Introduction

The Sichuan Basin in China is very prolific, producing from multiple Precambrian to Mesozoic reservoirs. By the end of 2008, a cumulative gas reserve of 1.72 tcm (60.74 tcf) was confirmed. The recently discovered Anyue gas field, with a gas reserve of 0.66 tcm (23.31 tcf), indicates a huge potential in the basin. No significant discovery has been made in Jialingjiang (T1j) Formation because of the complicated lithology association and facies distribution.

The T1j Formation in the central Sichuan Basin is a typical mixed system consisting of carbonates, siliciclastics, and evaporites. Examples of mixed siliciclastic-carbonate-evaporite systems were documented in Kiritimati, southeastern Tunisia, Eastern Alps, and Wyoming and Montana (Schoonmaker et al., 1985; Ismail and M’Rabet, 1990; Bechstädt and Schweizer, 1991; Parcell and Williams, 2005; Chiarella et al., 2016).

Outcrops, cores, and well data are commonly used to characterize mixed-sediment systems (Mitchell et al., 2001). To our knowledge, however, seismic data mainly have been analyzed based on their profile seismic-facies characteristics.

Multiple high-quality 3D seismic surveys have been conducted in well-controlled areas in the Sichuan Basin, which offers an excellent opportunity to advance seismic interpretation of mixed depositional systems. For this study, a 2,500 km², high-quality 3D seismic survey with a bin size of 20×20 m is available in the Gaoshiti–Moxi area. The dominant frequency is around 30 Hz in the target T1j Formation. There are 31 wells with wireline logs in the study area, including bulk density, acoustic, and gamma ray. Conventional cores were collected from four wells to understand reservoir properties such as porosity, permeability, density, and mineral composition. An integrated workflow was carried out to predict lithology in a mixed siliciclastic-carbonate-evaporite system of the T1j Formation.

Method and/or Theory

An integrated seven-step approach that combined core analysis, wireline-log interpretation, and seismic attribute analysis was applied to investigate types of lithologies:

- **Step 1:** Core samples from carbonate, anhydrite and siliciclastic rocks in the three cored wells were analyzed in the laboratory for porosity, permeability, density, and mineralogy composition.
- **Step 2:** GR, AC, and RHOB wireline logs in the three cored wells were calibrated using core measurements. The calibrated relationship between lithologies and logs was used to interpret anhydrite, siliciclastic rocks, and carbonates from wireline logs. Contents of these lithologies were calculated in all 31 wells.
- **Step 3:** With the synthetic tie between the logs and seismic data, the top and base of the target zone (T1j2L submember) were tracked on the -90° phase seismic data.
- **Step 4:** Interval seismic attributes were generated for the T1j2L submember.
- **Step 5:** A group of seismic attributes were selected according to their correlation coefficient with lithology contents in wells. Then, PCA was performed on the selected seismic attributes. The first two most-significant components were chosen as independent variables for regression analysis with measured lithology contents in wells.
- **Step 6:** The regression equation was used to calculate the contents of anhydrite, carbonates, and siliciclastic rocks from seismic data.
- **Step 7:** The lithofacies distribution of the T1j2L submember was estimated by interpreting an RGB blending map of the contents of anhydrite, carbonates, and siliciclastic rocks.

Estimation of lithology contents in wells

Three cored wells were selected for wireline-log interpretation in order to estimate the percentage of the end members of the lithology, i.e., anhydrite, dolostone, limestone and siliciclastic rocks. The core-measured density is in good agreement with the wireline-log
density. Mineral contents were calculated from the element-composition data by chemical analysis. Contents of CaO, MgO, SO₃, Fe₂O₃, Al₂O₃, and acid-insoluble material in a rock were measured and then transferred into contents of calcite, dolomite, and anhydrite. For example, in the M206 well (Figure 1), the high percentage of calcite, dolomite, anhydrite, and clay minerals were used as proxies for limestone, dolostone, anhydrite rock, and siliciclastics, respectively. Then, core-measured density and porosity—and log values of GR, RHOB, AC, and AI—were correlated with each lithology.

Anhydrite distribution

Twenty-one seismic attributes whose correlation coefficients are over 0.4 were selected for PCA. The first two principle components were used as independent variables to correlate with anhydrite contents in wells. Seismic mapping of anhydrite content in the study area was achieved in the 3D survey. Anhydrite increases from southwest to north, fitting with the general trend in the well map (Figure 2a). However, the seismic map reveals many more details of lateral variation of anhydrite content (Figure 2b).

Siliciclastic rock distribution

After correlating to siliciclastic rock content in wells, 18 seismic attributes with a correlation coefficient larger than 0.3 were selected to perform a PCA. The first two principle components cover 88.6% of the total information. Values of the two components at well locations were correlated to the siliciclastic rock contents in 31 wells. Distribution of
siliciclastic rocks was first revealed by interpolating well data and then calculated by seismic data. It decreases from south to north (Figure 3).

![Figure 3. Siliciclastic-content distribution calculated by (a) well data, and (b) PCA method. White arrow indicates interpreted fluvial channels.](image)

**Carbonate rock distribution**

Seven seismic attributes whose correlation with carbonate rock contents is bigger than 0.3 were selected from the 53 seismic attributes to perform PCA. The first two principle components contain 93.5% of the total information, and were used to relate seismic attributes to carbonate rock contents in wells. Distribution of carbonate rocks in the well-based map shows a decrease of content from the southwest and northeast to the central area (Figure 4a). In general, the PCA-derived results (Figure 4b) show a similar trend to that in the well-based map.

![Figure 4. Carbonate-content distribution calculated by (a) well data, and (b) PCA method.](image)

**Facies analysis**

Knowing the distribution of anhydrite, carbonate, and siliciclastic rocks, the sedimentary lithofacies was mapped by RGB blending method (Figure 5). The study area can be divided into five zones (I–V). In zone I, siliciclastic rocks are dominant. In zone II, lithofacies are mainly a mixture of carbonate and siliciclastic rocks. Zone III is characterized by carbonate rocks and rare to minor evaporites and siliciclastic rocks. In Zone IV, it consists of mixed anhydrite and carbonate deposits with a rare quantity of siliciclastics. In zone V, anhydrite and siliciclastic content decrease with carbonate increase, indicating an influence of open marine environment.
Conclusions

Lithologies in the T1j2L submember in the study area include anhydrite, tight dolostone, porous dolostone, limestone, and siliciclastic rocks. With wireline-log and core analysis, anhydrite and siliciclastic rocks can be separated from carbonate rocks by RHOB and GR logs in the T1j2L submember.

AI decreases from tight dolostone, anhydrite, limestone, and porous dolostone to siliciclastic rocks, with various overlapping. For thin-bed sequences in the study area, it is difficult to differentiate between anhydrite, siliciclastic, and carbonate rocks by using any single seismic attribute.

PCA is capable of condensing information from multiple seismic attributes to a small number of principle components. Compared to the original seismic attributes, PCA of multiple attributes leads to more-accurate mapping and prediction of lithofacies in the study area.

References


