# [PS]Analysis of Brittleness in Mudstone Caprock Using Conventional Well Logs: A Case Study from Northern Margin of Qaidam Basin*

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## Abstract

Brittleness index, generally estimated from array sonic logs or triaxial tests, is commonly used to quantitatively characterize the possible failure features in shale reservoirs. Because of the similarities in mineralogical composition between shale reservoirs and mudstone caprock, it is valuable to utilize brittleness index derived from conventional well logs for evaluating the brittleness of mudstone caprock. With the research object of Tertiary mudstone caprock in the northern margin of the Qaidam Basin, core samples of mudstone were taken from several significant wells. To construct the ternary diagram of mineralogy of the study area, the X-ray diffraction analysis was used for obtaining relative content of minerals (including quartz, carbonate, and clay). Then the brittleness index was calculated from mineralogical composition. Since conventional well logging signatures are sensitive to variation in mineral constituent, statistical regression analysis was carried out to probe the relationship between brittleness index and conventional well logs (such as GR, SP, Pe etc.). The relationship between the brittleness index and log data, like GR, Pe, were established. The results indicate that the ratio of GR to Pe has the best corresponding effect on brittleness index. Therefore, the brittleness index could be calculated from conventional logs. The brittleness of different formations ranges from 60%-70%, among which Shangganchaigou Formation (N1) and Lulehe Formation (E1+2) are the highest while Xiaganchaigou Formation (E32) is the lowest. The brittleness of different districts varies, the highest of which are in Lengdong and Lenghu No.5 structure belt, about 60%, while the brittleness of Lenghu No.4 structure belt is lowest, around 47%. Therefore, E32 brittleness is comparatively low so that natural fractures are not easy to form. Besides, the brittleness in Lenghu No.4 structure belt is lower; so it is more difficult for natural fractures to form than in the other part of research area. Thus, E32 caprock in Lenghu No.4 structure belt could be high-quality caprock. The result of the analysis is consistent with oil-test results. To conclude, the brittleness index could be estimated using conventional well logs and could be used as a new parameter to evaluate sealing capacity of mudstone caprock.

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Brittleness index, generally estimated from array sonic logs or triaxial tests, is commonly used to quantitatively characterize the possible failure features in shale reservoirs. Because of the similarities in mineralogical composition between shale reservoirs and mudstone caprock, it is valuable to utilize brittleness index derived from conventional well logs for evaluating the brittleness of mudstone caprock. With the research object of Tertiary mudstone caprock in northern margin of Qaidam basin, X-ray diffraction analysis was used for obtaining relative content of minerals (including quartz, carbonate and clay). Then the brittleness index was calculated from mineralogical composition. Since some kind of conventional well-logging signature is sensitive to variation in mineral constituent, statistical regression analysis was carried out to probe into such a corresponding relationship between brittleness index and conventional well logs (such as GR, SP, Pe, etc.). Therefore, the brittleness index could be calculated from conventional logs. The brittleness of different formations in districts varies. The result of analysis is consistent with oil test results. To conclude, the brittleness index could be estimated using conventional well logs and could be used as a new parameter to evaluate sealing capacity of mudstone caprock.

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## INTRODUCTION

Brittleness is one of the important mechanical properties of rocks (Kahramana and Altindag, 2004; Yagiz, 2009; Altindag, 2010; Meng et al., 2014).

The concept of rock brittleness combines both Poisson's Ratio and Young's Modulus. These two components are combined to reflect the rocks ability to fail under stress (Poisson's Ratio) and maintain a fracture (Young's Modulus) once the rock fractures. In view of these, ductile rock may be good caprock because the formation will want to heal any natural fractures. Brittle rock is more likely to be naturally fractured and will more probably lose oil and gas as caprock.

Brittleness index, generally estimated from array sonic logs or triaxial tests, is commonly used to quantitatively characterize the possible failure features in shale reservoirs. However, they are difficult to be applied widely in oil field company or research institute because of high cost. With the type of data available, significant correlations can be drawn by integrating the wireline log data as a tool to estimate the mechanical rock properties and geochemical analysis. Thus, the wireline analysis, once calibrated with core measurements, is very useful tool in extending the rock brittleness understanding as one moves away from the wellbore where actual lab data was measured.

## METHODS AND MATERIALS

Overview on the methods of calculating rock brittleness index

The brittleness is usually evaluated by brittleness index (Rickman et al., 2008; Sondergeld et al., 2010). In the last decades, the concept and measurement method of rock brittleness have long been discussed and have not reached a consensus (Goktan and Yilmaz, 2005). There is no standardized concept or measurement method exactly defining or measuring the rock brittleness up to now. The most acceptable methods of calculating brittleness are calculated from the XRD mineralogical composition or rock mechanical parameters. In this research, we took the former method to get the brittleness index in consideration of the laboratory equipments. Sondergeld et al. (2010) developed a mineralogical method to calculate the rock brittleness index. But there still is no uniform criterion for brittle minerals. The quartz, feldspar and carbonate are often regarded as brittle components. However, the feldspar minerals are relatively not brittle like quartz and carbonate. Generally, the most brittle rock has the most quartz and carbonate content but least clay content. The higher the magnitude of brittleness index, the more brittle is the rock (Goktan and Yilmaz, 2005).

