Deformation in Jurassic-Cretaceous Redbeds from Champasak and Khammouane, Lao PDR, Revealed by Anisotropy of Magnetic Susceptibility

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ABSTRACT

The anisotropy of magnetic susceptibility measurement technique was applied to the Jurassic-Cretaceous redbeds in the Champasak and Khammouane provinces of the southern and central part of Lao PDR, in order to define the correlation between the magnetic anisotropic data and degree of deformation in redbeds due to tectonic stress field focusing on the mountain belt and fault areas. The results show that the alignment of $K_{\text{max}}$ axes is predominantly parallel to the trending of the mountain belts (or fold axis) and the strike of faults. The orientation patterns of the principal axes of the susceptibility ellipsoid did not show the typical pattern usually found in undeformed sedimentary rocks. It can be concluded that the development of the triaxial and pencil structure patterns of secondary magnetic fabric correlates well with the degree of rock deformation which is caused by tectonic compression acting on the rocks.

Keywords: anisotropy of magnetic susceptibility, AMS, redbeds, deformation, Lao PDR

1. INTRODUCTION

Rock deformation has been investigated using various techniques analysing of deformation signatures and grain orientation. However, those techniques are difficult to apply for the deformed rocks that do not show any deformation markers at the mesoscopic scale. The anisotropy of magnetic susceptibility (AMS) has now been widely applied to study various geologic processes to give information on the magnetic fabrics to the rocks [1-8]. This technique also has been successfully used to investigate the deformation of sedimentary rocks. The aspects of the magnetic fabrics in this case generally depends on the degree of deformation: (i) for the weakly deformed rocks, magnetic fabrics record the initial stage of deformation under low strain condition in which the orientation of magnetic lineation ($K_{\text{max}}$ axes) is perpendicular to the shortening direction in...
compressive areas [6-8, 10] and parallel to stretching direction in extensional areas [2, 4, 11-13]. In this case, the magnetic fabrics preferably develop into triaxial shape. (ii) For moderately deformed rocks (or pencil structure and weak cleavage) the magnetic fabrics are characterized by neutral to prolate ellipsoids. The magnetic lineations are tightly clustered parallel to the fold axes and to the strike of thrust sheets, and magnetic foliation poles are perpendicular to either the bedding planes or the magnetic lineations. (iii) For strongly deformed rocks defined as strong cleavage structure, the magnetic fabrics are characterized by a relatively high degree of magnetic anisotropy, strongly oblate ellipsoids, magnetic foliations are well parallel to the bedding, and magnetic lineations grouped parallel to bedding/cleavage intersection lines. In case of the moderate and strong deformation (types ii and iii), the AMS analyses have been documented [1, 6-9, 14-19].

The studied redbeds are taken from the Champasak and Khammouane, the western provinces of the central and southern part of Lao PDR, eastern and northeastern parts of the Khorat Plateau. The geology of the area is similar to that of the Khorat Group in NE Thailand dominated with large non-marine depositional systems in the mainland of Southeast Asia [20-21].

The Champasak area, located in the southern part of Laos, consists mainly of Lower Jurassic to Cretaceous red sedimentary rocks or redbeds (Table 1, Figure 4a) exposing along the Mekong River, and the eastern part is bordered with the Bolaven Plateau having large areas of Neogene-Quaternary basalts [22]; Figure 4a. The redbeds mountain ranges are aligned approximately in the N-S trending along the Mekong River.

In Khammouane area, the rock formations named Ban Lao, Nam Phuoa, Nam Xot, Nam Noy, and Nong Boua formations are the Jurassic-Cretaceous redbeds [23-24]. Geology of this area is complicated with various faults and fractures. Thakhek Fault is a major thrust fault of which strike is trending in ca. NW-SE extending from Khammouane to the east central of Vietnam. This fault has occurred in Indosinian thermotectonic event resulting from the collision of the Indochina, South China, and Shan Thai terranes during the Lower Triassic [25-26]. Moreover, many other faults are also observed in this area (Figure 5a). The rock samples are taken from Jurassic to Cretaceous redbeds located near fault zones with an exception of site KM05 located far from the fault in nearby mountainous area (Table 1; Figure 5a). Deformation markers of the geologic structures are scarce in these areas; therefore, the analyses of anisotropy of magnetic susceptibility (AMS) of the rocks are necessary in order to reveal the effect of AMS in the geological structures relating to the tectonic/palaeotectonic activities acted on the rock.

