaxation in the compressional area associated with the subduction zone in southern Java. The reduction in compressional stress after the formation of an anticline allows magma to move along the created path to a shallower depth. The growth of dykes and sills is controlled by tectonic strain and stress due to plate subduction in southern Java. Faults and dike distributions can provide important information about the major stresses acting in the study area. [18] states that the tectono-magmatic evolution of an area is strongly influenced by the evolution of regional stress and deformation that occurs in the area.

Stereographic analysis of thrust fault data with strike/dip orientation of N80ºE/35ºS or having a west-east strike line and dipping to the south is shown in Figure 7 a. This thrust fault has a pitch angle of 83º and opens to the southeast. The results of this analysis indicate that this fault is formed by the strongest compressional stress (σ1) which is relatively horizontal from the North-South direction with a plunge/trend orientation of 10º/N345ºE (Figure 7). The weakest stress in the formation of this fault is in the vertical direction with a plunge/trend of 79°/N141°E. This structure produces a sill intrusion in the study area following the direction of rock layers with an orientation of N80°E/28°S or having a strike in the west-east direction and sloping towards the south by 28°. Dyke has a N275°E/80°N orientation or has a west-east strike with almost vertical dipping towards the north.

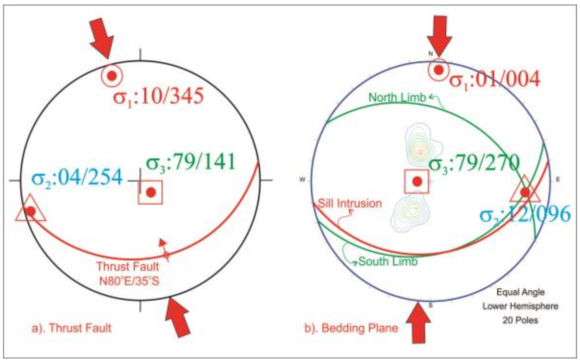

Fig. 7. a). Analysis of east-west thrust fault data. b). Analysis of sedimentary bedding planes.

Figure 7 b describes the analysis of the layers of sedimentary rock in the study area. North limb has an orientation of N299°E/29°N while the south limb has an orientation of N71°E/28°S. The results of this analysis indicate that this anticline is formed by the strongest compressional stress (σ1) which is relatively horizontal from the North-South direction with a plunge/trend orientation of 01°/N004°E (Figure 7b). The weakest stress in the formation of this anticline is in the vertical direction with a plunge/trend of 79°/N270°E.

The Cilacap area is generally a contraction zone associated with plate subduction in the south of Java Island. [19] described a magmatism model in this tectonic setting which is associated with the formation of thrust faults and folds (Figure 8). In Figure A, shows the movement of magma below the surface along the thrust fault plane. Figure B shows the effect of reactivation of vertical faults on the bedrock in the deformation of the overlying volcanic body, resulting in two splay faults, one normal fault and the other thrust fault. Figures C, D and E are photos in a flat view (left) and fault traces (right) from the experimental volcanic cone that overrides the bottom of the thrust fault, tilted to the left, with a different position to the crest. Figure C shows the top of the volcanic cone located on the footwall block. Figure D above shows the top of the volcanic cone above the surface of the thrust fault trail below. Figure D below is a cross-section of the deformation inside the volcanic cone. Figure E is the peak of the volcanic cone on the hanging wall block.

Figure 7 above shows the movement of magma in the crust along the thrust fault plane, illustrating that magma can spread to the surface in a tectonic regime characterized by contractional deformation (Figure 8.A). Thrust faults below the curved surface in a flat view, vertical tension fractures can form in the shallower part of the hanging wall, subparallel to the shortening that occurs. [19].

Figure 8 section B describes the effect of vertical bedrock faults in the destabilization process of the volcanic cones that override it. The results show that reactivation of bedrock faults resulted in the formation of two splay faults in the volcano, one normal fault and one thrust fault. Experimental models of volcanic cones located above brittle bedrock under compressive regional deformations show that volcanic loading produces stress separators influenced by bending and flattening of regional compressive structures. Although anticlinal thrust ridges are observed around many volcanoes, they are generally interpreted to be due to gravitational spreading. The results suggest that this is not the case, as they can also be a symptom of regional compression [19].