Though there are many methods to evaluate the rock brittleness (Goktan and Yilmaz, 2005; Guo et al., 2015), two common ways were generally adopted to define the brittleness index. One way is to calculate the brittleness index in terms of the proportion of brittle minerals (e.g.quartz or carbonate), and the brittleness index can be expressed as follows (Eq. (1), (2) and (3)(on condition that carbonate is treated as the brittle minerals like quartz).

$$BI1 = QZ / (QZ + Car + Clay) \times 100 \% \qquad (1)$$

$$BI2 = Car / (QZ + Car + Clay) \times 100 \% \qquad (2)$$

$$BI3 = (QZ + Car) / (QZ + Car + Clay) \times 100 \% \qquad (3)$$

In which BI1, BI2 or BI3 is the brittleness index, Qz is quartz and feldspar (plagioclase and K-feldspar) content, Car is the carbonate content, and Clay is the total clay content by weight. The scholars generally adopt the Eq. (1) when the quartz content is high in mudstone. On the contrary, the Eq. (3) may be taken when the carbonate content is relatively high. In the comparison of quartz and carbonate content in mudstone caprock of the research area, the author is inclined to adopt the Eq. (3) according to the ternary diagram of the mineralogy of seven wells.
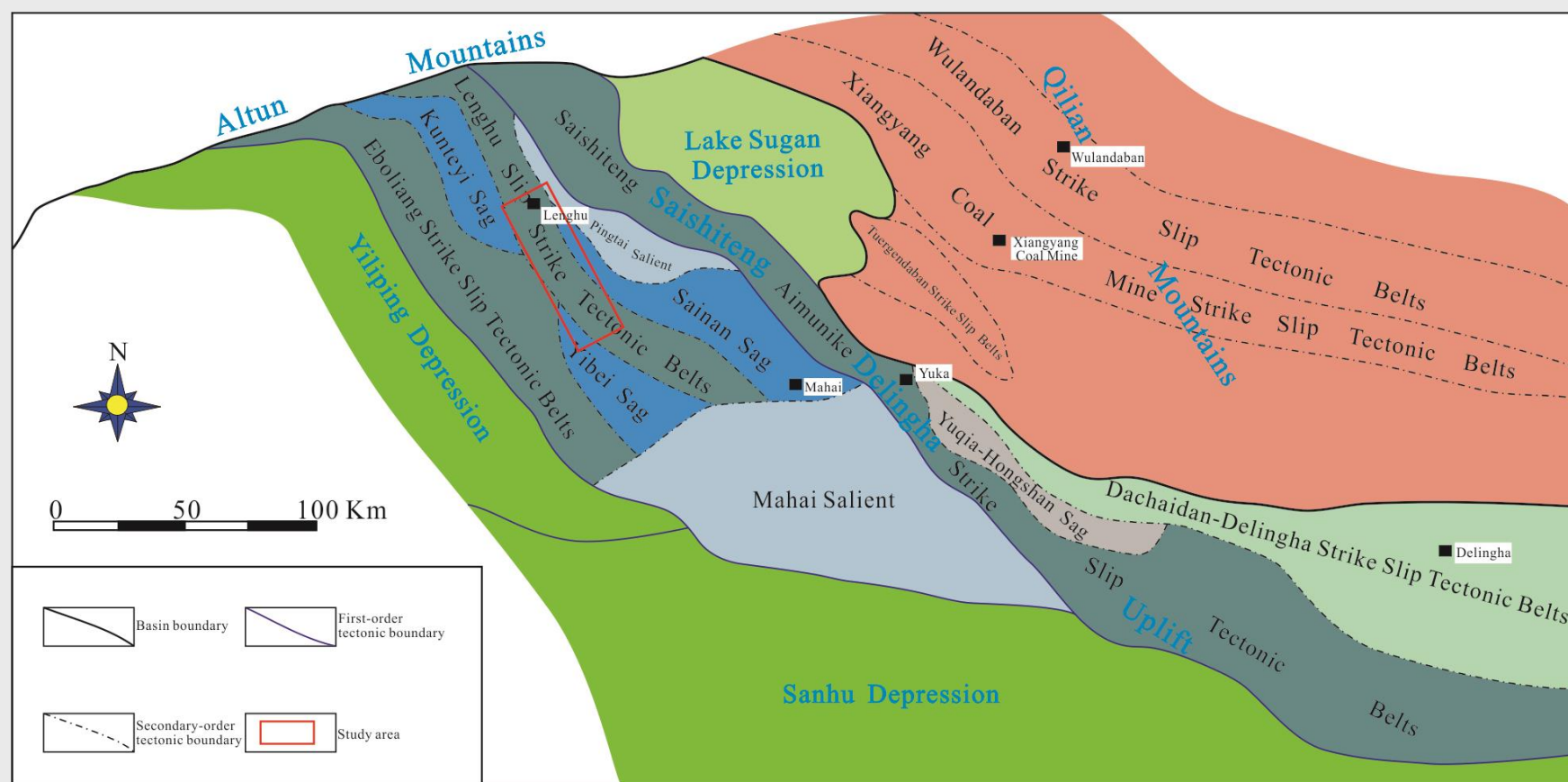


**Figure 1.** Location of research area



**Figure 2.** X-Ray Diffractometer



**Figure 3.** Core samples

The research area (Fig 1) is located in northern margin of Qaidam basin, China. With the research object of Tertiary mudstone caprock in northern margin of Qaidam basin, core samples (Fig 2.) of mudstone were taken from several significant wells. All samples were crushed for whole-rock X-ray diffraction and whole-rock geochemical analysis. Mineral X-ray Diffraction (XRD) analysis was performed at the Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education in China University of Geosciences to obtain semi-quantitative mineralogical data (clay, quartz, carbonate, etc.) and to identify the clay mineral species, I/S mixed-layer ratio, and the content of matrix and cements.

