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Classification and Evaluation Method for Complex Near-Surface Facies in Front of the Longmen Mountains

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Abstract: The near-surface of complex piedmont zones exhibits strong heterogeneity with significant variations in the thickness and velocity of low-velocity layers, which constitute key technical challenges in seismic exploration. This study proposes the concept, connotation and evaluation framework of near-surface facies, establishes a complete classification and evaluation workflow, and accurately divides the study area into 9 categories and 22 types of near-surface facies. The characteristics and spatial variation laws of near-surface facies are clarified from three dimensions, providing technical support for optimizing seismic exploration parameters. This research addresses the exploration challenges in the Longmen Mountains area and offers a valuable reference for similar studies in complex piedmont zones.

Keywords: Longmen Mountains, near-surface facies, classification, seismic exploration, excitation, reception.

INTRODUCTION

The Longmen Mountains and its piedmont zone have experienced multi-stage tectonic deformation, with the extensive development of various thrust-compression structural styles (e.g., imbricate thrust belts) [1-4]. The near-surface conditions and landforms in this area are highly complex and variable, and the thickness and velocity of low-velocity layers show obvious spatial heterogeneity. These features easily induce problems such as static correction errors, energy shielding and seismic wave scattering, thus becoming a bottleneck restricting the advancement of seismic exploration technology [5-6].

Taking the Guanxian-Guangyuan Fault Zone as the boundary (Figure 1), the plain area to its southeast is dominated by Jurassic alluvial fan and Cretaceous-Quaternary facies. In this area, low-velocity layers and velocity-reduction layers are thick, the vertical structure is mainly a three-layer pattern, and the variation in layer thickness is gentle. In contrast, the northern mountainous and canyon areas are characterized by thin low-velocity and velocity-reduction layers (with the velocity-reduction layer absent in some sections), a two-layer vertical structure, and drastic fluctuations in layer thickness. The differences in the vertical near-surface structure lead to distinct propagation paths and energy attenuation laws of seismic waves, which serve as an important basis for the subsequent optimization of seismic excitation and reception conditions.

Based on the above geological characteristics, this study conducts a systematic investigation on the classification and evaluation method of near-surface facies, relying on the seismic acquisition pilot project in the Longmen Mountains area. The concept and connotation of near-surface facies are elucidated, and a technical workflow for the classification and evaluation of near-surface facies suitable for the Longmen Mountains and its piedmont zone is established. The near-surface characteristics are precisely characterized, and targeted suggestions for optimizing excitation and reception parameters are put forward. This research can provide a technical reference for near-surface facies studies in other similar complex exploration areas and has broad popularization and application value.