The purpose of this study is to investigate the rock deformation of the apparently undeformed sedimentary rocks (redbeds) from Champasak and Khammouane provinces, Lao PDR, using the analysis of anisotropy of magnetic susceptibility (AMS), and to analyse for the magnetic minerals in the redbeds using magnetic examination.
Table 1. AMS data including of sampling sites and age of the redbeds from the Champasak and Khammouane provinces in the west of central and southern part of Laos.

<table>
<thead>
<tr>
<th>Site</th>
<th>N(n)</th>
<th>Age</th>
<th>Locality</th>
<th>Kmax x10^6 SI</th>
<th>Pj</th>
<th>T</th>
<th>AMS After Bedding correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lon(E)/Lat(N)</td>
<td>Dec./Inc. (e1/e2)</td>
<td>Kmax axes(°)</td>
<td>Kmin axes(°)</td>
<td></td>
</tr>
<tr>
<td>Champasak Province</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP01</td>
<td>10(37)</td>
<td>J1-2</td>
<td>105.9/15.33</td>
<td>295.1(18.1)</td>
<td>1.04(0.00)</td>
<td>-0.08(0.15)</td>
<td>173.5/13.2(22.1/7.9)</td>
</tr>
<tr>
<td>CP02</td>
<td>10(34)</td>
<td>J1-2</td>
<td>105.81/15.39</td>
<td>283.7(21.1)</td>
<td>1.04(0.01)</td>
<td>-0.06(0.20)</td>
<td>356.2/16.1(11.3/6.3)</td>
</tr>
<tr>
<td>CP03</td>
<td>15(55)</td>
<td>J1-2</td>
<td>105.81/15.10</td>
<td>264.8(36.6)</td>
<td>1.03(0.00)</td>
<td>-0.46(0.29)</td>
<td>352.5/6.8(7.4/2.7)</td>
</tr>
<tr>
<td>CP04</td>
<td>12(47)</td>
<td>J1-2</td>
<td>105.80/15.07</td>
<td>245.2(21.9)</td>
<td>1.03(0.01)</td>
<td>-0.31(0.34)</td>
<td>0.1/14.2(5.6/5.2)</td>
</tr>
<tr>
<td>CP05</td>
<td>11(28)</td>
<td>J3-K</td>
<td>105.86/15.03</td>
<td>467.0(71.4)</td>
<td>1.05(0.01)</td>
<td>0.36(0.43)</td>
<td>3.7/13.0(29.7/8.3)</td>
</tr>
<tr>
<td>CP06</td>
<td>11(32)</td>
<td>J3-K</td>
<td>105.84/15.05</td>
<td>542.5(11.4)</td>
<td>1.04(0.00)</td>
<td>-0.22(0.16)</td>
<td>359.1/21.7(3.7/3.3)</td>
</tr>
<tr>
<td>CP07</td>
<td>12(40)</td>
<td>J3-K</td>
<td>105.81/15.06</td>
<td>374.1(21.5)</td>
<td>1.05(0.01)</td>
<td>0.04(0.13)</td>
<td>353.4/17.3(6.2/5.0)</td>
</tr>
<tr>
<td>Mean</td>
<td>81(273)</td>
<td>-</td>
<td>-</td>
<td>337.2(105.1)</td>
<td>1.04(0.01)</td>
<td>-0.15(0.41)</td>
<td>356.1/14.1(α95=2.1)</td>
</tr>
<tr>
<td>Khammouane Province</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KM01</td>
<td>11(32)</td>
<td>J3(J3np)</td>
<td>104.40/17.89</td>
<td>125.8(4.3)</td>
<td>1.02(0.00)</td>
<td>-0.02(0.18)</td>
<td>127.3/13.0(8.0/7.2)</td>
</tr>
<tr>
<td>KM02</td>
<td>12(34)</td>
<td>J3(J3np)</td>
<td>104.47/17.81</td>
<td>36.8(3.4)</td>
<td>1.03(0.02)</td>
<td>0.23(0.38)</td>
<td>129.1/9.4(26.4/7.3)</td>
</tr>
<tr>
<td>KM03</td>
<td>11(31)</td>
<td>J3(J3np)</td>
<td>104.48/17.81</td>
<td>22.1(4.7)</td>
<td>1.06(0.03)</td>
<td>0.37(0.29)</td>
<td>143.8/5.0(31.5/7.4)</td>
</tr>
<tr>
<td>KM04</td>
<td>11(24)</td>
<td>Kl(Klnx)</td>
<td>104.75/17.49</td>
<td>66.9(2.8)</td>
<td>1.02(0.00)</td>
<td>-0.19(0.26)</td>
<td>157.2/76.2(14.0/3.3)</td>
</tr>
<tr>
<td>KM05</td>
<td>13(30)</td>
<td>J3(J3np)</td>
<td>104.48/18.18</td>
<td>162.3(9.3)</td>
<td>1.02(0.00)</td>
<td>-0.45(0.31)</td>
<td>226.7/3.3(11.7/5.2)</td>
</tr>
<tr>
<td>KM06</td>
<td>14(50)</td>
<td>J3(J3np)</td>
<td>104.34/18.21</td>
<td>135.0(9.1)</td>
<td>1.03(0.00)</td>
<td>0.35(0.20)</td>
<td>166.8/9.1(9.8/4.2)</td>
</tr>
<tr>
<td>KM07</td>
<td>11(25)</td>
<td>Kl or J3(J3np)</td>
<td>104.01/18.24</td>
<td>58.1(5.3)</td>
<td>1.02(0.01)</td>
<td>-0.07(0.36)</td>
<td>297.0/43.7(17.0/7.9)</td>
</tr>
<tr>
<td>Mean</td>
<td>83(226)</td>
<td>-</td>
<td>-</td>
<td>90.7(51.1)</td>
<td>1.03(0.02)</td>
<td>0.07(0.40)</td>
<td>320.8/17.1(α95=18.5)</td>
</tr>
</tbody>
</table>