**Table 1.** Mineralogy determined by X-ray diffraction of mudstone in northern margin of Qaidam basin.(Partial list of data because of limited space)

| Well | Sample | Depth | Whole rock mineralogy (weight %) | | | | | | | | | |
|------|--------|-------|--------|-----------|-------------|--------|----------|---------|-----------|--------|-----------|
| | | | Quartz | K-feldspar | Plagioclase | Calcite | Dolomite | Siderite | Anhydrite | Augite | Total clay |
| L89 | 1 | 1216.2 | 31.8 | 5.3 | 19.1 | 15.1 | | | | 2.9 | 25.9 |
| L89 | 2 | 1229.0 | 46.5 | 2.6 | 18.7 | 9.4 | | | | 1.0 | 3.3 | 18.4 |
| L89 | 3 | 1229.5 | 41.1 | 3.0 | 15.2 | 5.5 | 7.5 | | | | 3.3 | 24.4 |
| L89 | 4 | 1218.1 | 19.2 | | 10.5 | 11.2 | | 0.9 | 4.3 | 3.9 | 49.4 |
| L89 | 5 | 1221.1 | 28.5 | 1.8 | 8.3 | 3.6 | | 0.8 | | | 57.0 |
| L89 | 6 | 1226.6 | 26.1 | 2.2 | 10.9 | 9.3 | | | | 5.4 | 45.6 |
| L89 | 7 | 1241.6 | 35.2 | 1.5 | 12.1 | 15.2 | | | | | 36.0 |
| L89 | 8 | 1244.7 | 32.0 | 6.8 | 11.8 | 7.4 | | | | 4.2 | 37.7 |
| Y2 | 9 | 1210.8 | 20.7 | 4.4 | 7.6 | 24.2 | | | 1.7 | | 41.3 |
| Y2 | 10 | 1211.7 | 17.6 | 1.7 | 6.3 | 21.9 | | 5.0 | 1.6 | 3.7 | 42.1 |
| Y2 | 11 | 1212.5 | 26.1 | 2.9 | 7.4 | 14.8 | | | 2.1 | 4.0 | 42.7 |
| Y2 | 12 | 1218.0 | 25.6 | 1.3 | 8.5 | 11.1 | | 1.3 | 3.0 | 5.3 | 43.9 |
| Y2 | 13 | 1412.7 | 19.3 | 2.6 | 9.0 | 4.9 | 37.5 | | | 2.4 | 23.4 |
| Y2 | 14 | 1415.4 | 16.6 | 2.9 | 4.8 | 8.7 | 48.7 | | | | 18.3 |
| Y2 | 15 | 1419.8 | 23.1 | 2.3 | 9.7 | 8.6 | 14.1 | | 0.4 | | 41.8 |
| Y2 | 16 | 1422.3 | 27.2 | 5.0 | 10.9 | 23.5 | | | 4.8 | | 28.7 |
| Y2 | 17 | 1422.7 | 19.0 | 2.0 | 7.8 | 6.7 | 39.7 | | 1.1 | 1.9 | 21.8 |

