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Fluid migration along faults and gypsum vein formation during basin inversion: An example in the East Walanae fault zone of the Sengkang Basin, South Sulawesi, Indonesia

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ABSTRACT

In this study, field, petrographic, and sulfur isotope investigations were conducted for gypsum veins that were formed in the sedimentary rocks of the Walanae Formation in the Sengkang basin, South Sulawesi, Indonesia. Four types of gypsum veins developed in the study area: (1) veins sub-parallel or parallel to bedding, (2) veins perpendicular to bedding, (3) vein networks that fill in complex fractures, and (4) veins that surround carbonate concretions. Their internal structures suggest that fibrous gypsum in these veins grew antitaxially from both sides of the median zone toward the vein walls. Judging from the structural relationships of the orientation of veins with the Sengkang anticline, these gypsum veins were most likely formed as a result of hydraulic fractures or layer-parallel compression within a high fluid pressure environment triggered by the activation of the East Walanae fault under the E-W lateral compression during the Pleistocene basin inversion. The relatively wide range of sulfur isotope values indicates that sulfur in gypsum veins was delivered by the fluids that reacted with framboidal pyrites in the sedimentary rocks.

1. Introduction

Textural observations, and compositional analyses of veins are important for understanding the vein formation processes. Veins filled with gypsum often consist of a median zone with fiber zones on both sides of it (Fig. 2f), which is a distinctive feature of antitaxial fibrous veins (Bons et al., 2012).

Antitaxial gypsum veins have been reported in sedimentary basins worldwide (Shearman et al., 1972; El Tabakh et al., 1998; Philipp, 2008; Rustichelli et al., 2016; Meng et al., 2017, 2019; Zhao et al., 2020). The formation mechanism of the gypsum veins in some sedimentary basins has been suggested to be the result of hydraulic fracturing and filling of gypsum in the opening space (Philipp, 2008; Zhao et al., 2020). Gypsum veins are often found pervasively developed along deformation structures such as anticlines and fault zones (Philipp, 2008; Meng et al., 2017). In addition, the geochemical characteristics of gypsum veins are influenced by the origin of the fluid and their reactions to the fluid and wall rocks (Chen et al., 2016; Rustichelli et al., 2016). Therefore, gypsum veins may provide important information on the evolution of basin structures associated with the establishment of hydrocarbon reservoir systems. In this study, we report occurrence and sulfur isotope composition of gypsum veins develop in the Neogene sedimentary rocks of the Walanae Formation exposed in the Sengkang anticline in the east Sengkang basin, South Sulawesi, Indonesia. The purposes are: (1) to determine the timing of gypsum veins with respect to the basin inversion, and (2) to determine the source fluid of gypsum.

2. Geological setting

Sulawesi Island has a complex tectonic history related to the interaction of three large plates: the Indo-Australian, Eurasian, and Pacific plates (Jaya et al., 2017). Regional extension and block faulting caused enlargement of the basement rocks of the south arm of Sulawesi during the Middle Miocene (Van Leeuwen et al., 2010), resulting in the formation of the Sengkang basin (Fig. 1). Since then, the Sengkang basin continued to subside, allowing the deposition of reef limestones of the Taccipi Formation during the Late Miocene, followed by deposition of clastic sediments of the Walanae Formation until the Late Pliocene.

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Tectonic inversion during the Plio-Pleistocene changed the E-W trending extensional regime to contractional regime and repeatedly reactivated the EWF as a reverse fault (e.g., Jaya and Nishikawa, 2013), resulting in shortening and uplifting of the sedimentary succession in the Sengkang basin, and forming the N–S trending Sengkang anticlines at the eastern margin of the Tempe Lake (Fig. 1a–b; e.g., Van Leeuwen et al., 2010; Jaya and Nishikawa, 2013).

The Taccipi limestones are the reservoir and the Walanae clastic sediments are a seal of the petroleum system in the Sengkang basin (Grainge and Davies, 1983). During the Late Pliocene, the EWF functioned as a hydrocarbon migration pathway from the western area to eastern area of the Sengkang basin (Grainge and Davies, 1983; Mayall and Cox, 1988).