Note: N(n): number of samples (specimens); J1-2: Lower-Middle Jurassic; J3-K: Upper Jurassic-Cretaceous; J3: Upper Jurassic; J3np: Nam Phouan Formation (Upper Jurassic); Kl: Lower Cretaceous; Klnx: Nam Xot Formation (Lower Cretaceous). K95: site mean magnetic susceptibility; Pj: corrected anisotropy degree; T: shape parameter; s: standard deviation; Kmax and Kmin are the orientation of the maximum and minimum axes (Dec.: declination and Inc.: inclination) for each site is calculated by using the Jelinek statistic [30]; e1 and e2 are semi-angle of 95% confidence ellipse around the principal axes. Mean of Kmax and Kmin axes for each locality is defined by using the statistics of Fisher [43]: α95 is the cone of the 95% confidence of the Kmax and Kmin axes of susceptibility.

2. MATERIALS AND METHODS

The magnetic susceptibility is in fact the second rank tensor. The principal susceptibilities are described in term of a magnitude ellipsoid with Kmax, Kint, and Kmin presenting the maximum, intermediate, and minimum axes, respectively (Kmax ≥ Kint ≥ Kmin). The mean magnetic susceptibility (Km) of a specimen is defined as Km = (Kmax + Kint + Kmin) / 3 [27, 28]. The AMS parameters proposed by Jelinek [29] are used: Pj = exp[2(η1 - η3)2 - (η2 - η3)2] / (η2 - η1)2; T = (2η2 - η3 - η1) / (η2 - η1); where η1 = lnKmax; η2 = lnKint; η3 = lnKmin; where Pj and T are the corrected anisotropy degree and the shape parameter of susceptibility ellipsoid, respectively. The Pj is used to indicate the degree of anisotropy whereas the T describes the shape of susceptibility ellipsoid. Prolate ellipsoid (rod shape) corresponds to a negative value of T (-1 < T < 0), while the positive value (0 < T < 1), presents oblate ellipsoid (disc shape) and the ellipsoid becomes a neutral sphere when T=0. The technique of Jelinek [30] was used for statistical analyses of the AMS data. The data were analyzed using the Anisoft 4.2 software [31].