The well-log data were collected from Qinhai Oilfield Company of CNPC. The log measurements common to the wells comprise the conventional open-hole suites (the gamma ray (GR), photoelectric absorption cross section index (Pe), compensated neutron log (CNL), bulk density (DEN), and resistivity log (RT)) and spectral gamma (contents of potassium (K), thorium (Th) and uranium (U)). Core descriptions were correlated to well logs by correlating the GR signature with the core description to obtain the best match between core features and the well logs.
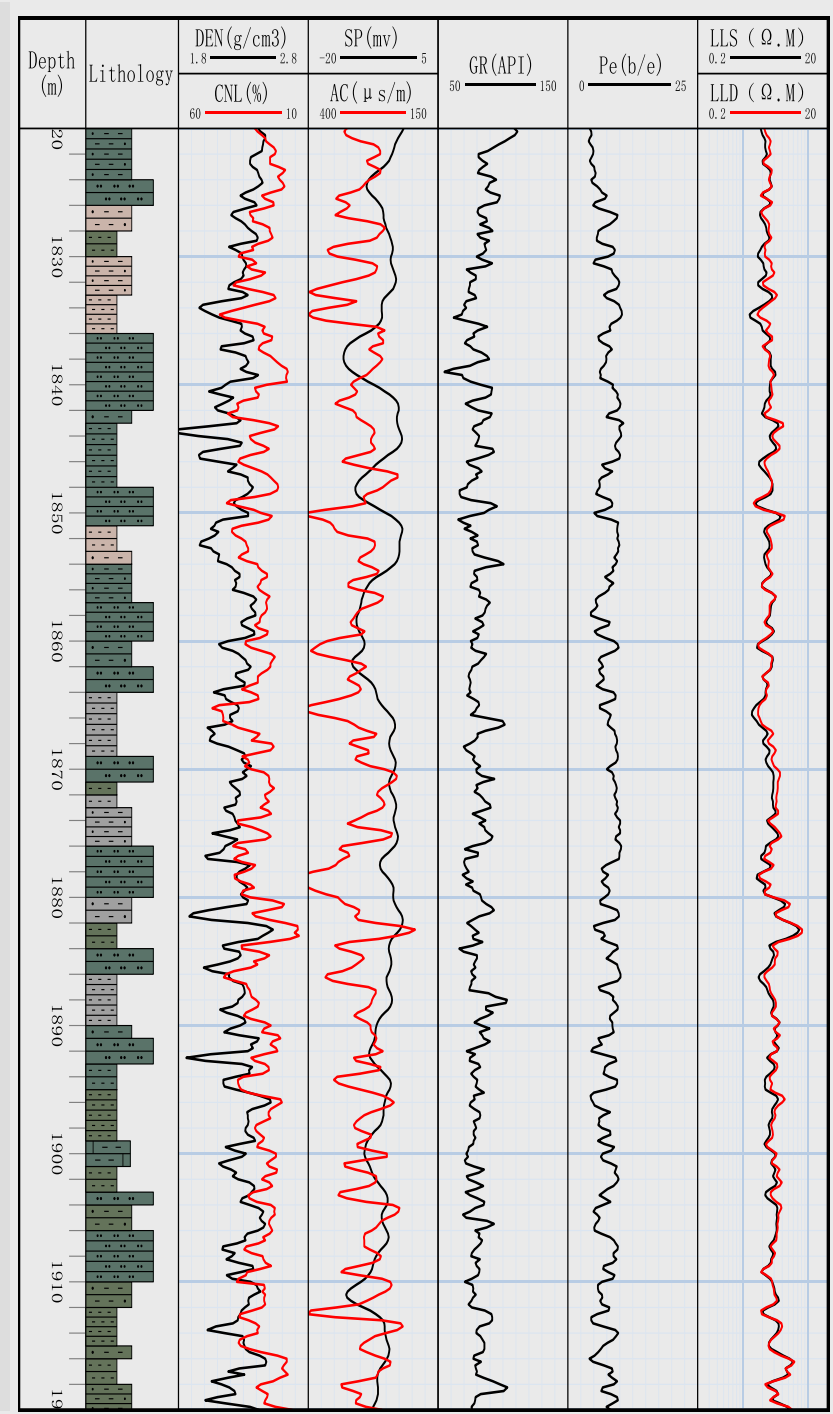


**Figure 4.** Typical well-log characteristics of mudstone caprock.

## RESULTS

Fig. 5 is the ternary diagram of quartz, carbonate, and clay percentage summary from XRD data for mudstone. This diagram suggests three minerals content and quartz and carbonate content is relatively high. So It is necessary to consider carbonate as a brittle mineral.

Fig. 6 shows that quartz content is lowest mineral in each formation.
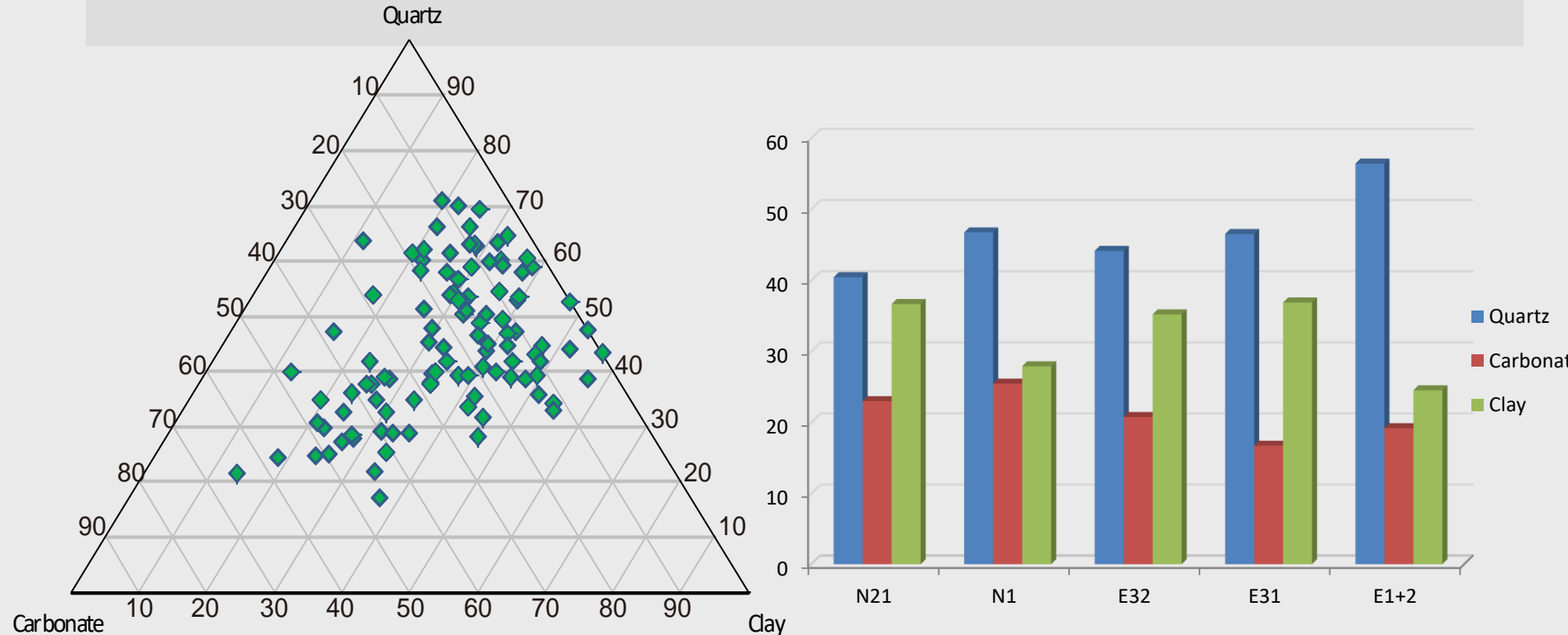