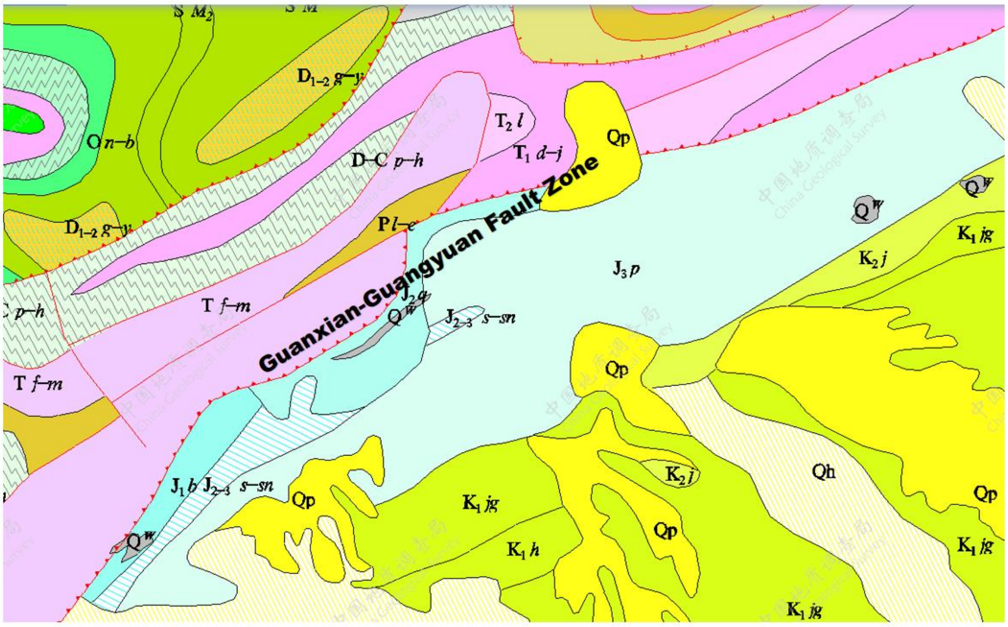

Figure 1: Geological Map of the Study Area

TRADITIONAL RESEARCH METHODS OF NEAR-SURFACE CHARACTERISTICS

During seismic wave propagation, the waves must traverse the near-surface low-velocity zone, which primarily consists of weathered layers and unconsolidated sediments. Due to lateral velocity variations in the near-surface, the arrival times of seismic waves exhibit inconsistent delays, leading to distortion in deep reflection events and making accurate positioning difficult[7-8].An accurate near-surface facies model (including parameters such as velocity and thickness) serves as the foundation for static correction calculations. It effectively corrects time discrepancies and restores the true subsurface structural geometry, forming a crucial prerequisite for subsequent structural interpretation and reservoir prediction.Additionally, a precise near-surface facies model can guide the optimization of acquisition designs. By understanding lateral variations in near-surface facies (e.g., gravel zones, swamps, and river channels) in advance, optimal placement of sources and receivers can be planned to avoid unfavorable geological zones, thereby improving the signal-to-noise ratio of raw data and enhancing operational efficiency.

Traditional near-surface studies mostly focus on single-attribute analysis, such as characterizing velocity structures based on micro-logging data[7], conducting lithologic division with the support of geological maps, or interpreting landforms by means of remote sensing images. Such studies have inherent limitations including a single research dimension and insufficient fusion of multi-source geoscience information, which make it difficult to comprehensively and accurately characterize the complex physical properties of near-surface media. Up to now, a systematic technical system for the classification and comprehensive evaluation of near-surface facies has not yet been established [8-9].

CLASSIFICATION AND EVALUATION METHOD OF NEAR-SURFACE FACIES

Concept and Core Connotation of Near-Surface Facies

In this study, near-surface facies is defined as the integrated characterization of near-surface media with unique geological, geomorphological and geophysical attributes in a specific spatial range. Affected by sedimentary environment, tectonic movement, weathering and denudation, the three attributes of near-surface media show complex spatial variations in different regions, specifically reflected in the following aspects:

(1) Differences in geomorphological attributes (e.g., terrain undulation, geomorphological type, slope gradient);

(2) Differences in geological attributes (e.g., stratigraphic age, lithology, stratum thickness and sedimentary facies);

(3) Differences in geophysical attributes (e.g., spatial variations of physical parameters such as layer thickness, velocity and resistivity).

Near-surface facies analysis refers to the classification, characterization, mapping and comprehensive evaluation of near-surface media in the study area based on the differences in the above three attributes, which provides a reliable geological foundation for seismic data acquisition, processing and geological interpretation.

Compared with traditional near-surface research methods, near-surface facies analysis has three distinct advantages:

(1) **Integrity:** It breaks through the limitation of single-attribute research, realizes the deep fusion of geomorphological, geological and geophysical attributes, and more comprehensively reflects the real geological characteristics of near-surface media.

(2) **Scale adaptability:** Following the research logic of "macro-micro-macro", it can be applied at different research scales according to actual needs, capturing both regional macroscopic distribution laws and local microscopic characteristic differences.

(3) **Practicality:** By compiling high-precision near-surface facies maps and constructing three-dimensional (3D) geological models, it provides a quantitative basis for the design of seismic excitation depth, optimal layout of micro-logging points and optimization of excitation and reception conditions, showing strong engineering application value.

General Idea for Near-Surface Facies Evaluation

The general idea of near-surface facies evaluation proposed in this study is multi-method integration, multi-information constraint and 3D modeling. A comprehensive near-surface investigation technology is developed, featuring the integration of point and area, electrical and seismic, shallow and deep, ground and airborne surveys. This technology is used to screen suitable investigation methods for the complex piedmont zone and establish a 3D near-surface geological model constrained by multi-dimensional spatial information, which provides core technical support for the fine division and comprehensive evaluation of near-surface facies.