The Jurassic-Cretaceous red sedimentary
rocks or redbeds were sampled from 14 sites at the mountainous area in Champasak province (7 sites CP01 to CP07) and near the fault zones in Khammouane province (7 sites KM01 to KM07), Lao PDR, (Figures 4a and 5a) using a portable gasoline-powered core drill. Totally 164 oriented samples were collected and oriented by both sun and magnetic compasses. A GPS was used to find the geographical location of the sampling sites. Standard specimens (cylinder of 2.5 cm diameter and 2.2 cm high) were prepared for measurement of the anisotropy of magnetic susceptibility at room temperature, using a low field spinning Kappabridge KLY-3S (Agico, Czech Republic) in the Paleomagnetic Laboratory, Prince of Songkla University, Thailand, in order to define the magnetic fabric of the rocks. For analyses of magnetic minerals, a CS3 furnace (Agico, Czech Republic) installed with the Kappabridge KLY-3S (in the Paleomagnetic Laboratory, Lule University of Technology, Sweden) was used to measure the magnetic susceptibility at different temperatures during heating and cooling.

3. RESULTS AND DISCUSSIONS
3.1 Magnetic Minerals
Thermomagnetic curves (low-field susceptibility vs. temperature) show reversible variation of susceptibility during heating and cooling cycles as illustrated in Figure 1. The susceptibility drops sharply between ca. 520 and 580°C during heating indicating the presence of magnetite in the studied redbeds (Curie Temperature for magnetite; $T_c$=580°C). A small variation of susceptibility at temperature above 580°C could indicate the presence of hematite ($T_c$=680°C for hematite). The susceptibility increasing steadily from room temperature (20°C) to ca. 520°C is probably resulted from various grain sizes of magnetic minerals having different unblocking temperatures. In summary, the magnetic minerals found in the studied redbeds are both magnetite and hematite similar to those found in other redbeds in Laos [32] and in the Khorat Group, NE Thailand [33-34]. Both magnetite and hematite are commonly found in the continental or fresh-water sedimentary rocks of the world.

![Figure 1. Thermomagnetic curves of representative samples used to identify the magnetic mineral in the red sedimentary rocks (redbeds). (a) and (b) denote the representative samples from Champasak (site CP03) and Khammouane (site KM04) provinces, respectively.](image-url)
3.2 Magnetic Susceptibility

The magnetic susceptibility of the studied redbeds depends on their lithologies and geographic locations relating to depositional environments during and after deposition. The site means of the susceptibility ($K_m$) are summarized in Table 1. The susceptibility of all sites of these studied redbeds is low ($<500 \times 10^{-6}$ SI) indicating that the magnetic minerals are mainly diamagnetic and paramagnetic presenting in the rock with a very low amount of ferrimagnetic minerals commonly found in the sedimentary rocks, e.g. $<500 \times 10^{-6}$ SI; [3] and ca. $133 \times 10^{-6}$ SI for sandstones [6].