The study area is a hilly land along the Sengkang anticline extending NNW-SSE direction in the central part of the basin. The upper unit of Walanae Formation, consisting of Pliocene fluvio-deltaic and estuarine deposits predominantly composed of alternating beds of semi-consolidated siltstone, alternating bed of sandstones and siltstones characterized by channel filling beds, cross-bedding, leaf fossils, mollusks and trace fossils is exposed along the anticline. These sedimentary rocks contain abundant framboidal pyrite. The studied gypsum veins are hosted in this unit. According to well data, the lower part of the succession is predominantly mudstones with arkosic lithic sandstones, which often contain abundant biotite, and subordinately tuffaceous sandstones (Grainge and Davies, 1983; Mayall and Cox, 1988).

The fault plane of the EWF is located beneath the western limb of the Sengkang anticline. The bedding planes of the sedimentary rocks in the western limb generally strike the NNW-SSE direction. The bedding planes of the western limb moderately dip ranging from 35° to 50°, while those of the eastern limb were steeper, ranging from 55° to 70° (Fig. 1b).

3. Method

We conducted field observations of the gypsum veins at eight outcrops in the western part of the Sengkang anticline that cuts across the western limb of the anticline where veins occur in large numbers (Fig. 1b). We performed vein orientation measurements and

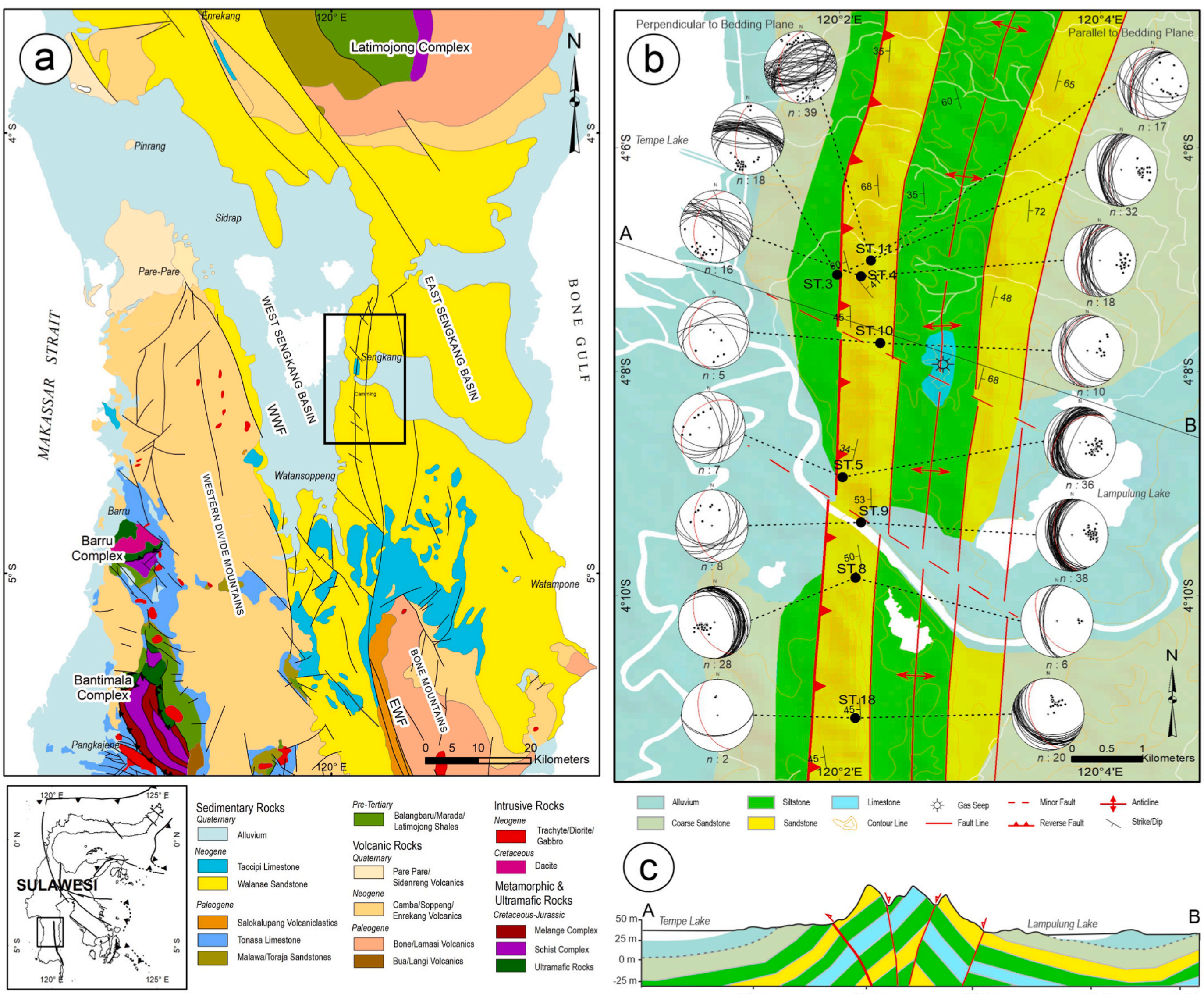

Fig. 1. a) Geological map of South Arm Sulawesi (Jaya and Nishikawa, 2013). b) Geological and sampling locality of the rectangle in a). Orientation data were plotted on lower hemisphere stereographic projection, where vein planes and bedding are drawn in black and red, respectively. *n* is the number of veins measured. c) Structural cross-section of the Sengkang anticline. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observations of their morphologies, along with sample collection. To ensure the structural control of the gypsum veins, orientation data of gypsum veins were plotted on the stereonet with orientations of bedding planes and the crest line of the anticline (Fig. 1b).

Petrographic observations were performed using an optical microscope. We focused on the growth direction of the gypsum fibers, crystal morphology, internal growth plane, and median zone.

Sulfur isotope analysis was performed for five selected gypsum vein samples (Table 1). Measurement was conducted at Actlabs (Activation Laboratories, Ltd., Canada). Sulfur was measured as SO2 applying the infrared cell method using an ELTRA elemental analyzer.

4. Results

4.1. Occurrence and orientation of veins