- **Point-area integration**: Combines microscopic control point data with macroscopic regional coverage data. Point data are used to obtain high-precision local physical parameters, and areal data to grasp the macroscopic distribution characteristics of near-surface media, compensating for the limitations of single-point discrete data.
- **Electrical-seismic integration**: Fuses electrical and seismic exploration data. Electrical exploration methods, which are highly sensitive to medium resistivity, are used to identify the boundary of near-surface facies and supplement seismic exploration data, achieving mutual verification and correction of multi-source geophysical data.
- **Shallow-deep integration**: Conducts a synergistic analysis of shallow surface and middle-deep stratum characteristics, revealing the genetic mechanism of near-surface facies development and providing a geological basis for facies division.
- **Ground-airborne integration:** Combines ground field survey data with remote sensing image data. Ground surveys provide measured physical parameters of near-surface media, while remote sensing technology is used to quickly identify large-scale geomorphological and lithologic characteristics, forming a systematic and complete multi-source data source system.

Technical Workflow for Near-Surface Facies Classification and Evaluation

Combined with the actual geological conditions of the YC3D work area in the front of the Longmen Mountains, this study establishes a complete technical workflow for near-surface facies classification and evaluation: Initial modeling → Multi-source data fusion → Attribute extraction and analysis → Facies classification and nomenclature → Planar mapping and model construction （Figure 2).

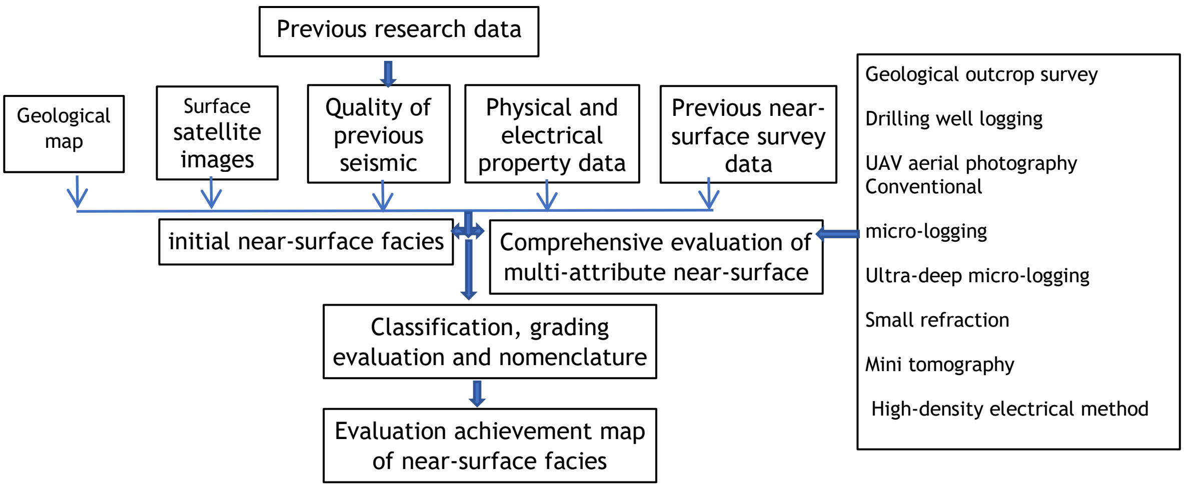

Figure 2: Flow Chart for Classification and Evaluation of Near-Surface Facies in Piedmont Zone

Construction of the Initial Near-surface Facie Through progressive multi-step analysis, fine characterization and comprehensive evaluation of near-surface facies in the study area are realized.

s Framework

Geological maps, remote sensing images and seismic section data of the study area are collected and preprocessed to eliminate abnormal and low-quality data. Stratigraphic ages are determined based on geological maps, landforms are identified via high-resolution satellite images, and the distribution and thickness trends of near-surface high- and low-velocity layers are clarified in combination with seismic sections. After comprehensive geoscience analysis, the study area is preliminarily divided into several macro geologic units, with their basic characteristics and boundary ranges clarified, and an initial near-surface facies framework is constructed to provide a basis for subsequent regional division and field investigation work.

Multi-source Data Fusion and Supplementary Investigation

Various near-surface investigation methods (e.g., field geological outcrop profile measurement, micro-logging data acquisition and reinterpretation, electrical prospecting) are used to supplement data acquisition and realize the fusion of multi-source geoscience data, so as to make up for the lack of initial data and improve the accuracy of near-surface facies analysis. After the completion of data acquisition, preprocessing is first carried out to unify different types of data into the same spatial coordinate system, and then professional data fusion technology is applied to achieve mutual verification and supplementation of multi-source data, thus establishing a complete and unified near-surface data source system for the study area.