**Figure 5.** Ternary diagram of mineral composition. **Figure 6.** Mineral histogram .

The Fig. 7 indicates that both B1and B2 are positive correlation with B3. Especially, B2 and B3 have a better correlation. The same rule is suitable for well Y2 and the correlation index $R^2$ is 0.85. So the authors are inclined to take B3 as brittleness index to evaluate the mudstone in research.
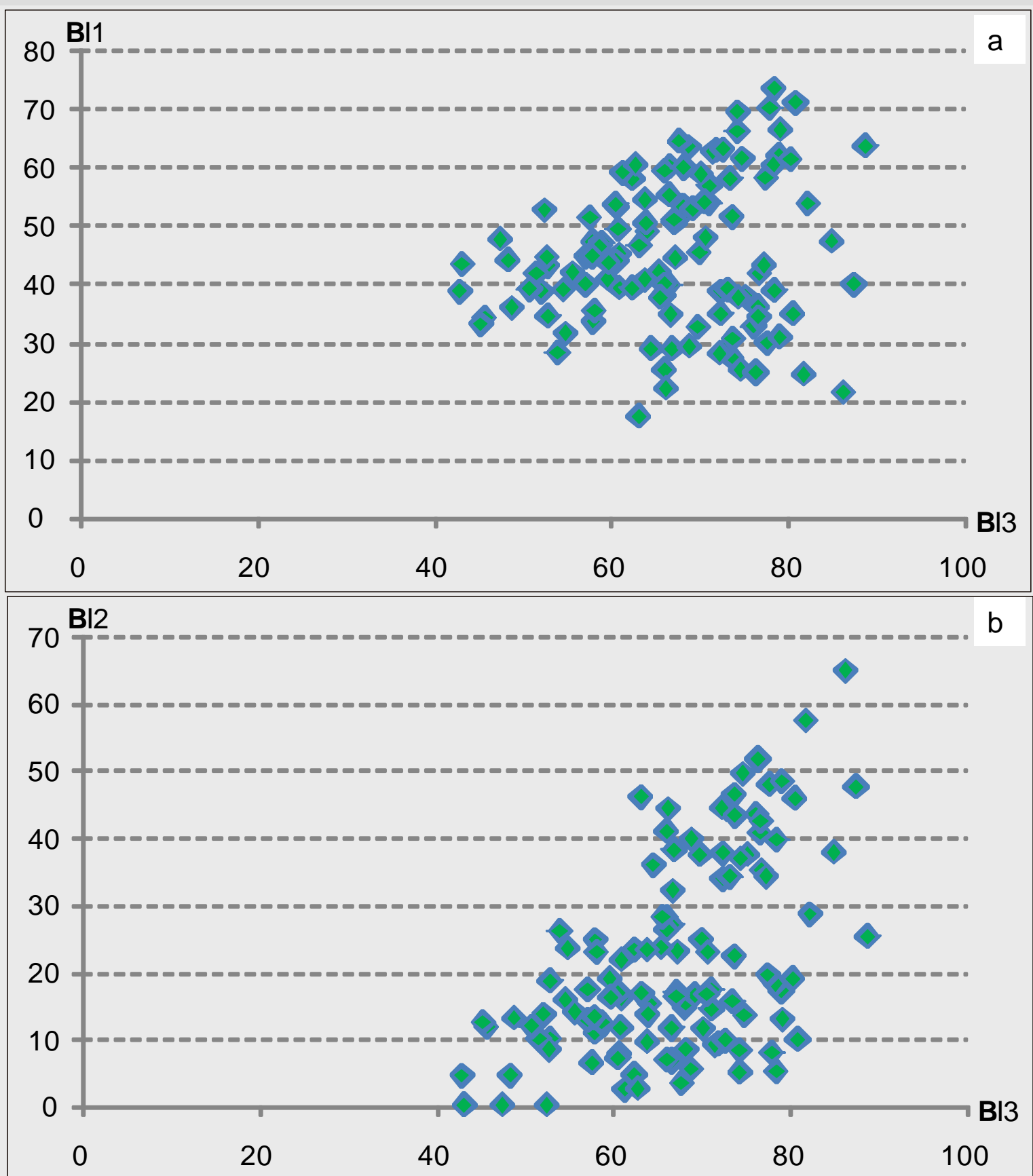


**Figure 7. a:** plot fo BI1versus BI3; **b:** plot of BI2 versus BI3.

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**Figure 7.** c:plot of BI1 versus BI3 in well Y2; d: plot of BI2 versus BI3 in well Y2.