Gypsum veins only occur in the beds in the western limb of the anticline (Fig. 1b). They are predominantly parallel or sub-parallel to the bedding plane with NNW-SSE and NE-SW strikes, with moderate dip angles (Figs. 1 and 2a), and subordinately perpendicular or oblique to the bedding plane striking NW-SE (Fig. 1). The gypsum veins mostly exhibit a platy morphology, ranging from centimeters to tens of meters in length and from millimeters to 5 cm in width. Those cutting the bedding planes often fill the meso-scale fault cores (ST.11 in Figs. 1 and 2b). Lenticular or sigmoidal shapes are common in these types of veins (Fig. 2a). Some vein populations are composed of differently oriented veins forming densely interconnected networks (Fig. 2c). There is a unique type of gypsum vein that encloses the rim of ellipsoidal concretions (Fig. 2e), with their long axis parallel to the bedding plane and a diameter ranging from 5 cm to 50 cm. The inside of the concretion is cemented by calcite, and the surrounding gypsum veins consist of satin spars. This type of gypsum vein has not been previously reported in the Walanae Formation (Fig. 2e).

Branching veins interconnecting with each other through the wing-crack veins at the tip of the parent veins are often observed (Fig. 2d). Veins with pinch-out shapes and sub-parallel arrays of lenticular veins with a length ranging from 20 cm to 30 cm also occur in the study area (Fig. 2a).

Table 1
The $\delta^{34}S$ values for the gypsum veins (in ‰).

Sample ID	Sample Types	$\delta^{34}S$
ST-03	Gypsum vein	8.1
ST-05	Gypsum vein	4.5
ST-09	Gypsum vein	−1.3
ST-10	Gypsum vein	−1.5
ST-18	Gypsum vein	−10.8

4.2. Internal structure of veins

In petrographic observations, the median zone generally occupies the central part of the vein dividing the fiber zones into two parts, but some are formed closer to the one-vein wall side (Fig. 3a). The median zones occasionally contain host rock materials or blocky gypsum grains (Fig. 3c–d). The blocky crystals are randomly distributed, indicating the precipitation in the open space at the initial stage of vein formation (Fig. 3a and c). At the vein wall, gypsum fibers show sharp contact with host rocks without any intercalation of blocky crystals (Fig. 3c–d). The texture of the fibrous vein that is accompanied by blocky grains near the boundary with the median zone indicates an outward growth competition initiated from the median zone (e.g., Zhao et al., 2020). Fibers on both sides of the median zone simultaneously grew toward the opposite vein walls. The median zones located closer to one side of a vein may indicate asymmetric fiber growth from the median zone. These internal structures indicate that most of the gypsum veins in the Sengkang anticline are of the antitaxial type. Most of the gypsum fibers are elongated, straight, or slightly curved, showing sigmoidal shapes (Fig. 3c–d). Each gypsum fiber exhibits a consistent crystallographic orientation and a continuity of fiber without fracturing, which is consistent with the observations in previous studies (Hilgers and Urai, 2005; Bons et al., 2012).

