INTRODUCTION

The Nanpu Oilfield in Bohai Bay Basin is discovered by PetroChina Jidong Oilfield company in 2002. The main hydrocarbon-bearing stratigraphic units are the Eocene Shahejie and Paleogene Dongying Formation. Fractures control the subsurface fluid flows. Fracture detection and evaluation (type, frequency, state, and orientation) via petrophysical logs are important for the production and development plans of oilfields. In addition, the determination of in-situ stress is crucial for understanding the subsurface fracture system, which is essential for exploration and exploitation of subsurface hydrocarbons.

Fracture detection and in-situ stress determination via well logs are important for exploration and exploitation of subsurface hydrocarbons. Cores, thin sections, and image logs are used to describe and interpret the subsurface fractures and in-situ stress in the Paleogene Dongying sandstones in Nanpu Sag, Bohai Bay Basin, China. The maximum horizontal stress (SHmax) indicates a nearly east-west trend according to the borehole breakouts and drilling-induced fractures. Natural fractures in the Dongying sandstones are classified into: (1) open fractures and (2) closed fractures. The cement-filled (closed) fractures are commonly detected by image logs as bright discontinuous sinusoidal waves due to resistive filling materials, while the open fractures are evident on image logs appearing as dark sine waves. The open fractures are of dominantly high dip angles, and the rose diagrams confirm the presence of two sets of fractures: northwest-southeast and northwest-southeast orientation. Fractures with strikes approximately parallel to the SHmax have good connectedness, making a significant contribution in hydrocarbon production. In addition, the oil-bearing layers are mainly associated with the intervals with open fractures. The presence of natural fractures provides important pore spaces and fluid flow conduits. Insights can be provided into the subsurface fracture (natural and induced) detection and characterization using image logs.

KEYWORDS
Dongying Formation, fracture, image logs, in-situ stress, Nanpu Sag
FIGURE 1 Location map of the Nanpu Sag in Bohai Bay Basin (A) within China (B) and the structural belts of Nanpu Sag (C) of the Nanpu Sag.
stress state is important for wellbore stability and oil recovery enhancement.\textsuperscript{16-18} The oriented and high-resolution image logs are the principle specialized tools for fracture detection and present-day stress evaluation.\textsuperscript{5,19-23}

This study utilizes the image logs (calibrated with core) for in-situ stress determination and fracture detection and characterization in Dongying Formation of Nanpu Sag. The fracture state is surveyed through core data, thin sections, and routine core analysis. The image logs are processed and interpreted in terms of cross beddings, bedding planes, and fractures. The in-situ stress directions including $S_{H_{\text{max}}}$ and $S_{H_{\text{min}}}$ (minimum horizontal stress) are determined by separating the types of fractures (natural fracture and induced fracture) and rock failure (breakouts). Then the natural fracture states and attitudes are investigated through picking out the fracture traces on image logs and calculating the fracture parameters. Rose diagrams of natural fractures and induced fractures are used to investigate the fracture

\textbf{FIGURE 2} Fractures observed in the Dongying sandstones of Well N23-2704 in the Nanpu Sag. The red arrow is high-angle fracture, the blue arrow is vertical fracture, and the yellow is horizontal fracture.
FIGURE 3 Thin section images showing the microfractures in the Paleogene Dongying Formation in Nanpu Sag. A, N1, 2631.14 m; B, N1, 2391.75 m; C, N11-E4-X508, 2778.15 m; D, N208, 2397.6 m; E, N1, 2626.35 m; F, N208, 397.6 m

effectiveness to better understand the links between fracture and stress, how that contributes to enhanced flows from producing wells. Utilizing the image logs calibrated with cores provides important insights into the subsurface fracture and in-situ stress evaluation.

2 | GEOLOGIC SETTINGS

The Nanpu Sag is located at the northeastern Huanghai Depression in the north Bohai Bay Basin (Figure 1). The Bohai Bay Basin is a Mesozoic-Cenozoic rift basin which displays a “lazy-Z” pattern. The Nanpu Sag is a typical dustpan-shaped faulted sag (Figure 1). The Nanpu Sag experienced a rifting stage during the Paleogene and then a postrifting stage since Neogene. Eight structural units including the Nanpu No.1 to No.5 structural belts, Beipu, Gaoliu, and Laoyemiao oilfields are divided in the Nanpu Sag (Figure 1).

The Cenozoic stratigraphic units in the Nanpu Sag include the Eocene Kongdian (Ek), Paleogene Shahejie (Es), Paleogene Dongying (Ed), Miocene Guantao (Ng), Minghuazhen (Nm), and the Quaternary Pingyuan Formation (Qp) (Figure 1). The Dongying Formation is in unconformable contact with the underlying Shahejie Formation. The lithology of Dongying Formation in Nanpu Sag consists of mudstones, fine to medium-grained sandstones, peppy sandstones, and conglomerates. The depositional facies are interpreted by many scholars as alluvial, braided-fan delta, beach-bar as well as gravity flows (sandy debris flow, slump, and turbidite), and lacustrine facies. The structural (faulted block) and structure-related lithologic traps are the principle traps for hydrocarbon accumulation in the Nanpu Sag.