Brittle rock usually presents high brittle minerals content and/or low clay content. The brittleness index in terms of mineralogy brittleness index could easily be calculated using brittle mineral content.. However, the XRD data could not be collected in every well due to the high expense. Predicting the brittleness index by taking full advantage of conventional well logs is of great importance for the brittleness evaluation in wells without dipole acoustic logs.

As discussed above, the detailed brittleness index could be calculated from XRD data. The mineralogical brittleness index by XRD could serve as "standard". But the XRD result derived from core samples is not continuous; therefore, the calculation of brittleness index by conventional logs is of great importance. In this section, the relationship between mineralogy brittleness index and conventional logs is established to serve as the prediction model.

 In this section, the point-to-point log response characteristics of the core samples on which the XRD analysis was performed are summarized. For each core sample, the corresponding values of wireline logging measurements (with core-to-log depth matched) are read from the log curves. The model for estimating the brittleness index using conventional log suites is established by regression analysis.



**Figure 8.** Plot of BI3 versus GR (a) and the ratio of GR to Pe (b) in well Y2

## DISCUSSION

Statistical regression analysis was carried out to find the relations between brittleness index values and conventional well logs, including GR, Pe, CNL, DEN and SP. It is seen that there is no obvious relation between the brittleness index values and any single well log curve (like GR, Fig.8a). Only by translating brittleness index to the combination of two or even more log curves, the prediction model of brittleness index could be established.

As we know, GR logs and Pe logs are sensitive to the variation in lithology and mineralogical composition. Higher GR counts are commonly attributed to mudstone. The Pe values of various minerals are largely different, and the effect of fluids on PE readings is very small. Base on above analysis, GR log and combined with Pe logs are selected to be used to estimate the brittleness index of shaly sandstones.