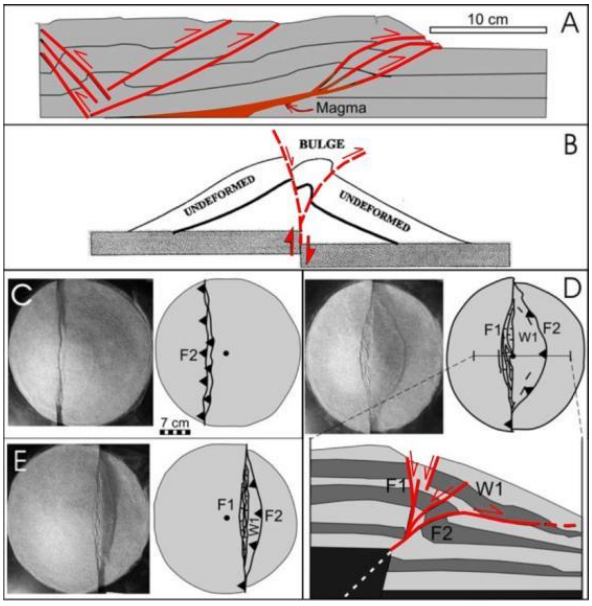

Fig. 8. Model of volcanism in a contractionary tectonic setting [19].

Publication by [20] describes the system of tectonic stresses and their relationship to the dipping of the resulting sill/dyke intrusion (Figure 9). The vertices of the triangle are the location of the stress tensor with different orientations. The top of the upper triangle has -σ1, 2 and 3 with oblique angles, under this stress field condition, more centrally-inclined sheets will form.

The local -σ1 tilt orientation is a function of the shape and overpressure of the magma chamber. The consequence of the -σ1 direction is that intrusion arrays can range from spherical **m**agma chambers to centrally-inclined sheets diverging with equal dip angles. As the distance from the magma chamber increases, the inclined dike and intrusion can turn to reach a state of equilibrium following the stress orientation which locally has -σ1 and -σ2 horizontal as in the left side of the triangular tip [20].

Above the center of the magma chamber there is the possibility of the formation of vertical or sub-vertical magma channels that drain magma to the volcanic axis. This possibility is increased by the presence of horizontal -σ3 below the volcanic axis (top right triangle of Figure 9) which can be caused by extensional regional tectonics or local deformation [20]. As the distance from the magma chamber increases, the effect of magma overpressure begins to decrease and the sheet intrusion can change from a sloping sheet to a vertical dyke to a lateral intrusion. These dykes can be parallel to each other, forming a group of dykes perpendicular to the -σ3 region, or can be radially patterned if the regional tectonic influence is small. Above the magma chamber, the slope of the dike can bend into a sill following the re-orientation of the stress (left-hand tip of the triangle). This can occur due to several conditions involving the presence of stress barriers and major mechanical contrasts between different rocks [20].

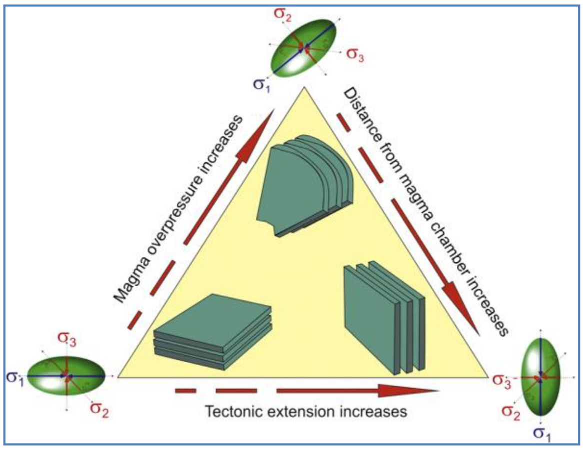

Fig. 9. Triangle of the main stress system in the upper magma channel [20].

4 Conclusions

The main stresses forming the structure in the study area are relatively in the north-south direction. This force creates a thrust fault structure with a west-east direction and a strike line of sedimentary rocks trending west-east following an anticline structure. The thrust fault then becomes a vertical magma channel or dyke which then penetrates the sedimentary rock layer to form a sill.

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