3 | MATERIALS AND METHODS

Direct fracture observations were based on cores, which were taken from 8 wells. Routine core analysis data of 300 core plug samples were collected from PetroChina Jidong Oilfield Company. Routine core analysis was also performed on the samples under various net confining pressures (2.5, 3.5, 5.0,
7.0, 9.0, 11.0, 15.0, and 20.0 MPa, respectively). The thin sections were impregnated with blue resin to highlight pores/fractures and were observed using a Leica microscope under plane and cross-polarized light.

The conventional logs include sonic interval transit time (AC), caliper (CAL), neutron porosity (CNL), bulk density (DEN), natural gamma ray (GR), and resistivity logs (Rxo, RT). Image logs are collected from 6 wells drilled with water-based muds: N1-4, N1-5, N1-29, N1, N2-1, and N208. Electrical image logs are widely used for the structural analysis and sedimentary characterization.5,10,20,41-43

The raw Schlumberger’s FMI (Fullbore Formation MicroImager) digital data (DLIS data) were processed into the static and dynamic images using professional software (GeoFrame) through the processes of speed and eccentricing correction, and normalization.10,43 FMI contains eight orthogonal pads, and each includes 24 electrodes, therefore, a total of 192 microresistivity curves can be collected.44

**FIGURE 4** Crossplots of core-measured permeability versus net confining pressures for Sample A and Sample B. Note the declining permeability with confining pressure, indicating that these are stress-sensitive fractures.

**FIGURE 5** In-situ stress state is described by (1) vertical stress (Sv), (2) maximum principal horizontal stress (SHmax), (3) minimum principal horizontal stress (Shmin). The SHmax is parallel to the induced fractures, and Shmin is parallel to the wellbore breakouts.
The FMI imaging tools offer oriented images with a vertical resolution of 5 mm, and a borehole coverage of 80% in an 8.5 inch borehole.43,45-49 The static images can be used for comparison over an entire well, while the dynamic image is used to bring out local detail.50,51

In the image logs, the open fractures display as dark continuous or discontinuous sinusoidal waves and can be manually traced in the software and determined of dip angles and directions.20,50,52 Stress-induced fractures are classified as drilling-induced (tensile- or shear-induced) fractures and wellbore breakouts.43,53,54 The drilling-induced fractures are open mode fractures and appear as vertical fracture oriented at 180° from each other.6,43 Breakouts (wellbore enlargements) are recognized as broad, parallel, dark bands separated by 180° on image logs.43,47

**FIGURE 6** The orientation of the minimum horizontal stress (Shmin) determined from the borehole breakout (N1–4)

4 | RESULTS

4.1 | Fracture observation

Multi-scale fractures with various attitudes and states are detected in the Dongying sandstones. By core observation and thin section analysis, both the macrofractures (visual in core or on image logs)6,55 and microfractures (aperture < 0.1 mm)56 can be observed (Figures 2 and 3). Core provides the most direct method to evaluate subsurface macrofractures.4 Fractures with a wide range of dip angles and apertures are detected by core observation (Figure 2). There are some open fractures not filled with cements (calcite and quartz) and have high dip angles or are horizontal (Figure 2). The open fracture could constitute a favorable natural fracture system in the fault-block reservoirs. The opening-mode fractures in Figure 3 are nearly vertical, and
the high-angle or vertical fractures will make a significant contribution in hydrocarbon production.\textsuperscript{10,43,57} The microfractures are strongly related to the core-observed macrofractures,\textsuperscript{44} and they can also act as major pathways for fluid flow (Figure 3).\textsuperscript{4} Occasionally the bitumen can be found to be residued in the microfractures under microscopic observations (Figure 3E,F). Routine core analysis performed under various net confining pressures reveals that permeability is significantly decreased with the increasing net confining pressures, which implies the closure of some microfracture systems under high net confining pressures (Figure 4).

\subsection*{4.2 In-situ stress analysis}

In-situ stress refers to the present-day natural stress related to the tectonic and gravitational stress.\textsuperscript{14,43,58,59} In a vertical well, the orientation of the minimum (Sh\textsubscript{min}) and maximum (Sh\textsubscript{max}) horizontal stress can be determined from borehole breakouts and drilling-induced fractures assuming one of the principal stresses to be vertical (Figure 5).\textsuperscript{16,43,47,59-65} Borehole breakouts (wellbore enlargements) are easily to be picked out and are recognized as broad and dark bands and are suggested to be parallel to the orientations of Sh\textsubscript{min} (Figure 5). The orientation (rose diagram) of the breakouts in Figure 6 is determined approximately a north-south trend (170°-180°), and this suggests a Sh\textsubscript{max} orientation of about 80°-90° (Figure 6). The drilling-induced tensile fractures are only occasionally observed in this study. The average trend of the drilling-induced shear fractures (en-echelon fractures), which formed parallel to Sh\textsubscript{max}, are approximately east-west (80°-90°) in all six wells Figure 7. Therefore the direction of the Sh\textsubscript{max} in the Dongying Formation in the Nanpu Sag was measured to be 80°-90° (Figure 6 and 7).
4.3 Well log expressions of open fractures