4.3. Isotope chemistry

The sulfur isotope ratios ($\delta^{34}S$) of the gypsum veins are listed in Table 1. The $\delta^{34}S$ values of gypsum veins range from −10.8‰ to 8.1‰ with an average of −0.2‰.

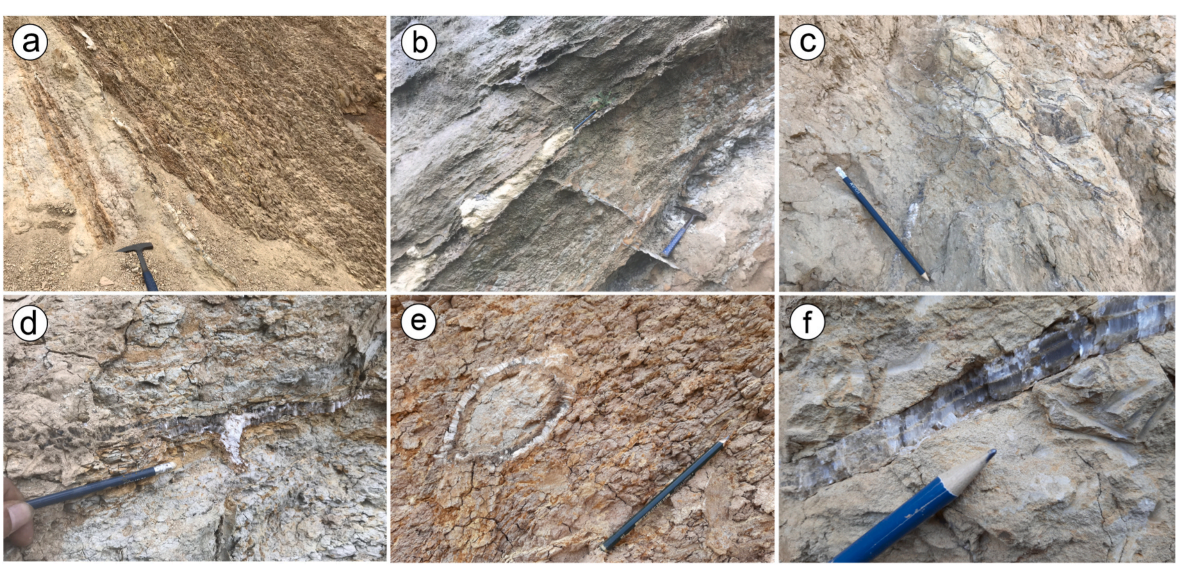

Fig. 2. Field characteristics of gypsum veins. a) A type of bedding-parallel and sub-parallel veins in the siltstone layer (ST.3). b) A vein network in the mudstones (ST.11c) Veins filling the fractures in the meso-scale faults of sandstones (ST.11). d) A wing-crack vein that is sub-vertical to the parent vein and wall rocks of sandstones (ST.5). e) A gypsum vein enclosing around the spherical carbonate concretion embedded in sandstones (ST.5). f) An antitaxial vein that has multiple median zones. Gypsum crystals grew obliquely to wall rocks of sandstones (ST.18).