The ratio of GR values (API) to Pe readings (b/e) seems to be a sensitive indicator for the variation in mineral composition or even the brittleness index. As can be seen from Fig. 7b, the content of brittleness index (BI3) shows a strong negative correlation ($R^2$=0.76 with the GR/Pe values (Fig. 7b) between GR/Pe and brittleness index (BI3) from XRD results. Therefore, the estimated model has the potential to be used for the brittleness index prediction using conventional log suites (GR and Pe).
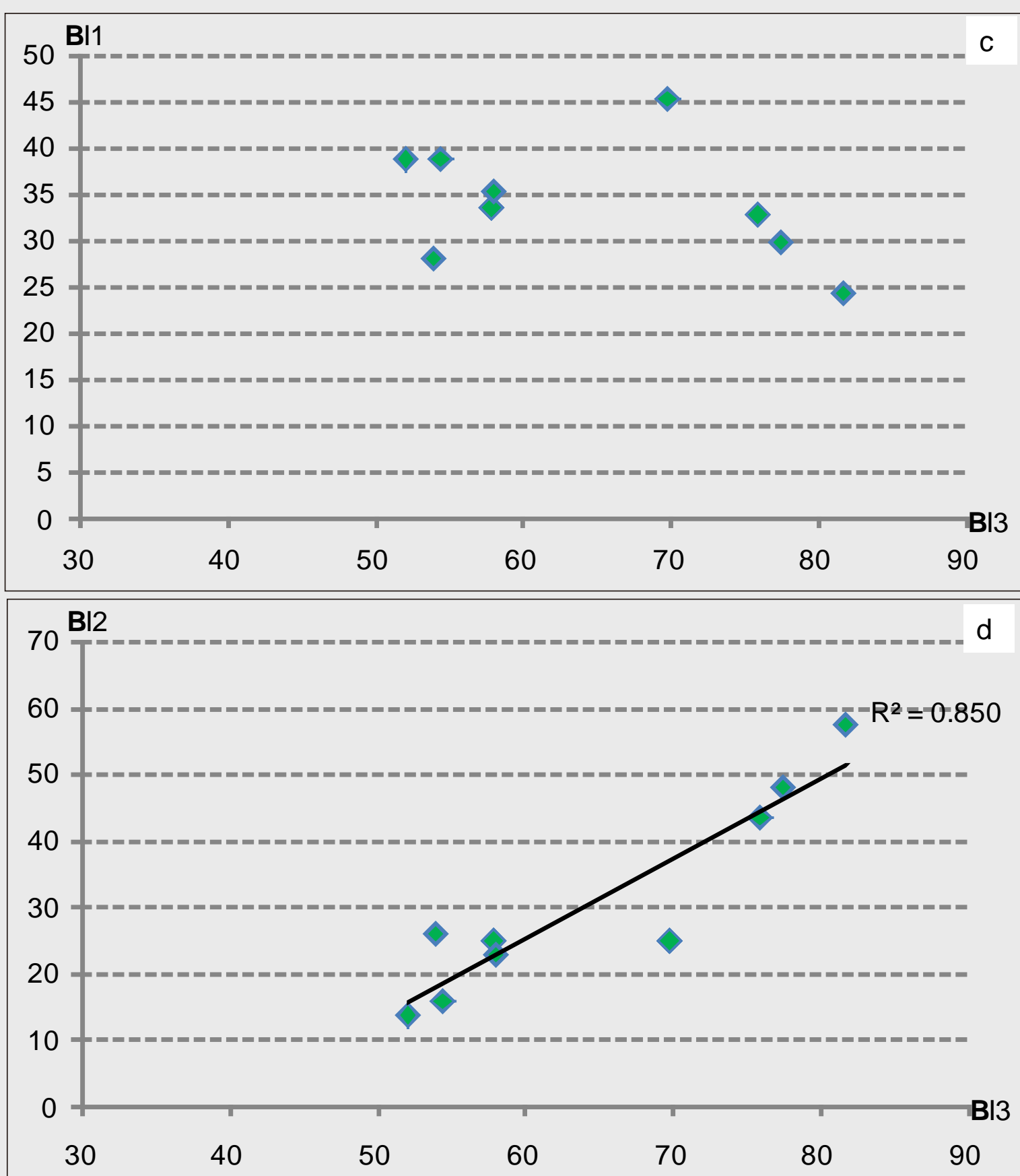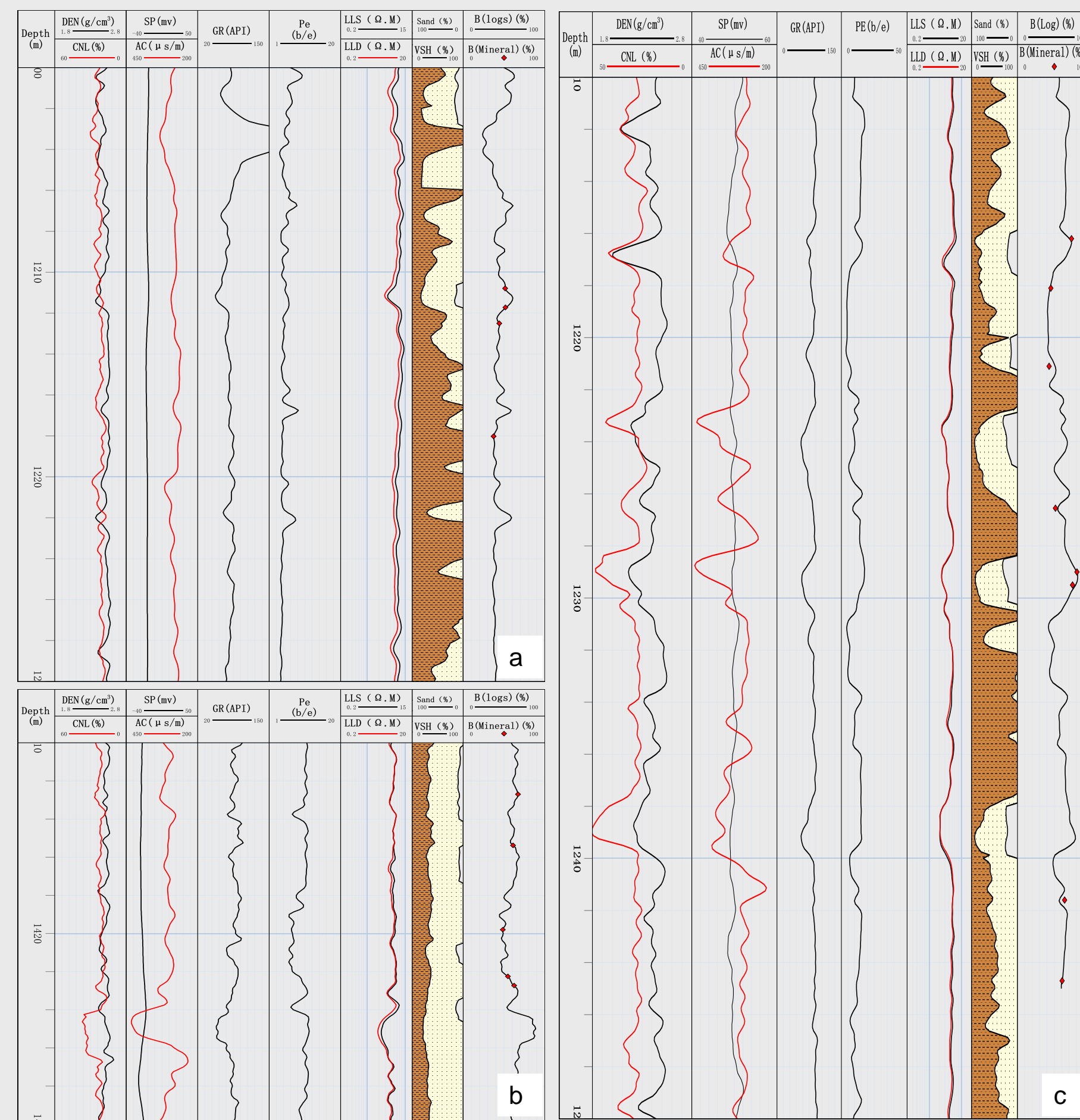