Sealed fractures, which are filled by resistive calcite cements, are common in Dongying sandstones, and they are displaying as bright continuous/discontinuous sinusoidal waves on the image logs Figure 8. The brighter colors on image logs refer to densely cemented resistive rocks (Figure 8). The sealed fractures have no obvious responses on the conventional well logs. Open fractures are more evident on electrical image logs (Figure 9). In case there are open fractures encountered (water-based drilling muds), the corresponding resistivity in the borehole wall will be reduced since the fractures are filled with conductive muds, and the open fractures will appear as dark sinusoidal waves (Figure 9). Many scholars have revealed that the presences of natural fractures will cause a significant decrease in resistivity (RT, Rxo) and in bulk density (DEN), and will result in an increase in sonic transit time.
(AC) in case of water-based drilling muds.\textsuperscript{10,12,44} The dip angle of the fractures can be indicated by the amplitude of the sin wave, while the dip direction is estimated as the lowest point of the sine wave (Figure 9).\textsuperscript{33,51,67} For instance, the manually traced natural fractures in Figure 9 have a dip direction of 70°-80°, and the dip angle is about 60°-70° (Figure 9). Besides the determination of fracture attitude and state, the image logs can also be used for the calculation of fracture parameters: fracture length (FVTL), fracture aperture (FVAH), fracture porosity (FVPL), and fracture density (FVDC).\textsuperscript{3,6,43,68,69} Image logs of well N208 show that there is mainly one assemblage of natural fractures existing in the Dongying sandstones with a northwest-southeast orientation, as revealed by the composite rose diagram (Figure 10).

5 | DISCUSSION

The cross beddings, bedding planes, induced fractures, and conductive and resistive fractures, which can be observed on the image logs, are manually picked out in the GeoFrame/Techlog software (Figures 10, 11). In addition, the fracture parameters (FVTL, FVAH, FVPL, and FVDC)
are calculated by correlating the microresistivity curves with the Rxo (Figure 10). Fractures with strikes approximately parallel to (<30°) the SH$_{\text{max}}$ are suggested to exhibit open state and have a good connectivity even are deeply buried. Fracture image-log observations in Well N208 reveal that the northwest-southeast set is the most abundant natural fracture set in the Dongying sandstones (Figure 10). However, the orientation of the SH$_{\text{max}}$ of Well
N208 is determined as east-west direction (Figure 10). The composite rose diagram reveals that the strikes of the open natural fracture trends are not consistent with the SH$_{\text{max}}$, therefore, the natural fractures are suggested to have a relatively low aperture and poor connectivity. The resistive (closed) fractures also have a northwest-southeast trend (Figure 10).

The orientation of SH$_{\text{max}}$ in N1-4 Well is determined as northeast-southwest (45°-60°), which is a little different from the N208 Well (Figure 11). From the composite rose diagram, it can be concluded that the natural open fractures have a dominant strike of northeast-southwest, which is consistent with the SH$_{\text{max}}$, therefore, the natural conductive fractures are suggested to have large fracture aperture and could significantly enhance hydrocarbon production (Figure 11).\textsuperscript{16,43,70} Well test and production data reveal that the intervals within 2688-2722 m have a daily oil production of 121.3t after blowout through a 9.53 mm choke, and image logs confirm the presence of natural fractures of which the orientations are nearly parallel to the SH$_{\text{max}}$ (Figure 11).

The cross section from LPN1-x242-NP208 reveals that three faults are encountered, and the oil-bearing layers are discontinuously distributed in the wells (Figure 12). The presences of fractures result in the heterogeneous distribution of oil layers. Additionally, the image-log fracture observation confirms that fractures are commonly detected in the Well NP 208, which is adjacent to the fault plane. Furthermore, the oil-bearing layers, which are evidenced by the oil test data, are mainly associated with the layers containing fractures. The three intervals in Figure 12 are layers with natural (open) fractures, and they are all oil-bearing layers. Especially, the middle layer, which is highly fractured zone according to image logs, is the important hydrocarbon-producing zone. Therefore, the presences of fractures help enhance reservoir quality, and they can be important pore spaces and fluid flow conduits.

**FIGURE 11** Evaluation of natural (conductive and resistive) fractures, and induced fractures using image logs (N1-4)
6 | CONCLUSIONS

1. According to the drilling-induced fractures and borehole breakouts, the maximum horizontal stress ($S_{H_{\text{max}}}$) indicates a nearly east-west trend.

2. Natural fractures in the Dongying sandstones are classified into: (1) open fractures and (2) closed fractures. The closed fractures are commonly detected by image logs, while the open fractures appearing as dark sinusoidal waves have high dip angles. The rose diagrams confirm the presences of two sets of fractures: northwest-southeast and northwest-southeast orientation.

3. Fractures with strikes approximately parallel to the $S_{H_{\text{max}}}$ exhibit open state and have good connectedness. The presences of fractures help enhance reservoir quality, and they can be important pore spaces and fluid flow conduits.

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