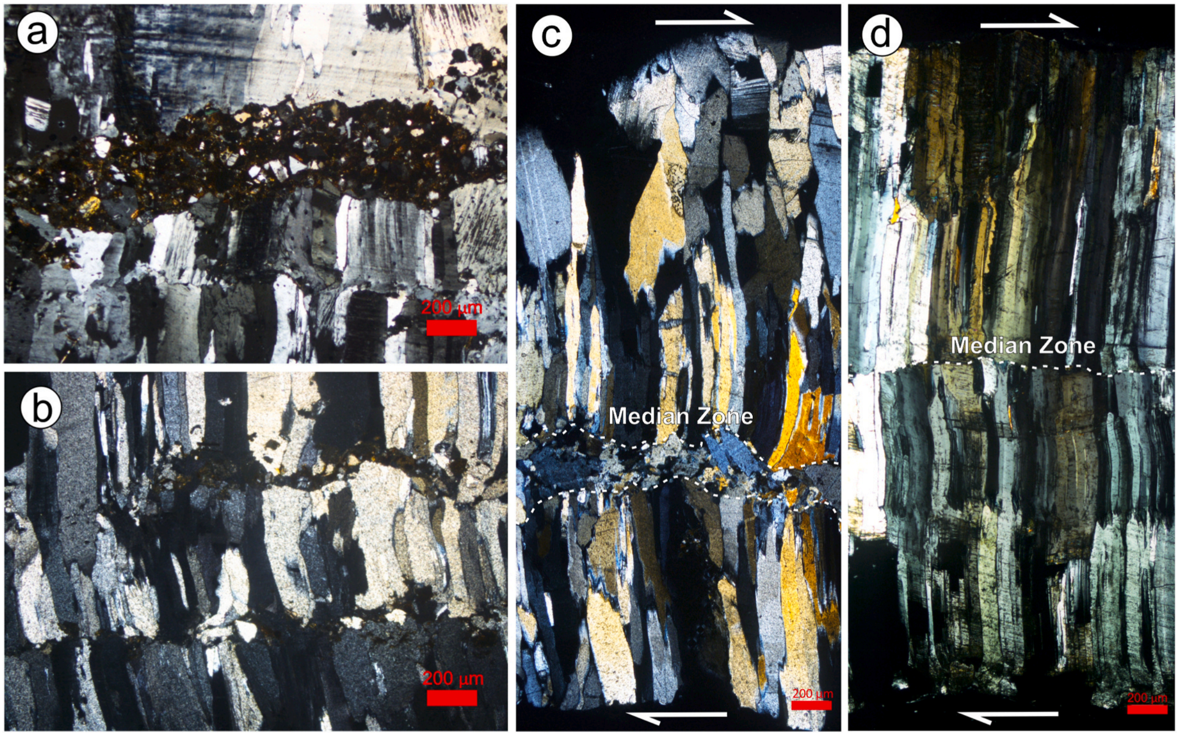

Fig. 3. Photomicrograph of gypsum veins (cross-polarized light). a) A median zone filled with multiple materials of host rocks. b) Two parallel median zones which consist of small gypsum crystals and materials of the host rocks (ST.10). c) The median zone formed closer to one side of the vein wall and was filled by blocky gypsum grains (ST.18). d) The median line was placed in the center of the vein (ST.9).