As illustrated in Table 1 and Figure 2, the site means of bulk susceptibility for the Champasak redbeds reveal higher values ranging from $245.2 \times 10^{-6}$ to $542.5 \times 10^{-6}$ SI (formation mean; $K_{mean}=337.2 \times 10^{-6}$ SI, with standard deviation; $s=105.1 \times 10^{-6}$ SI) indicating a relatively strong influence of ferrimagnetic minerals to the magnetic susceptibility, e.g. ca. $350-460 \times 10^{-6}$ SI [35-36]. In contrast, the susceptibilities of the Khammouane redbeds are lower values varying from $22.1$ to $162.3 \times 10^{-6}$ SI ($K_{mean}=90.7 \times 10^{-6}$ SI, with $s=51.1 \times 10^{-6}$ SI). The susceptibilities of the specimens from Champasak redbeds are relatively higher (mean $\sim 337.2 \times 10^{-6}$ SI) than those of Khammouane redbeds (mean $\sim 90.7 \times 10^{-6}$ SI) indicating a significant difference of susceptibility of Champasak and Khammouane redbeds. Relatively high susceptibility of Champasak redbeds is probably due to the presence of a little higher content of newly formed ferrimagnetic minerals in Champasak redbeds, most probable magnetite. The magnetite would be secondary mineral formed during folding in a high temperature and/or high pressure conditions probably resulting from tectonic compression in this region [37-38]. Secondary magnetite is believed here as a reduction product of hematite in the presence of moisture [39], whereas hematite is the primary magnetic mineral found in most redbeds in the Khorat Plateau. Syn-fold remanent magnetization carried by magnetite found in the redbeds from Savannakhet province, north of Champasak [32] supports the hypothesis that magnetite is secondary magnetic mineral originated in the rock during folding. On the other hand, the lower susceptibilities of Khammouane redbeds represent both magnetite and hematite, which has been commonly found in all redbeds formations of the Khorat Plateau. This finding is in agreement with those results from previous palaeomagnetic studies, for example, the positive fold test found in the Khammouane redbeds [40] and in other redbeds formations in the Khorat Plateau [32-34]. Those positive fold tests strongly supported that hematite is primary magnetic mineral occurred before folding of the redbeds.

![Figure 2. The histogram showing the distribution of magnetic susceptibility of the redbeds specimens from Champasak and Khammouane provinces. $K_{mean}$ axes and $s$ are the formation mean of magnetic susceptibility in SI unit and standard deviation, respectively. The curves illustrate the normal distribution (Gaussian) fit to the data.](image-url)
3.3 Anisotropy of Magnetic Susceptibility (AMS)

The AMS parameters of a sedimentary rock depend on the type of magnetic minerals, effects of depositional environment, and tectonic activities acted on rocks during and after rock formation.

The typical patterns of magnetic fabric of the studied redbeds can be classified on the basis of the distribution of the susceptibility ellipsoids, the shape parameter, and the degree of anisotropy as summarized in Table 1. The corrected anisotropy ($P_j$) of rock samples from all sites is mostly low values ($P_j<1.06$), whereas the shape parameter ($T$) shows both positive and negative values (Table 1; Figure 3). For the Champasak redbeds as demonstrated by Table 1 and Figure 3a, the site means of $P_j$ and $T$ (with standard deviation; $s$) range between 1.03 and 1.05 ($s=0.01$), and -0.48 and 0.36 ($s=0.41$), respectively. For the Khammouane redbeds, the site means of the $P_j$ and $T$ (with $s$) illustrated in Table 1 and Figure 3b are from 1.02 to 1.06 ($s=0.02$), and from -0.45 to 0.37 ($s=0.4$), respectively.

Orientations of the susceptibility ellipsoids plotted on the stereographic projection on lower hemisphere after bedding correction together with the $P_j$ vs.$T$ diagrams are presented in Figure 3, and basic schemes of magnetic fabric relating to geological structures are shown in Figures 4b and 5b. Two major types of AMS distribution patterns are differentiated as follows.

The first type, the directions of the $K_{max}$ and $K_{min}$ axes display a girdle distribution around the bedding plane, whereas the orientation of magnetic lineation ($K_{max}$ axes) is well grouped on the bedding plane (Figures 3a and 4b). The $P_j$ vs.$T$ diagrams (Figure 3a) show a typical prolate shape of susceptibility ellipsoid with a low degree of anisotropy ($P_j<1.05$). Even though the $P_j$ is low, the pattern of the magnetic fabric is not typically found for undeformed sedimentary rocks. In addition the $P_j$ vs.$T$ diagrams (Figure 3a) show the pencil structure as illustrated in Figure 4b. This probably indicates a medium to strong deformation degree of rocks which are observed from all sites of the Jurassic-Cretaceous redbeds in Champasak. The observed $K_{max}$ axes of all sites are approximately trending in N-S and NNE-SSW at Champasak mountain belts exposing along the bank of the Mekong River (sites CP03 to CP07) and to the north of this studied area (sites CP01 and CP02) (Figure 4a). These mountainous areas are close to Ubon Rachathani anticlines in NE Thailand that is believed that deformation events occurred in the Mid-Cretaceous [21, 41-42]. This can be interpreted that the tectonic stress could be perpendicular to the $K_{max}$ axes as illustrated in the model shown in Figure 4b that are similar to those found in the previous models in other areas affected by tectonic compression [8-10, 17, 43].