**Figure 9.** Calculation of brittleness index in well Y2 (a, b) and L89 (c) using brittle Mineral and logs data

As is evident from Fig. 8, significant relations exist between brittleness index and GR/Pe values; therefore, the mineral brittleness index can easily be estimated from relations (Fig. 8; $y = 219x^{-0.51}$). To verify the accuracy of the predictive model of brittleness index, a blind test was administered to two wells with another well (Fig.8c). The brittleness index (BI) in well L89 was calculated using the relationship presented in Fig. 8b. The result demonstrates that the tow brittleness indeces calculated from mineral brittleness and conventional suite logs match well in Fig. 9c. As is evident from Figs. 9 and 10, the mineralogical brittleness index (BI2) is generally consistent with the geomechanical brittleness index (BI3), and that the calculated brittleness index from conventional logs (GR/Pe) is reliable. For wells without core samples, brittleness index can be easily estimated by conventional well logs.
The reliability of the brittleness index estimation model using conventional well logs is also verified by comparing it with other factors in evaluating mudstone caprock. A higher brittle mineral content leads to a higher mineralogical brittleness index and thus a better fracturing potential. Therefore, a high brittleness-index layer is likely to be naturally fractured and will probably lose oil and gas as caprock.

The brittleness of different formations mainly ranges from 60%-70%, among which Shangganchaigou Formation ($N_1$) and Lulehe Formation ($E_{1+2}$) are the highest while Xiaganchaigou Formation ($E_5{}^2$) is the lowest. The brittleness in different districts varies, the highest of which are in Lengdong and Lenghu No.5 structure belt, about 60%, while the brittleness of Lenghu No.4 structure belt is lowest around 47%. Therefore, $E_5{}^2$ brittleness is comparatively low so that natural fractures are not easy to form. Besides, the brittleness of Lenghu No.4 structure belt is lower; so it is more difficult for natural fractures to form than in the other part of research area. Thus, $E_5{}^2$ caprock in Lenghu No.4 structure belt could be high-quality caprock.
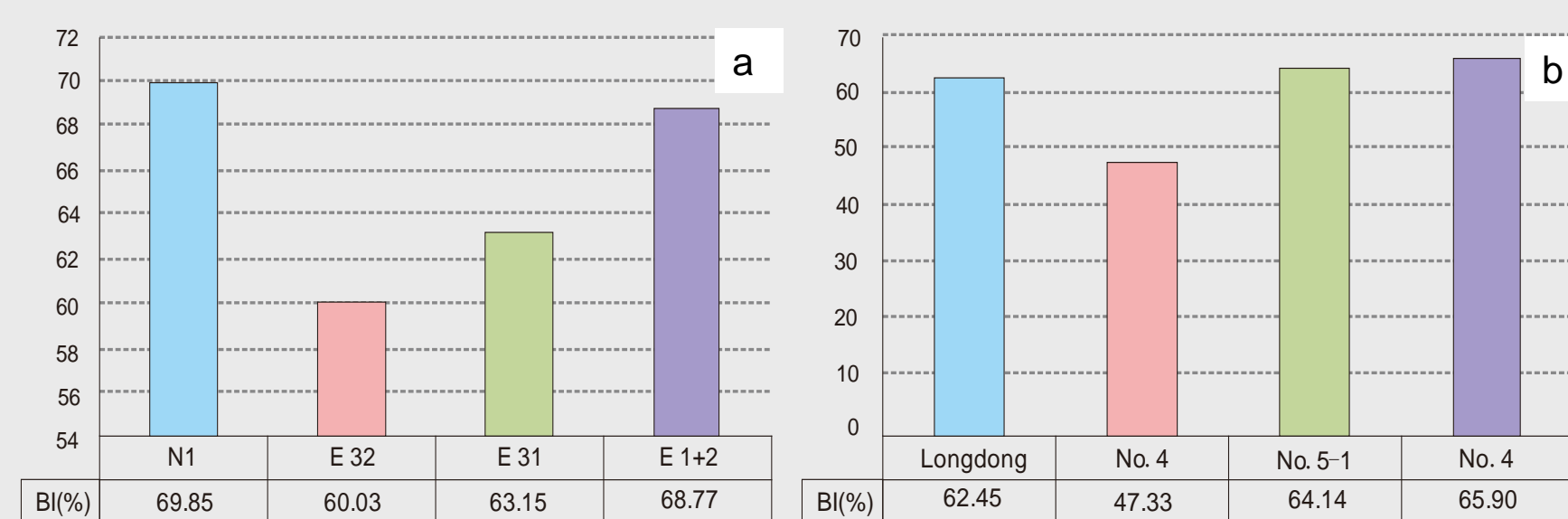


**Figure 10.** Characteristic of brittleness index in different formations(a) and areas(b).

## CONCLUSIONS

1. The ratio of GR to Pe is sensitive to the variation in mineral composition and the brittleness index. The prediction model of brittleness index using GR/Pe values when it is corrected for mineralogical brittleness from XRD data is reliable. Therefore, the brittleness index could be calculated using conventional well logs without array sonic logs.

2. High brittleness index means a better ability to form fractures and difficult to heal natural fractures. The favorable mudstone caprock is characterized by low brittleness. So it is thought that brittleness index should be regarded as a new parameter to evaluate the healing capacity of mudstone caprock.

## ACKNOWLEDGEMENT