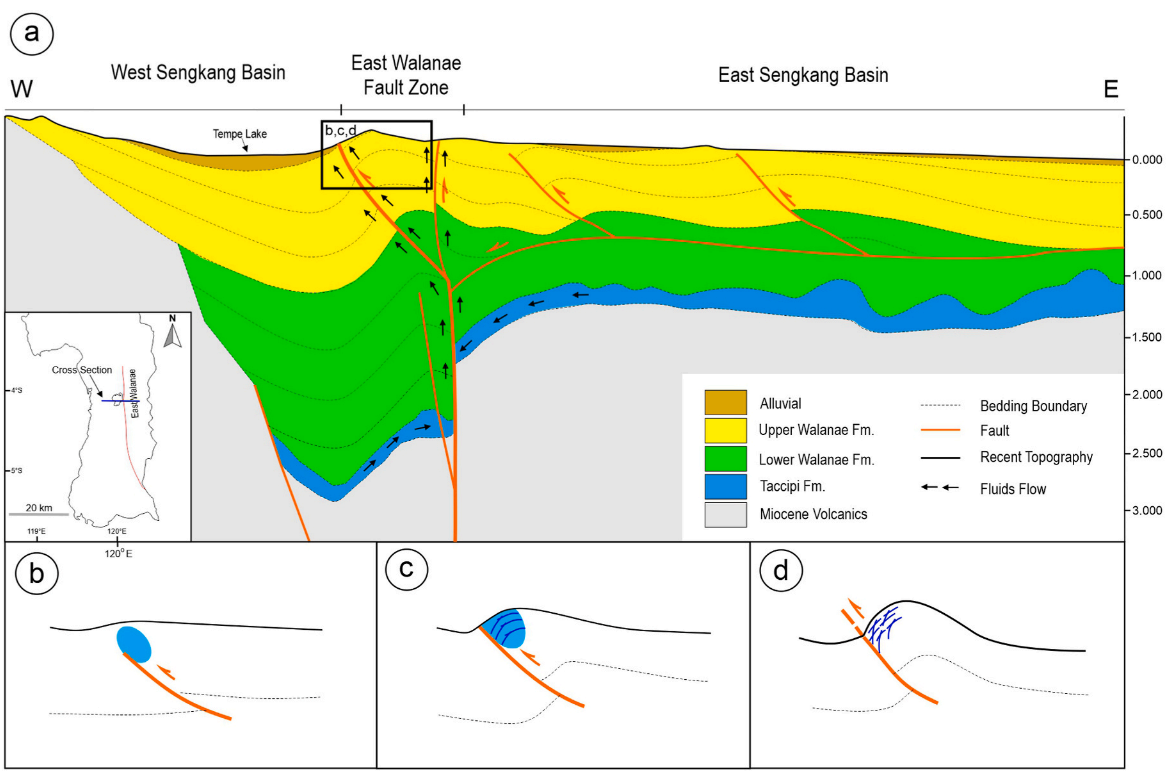

Fig. 4. a) Schematic cross-section across the Sengkang Basin and EWF, modified from Grainge and Davies (1983), illustrating that fluids were transported upward from the carbonate rock along the fault zone. Schematic illustration of b) the area of overpressure formed at the propagating EWF tip, c) the fracturing and formation of gypsum veins near the surface, and d) the building of the Sengkang anticlinal hill.

5. Discussion

The development of gypsum veins is limited to a narrow area along the western limb of the Sengkang anticline, below which the EWF cuts the strata of the Walanae Formation (Fig. 1). Thus, the propagation of EWF would be involved in the formation of the Sengkang anticline and also closely related to the formation of veins. Fluids migrating along the EWF were most likely concentrated around the fault tip increasing the pore pressure (Fig. 4). The initial opening of the gypsum veins could have been caused by hydraulic fracturing or layer-parallel compression under a generally high fluid pressure condition (e.g., Philipp, 2008; Meng et al., 2017, 2019; Hooker et al., 2019; Zhao et al., 2020). The veins were formed predominantly nearly parallel to the bedding plane. In the hinge zone of an anticline under the E-W contractional regime, the minimum principal stress axis is probably vertical. Therefore, vein formation can be considered to have occurred in the early stages of fold growth (Fig. 4b).

The gypsum veins in the study area exhibit typical characteristics of antitaxial fibrous veins with median zones. This type of veins most likely widened continuously after the initial fracturing as a control valve of pore pressure without repeated fracturing of gypsum fibers (e.g., Sibson, 1990).

The reef limestones of the Taccipi Formation, which is the reservoir rock of the Sengkang gas field at a maximum depth of less than 1 km (Fig. 4; Grainge and Davies, 1983; Mayall and Cox, 1988) most likely supplied calcium ions to the fluid, from which gypsum precipitated.

There is little magmatic activity, and no evaporites have been reported in this sedimentary basin. The distribution of $\delta^{34}S$ values of gypsum veins in the Sengkang anticline shows a relatively wide range of values (±10‰) across 0‰. The fluid in the reservoir of the Sengkang basin, which mainly consists of marine strata, would be of seawater origin and have heavy $\delta^{34}S$ values similar to seawater and evaporite (ca. 20‰). Although sulfide isotope values were not measured in the study area, biogenic sulfides (framboidal pyrite) in sediments are generally known to have light and broad sulfur isotopic compositions ranging from −5 to −40‰ (Komuro and Sasaki, 1985; Kohn et al., 1998; Zuo et al., 2021). Therefore, we interpret that the development of the gypsum vein is greatly contributed by the water of meteoric origin circulating in the shallow underground that oxidized the pyrite in the sedimentary rock, as well as formation water delivered from the Taccipi reservoir rocks (e.g., Holser and Kaplan, 1966; Chen et al., 2016; Pierre and Rouchy, 2020). The mixed fluid of water with a light $\delta^{34}S$ value of meteoric origin and that originated from seawater with a heavier $\delta^{34}S$ signature would have had an intermediate $\delta^{34}S$ value, and could potentially precipitate sulfates with a similar sulfur isotope composition. The variation in isotope values may reflect the variation in sulfide isotope ratios and fluid mixing ratios from place to place.

6. Conclusions

We highlight the role of fault activity on fluid behavior in the Sengkang basin during basin inversion by integrating structural and geochemical analyses. We interpret that the various styles of antitaxial veins formed in the Sengkang anticline were generated by hydraulic fracturing or layer-parallel compression under a generally high fluid pressure condition around the propagating fault tip. Our work on the case of the Sengkang gas-producing basin is useful in modeling fluid migration in oil plays.

Credit author statement

Asri Jaya: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing - original draft; Writing - review & editing. **Osamu Nishikawa**: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing - review & editing. **Sufriadin**: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation, Writing - original draft. **Sahabuddin Jumadil:** Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation, Writing - original draft.

Declaration of competing interest

The authors declare that they have no potential conflicts of interest or personal relationships that could have influenced the work reported in this paper.

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