Extraction and Analysis of Near-surface Facies Attributes

Based on the fused multi-source geoscience data, three categories of core attributes (geomorphological, geological and geophysical) of near-surface facies are extracted and quantitatively analyzed to clarify their spatial variation characteristics and internal correlation laws.

Geomorphological attributes are extracted based on high-precision remote sensing images and digital elevation model (DEM) data, the geomorphological pattern of the study area is systematically analyzed, geomorphological units are divided, and the correlation between geomorphological characteristics and strata, lithology is explored.

Geological attributes are extracted relying on field geological outcrop profiles and drilling data, revealing the regional geological evolution background and clarifying the differences in lithologic associations and sedimentary environments of different geologic units.

Geophysical attributes are extracted based on geophysical exploration data (e.g., micro-logging, seismic, electrical prospecting), reflecting the macro and micro variation characteristics of physical parameters such as near-surface velocity, resistivity and density.

After attribute extraction, a comprehensive correlation analysis of the three types of attributes is carried out to clarify their internal coupling relationships, achieving mutual verification and cross-validation of attribute data and improving the reliability of near-surface facies analysis results.

Classification and Nomenclature of Near-surface Facies

Following the principles of multi-level classification, comprehensive characterization, conciseness and standardization, a "class-type" two-level classification system is adopted for the fine division of near-surface facies based on the results of attribute analysis. Classes are divided according to the lithology of near-surface media (the core controlling factor), and types are further divided according to topographic, physical and hydrological attributes (e.g., terrain undulation, stratum dip angle, water content, cementation degree), completing the fine classification and evaluation table of "nine classes and twenty-two types" of near-surface facies in the YC3D (Table 1). The classification scale follows the progressive principle of "macro-micro" and is divided into three levels:

(1) Regional near-surface facies belts are divided based on the macro analysis of geomorphological and geological attributes of the whole study area;

(2) Primary near-surface facies division is carried out for each facies belt through comprehensive analysis combined with local landform and lithologic characteristics;

(3) Secondary near-surface facies division is conducted for local characteristic differences within some primary near-surface facies.

Due to the actual research objectives and engineering application needs, the facies division in this study stops at the secondary level. The nomenclature of near-surface facies adopts the unified form of "landform + lithology + sedimentary facies", which can directly and clearly reflect the core characteristics of near-surface media.

Planar Mapping and Model Construction of Near-Surface Facies

Based on the results of near-surface facies classification and constrained by multi-source geoscience data, the planar map of near-surface facies in the study area is compiled by integrating manual delineation and professional data interpolation methods. With high-resolution UAV aerial images as the base map, the mapping work integrates surface geological maps, remote sensing images and geophysical exploration data, and delineates the boundary of near-surface facies under the constraints of typical surface geological features to ensure the mapping accuracy. The specific mapping steps are as follows:

(1) Conduct preliminary lithologic zoning of the study area based on surface geological maps;

(2) Revise the lithologic zoning results using high-precision remote sensing and field survey data, complete the geomorphic zoning and classification in combination with geomorphic features, and refine the boundary of near-surface facies belts;

(3) Reinterpret micro-logging data of the study area, and perform first-break layer inversion on seismic survey line data to obtain high-precision near-surface velocity and thickness parameters;

(4) On the basis of lithologic zoning, delineate the preliminary distribution map of near-surface facies by combining the results of geomorphic division and geophysical parameter inversion, and further refine the boundary of each near-surface facies according to typical surface geological features;

(5) Combine the dynamic characteristics of micro-logging data to provide a quantitative basis for the optimal design of seismic acquisition excitation well depth;

(6) Analyze the optimal layout density of micro-logging points under the dual constraints of near-surface facies characteristics and exploration engineering requirements, to guide the layout of new observation points for subsequent seismic acquisition and construction.