The second type of AMS pattern, the magnetic fabrics are predominantly well defined as a triaxial pattern that all axes are developed and well grouped, and the $K_{min}$ axes are slightly to highly tilted from the bedding pole (Figure 3b). The degree of anisotropy is slightly higher and the magnetic fabrics show both prolate and oblate ellipsoids, while the preferred orientations of the observed $K_{max}$ axes are predominantly both paralleled to the strike of the fault zones (i.e. aligned ca. NW-SE trend for sites KM01 to KM04, KM06, and KM07) and parallel to fold axis at a mountain belt area (i.e. ca. NE-SW trend for site KM05) (Figures 3b and 5a,b). The magnetic fabrics are probably developed by tectonic compression. Even though the sampling sites are located in fault and fracture areas, the Jurassic-Cretaceous redbeds were...
deposited at a time after faulting of the Thakhek Fault in the Lower Triassic time. The events of deformation had occurred in this region during mid-Upper Cretaceous time, e.g. Khammouane and Nam Leuk uplifts in Laos and Phu Phan Uplift, in NE Thailand [21, 41-43]. It can be concluded that this triaxial pattern of AMS indicates a weak to moderate deformation dominated by palaeotectonic stress on the studied red beds expressed as the $K_{max}$ axes perpendicular to the strike of the faults as shown in Figure 5b corresponding to the previous models, e.g. [2-3, 6, 8-10, 12, 16-17].

Figure 3. T vs. Pj diagrams of all the specimens from all sampling sites, and equal area stereoplots projected on the lower hemisphere of the AMS axes, after bedding correction for each site. (a) Champasak Province (CP01 to CP07), and (b) Khammouane province (KM01 to KM07).
Figure 4. (a) Geologic map of Champasak Province modified from a map of geology and mineral resources of the south of Laos; 1:500,000 [22] together with rose diagrams of alignment (Declination) of the $K_{\text{max}}$ and $K_{\text{min}}$ axes. (b) Geologic model in the Champasak mountain belt area associated with magnetic fabrics defined by AMS measurement. J1-2: Lower-Middle Jurassic; J3-K: Upper Jurassic-Cretaceous; bN2-Q1: Neogene-Quaternary basalts; bQ1: Quaternary basalts.
4. CONCLUSIONS

The results of the application of AMS studied on the Mesozoic redbeds in Laos can be summarized as follows;

(1) The magnetic minerals in the redbeds interpreted from thermomagnetic measurement are mainly both magnetite and hematite with various grain sizes.

(2) This study is important indications to understanding of rock deformation related tectonic stress in the region. The magnetic fabrics yield weak to moderate deformation of rocks affecting by tectonic events at the fault zones in Khammouane area, and strong deformation remarked as the pencil structure of the magnetic fabrics are observed near Champasak mountain belts.

Figure 5. (a) Geologic map of Khammouane Province modified from geological maps of Thakek and Khamkeut in mid-central Laos; 1:200,000 [23-24] together with rose diagrams of alignment (Declination) of the Kmax and Kmin axes. (b) Geologic model at a fault zone associated with magnetic fabrics defined by AMS measurement. J: Jurassic, Kl: Lower Cretaceous; T2Lk: Ling Kho Formation (Lower Triassic); C1bp: Boulapha Formation (Carboniferous).
(3) The $K_{ma}$ axes are predominantly perpendicular to the stress directions or the $K_{ma}$ axes are parallel to the fold axis of the mountain belts and to the strike of the faults. Our AMS models relating geological structures caused by paleotectonic activities are in good agreement with the results of the previous works.

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