Table 1: Classification and Evaluation Table of Near-Surface Facies

Class	Principles for Type Division	Specific Type	Near-Surface Characterization	Near-Surface Characterization	Excitation Effect	Reception Effect
Limestone	Topography, stratigraphic occurrence, geological age, rock integrity, water content, electrical property, physical property, excitation surrounding rock velocity; topsoil coverage, etc.	Permian low-angle limestone outcrop area in mountainous regions	Large topographic relief, high velocity, high resistivity, high density, dip angle < 30°	Thick topsoil, thin topsoil, bedrock outcrop	Poor	Bad
		Permian high-angle limestone outcrop area in mountainous regions	Large topographic relief, high velocity, high resistivity, high density, dip angle > 30°	Thick topsoil, thin topsoil, bedrock outcrop	Bad	Bad
		Triassic low-angle limestone outcrop area in mountainous regions	Large topographic relief, high velocity, high resistivity, high density, dip angle < 30°	Thick topsoil, thin topsoil, bedrock outcrop	Poor	Bad
		Triassic high-angle limestone outcrop area in mountainous regions	Large topographic relief, high velocity, high resistivity, high density, dip angle > 30°	Thick topsoil, thin topsoil, bedrock outcrop	Bad	Bad
		Limestone collapse and fractured area in mountainous regions	Large topographic relief, low velocity, low resistivity, low density	Thick topsoil, thin topsoil, fractured accumulation	Extremely poor	Bad
Conglomerate	Topography, cementation degree, water content, electrical property, physical	Jurassic conglomerate outcrop area in mountainous regions	Relatively large topographic relief, low velocity, high resistivity, relatively low density	Thick topsoil, thin topsoil, bedrock outcrop	Slightly good	Medium

	property, excitation surrounding rock velocity; topsoil coverage, etc.	Jurassic calcareous cemented conglomerate outcrop area in mountainous regions	Relatively large topographic relief, low velocity, high resistivity, high density	Thick topsoil, thin topsoil, bedrock outcrop	Slightly poor	Bad
Fractured Accumulation	Water content; topsoil coverage, etc.	Anhydrous fractured accumulation area	Small topographic relief, relatively high velocity, high resistivity, low density	Thick topsoil, thin topsoil, fractured accumulation	Extremely poor	Bad
		Water-bearing fractured accumulation area	Small topographic relief, relatively high velocity, low resistivity, low density	Thick topsoil, thin topsoil, fractured accumulation	Poor	Bad
Sand-Mudstone	Topography, stratigraphic occurrence, cementation degree, water content, electrical property, physical property, excitation surrounding rock velocity; topsoil coverage, etc.	Anhydrous sand-mudstone area	High velocity, high resistivity, high density	Thick topsoil, thin topsoil, bedrock outcrop	Good	Excellent
		Water-bearing sand-mudstone area	High velocity, relatively low resistivity, high density	Thick topsoil, thin topsoil, bedrock outcrop	Excellent	Excellent
		Anhydrous unconsolidated sandstone area	Relatively low velocity, high resistivity, low density	Thick topsoil, thin topsoil	Bad	Excellent
		Water-bearing unconsolidated sandstone area	Relatively low velocity, relatively low resistivity, low density	Thick topsoil, thin topsoil	Slightly poor	Excellent
Yellow Clay with Pebbles	Electrical property, excitation surrounding rock velocity; topsoil coverage condition	Yellow clay with pebbles area	Low velocity, low resistivity	Thick topsoil, thin topsoil	Fair	Excellent
Large Pebbles	Water content; topsoil coverage, etc.	Anhydrous large pebbles area in piedmont zone	Small topographic relief, low velocity, relatively high resistivity, large particle size	Thick topsoil, thin topsoil, large pebbles outcrop	Bad	Medium
		Water-bearing large pebbles area in piedmont zone	Small topographic relief, low velocity, relatively low resistivity, large particle size	Thick topsoil, thin topsoil, large pebbles outcrop	Slightly good	Medium
		Large pebbles area in river beach	Flat terrain, low velocity, low resistivity, large particle size	Pebbles outcrop	Good	Medium
Small Pebbles	Water content; topsoil coverage, etc.	Small pebbles area in flat dam	Flat terrain, low velocity, low resistivity, small particle size	Thick topsoil, thin topsoil	Excellent	Medium
Artificial Rock Terrain	Hard ground including roads, houses and towns	Hard ground	Flat terrain, high velocity, high resistivity	No topsoil	Bad	Medium

Complex and Special Area	Poor previous data, water area, factories and mines	Area with poor previous data	Comprehensive influence of multiple factors		Poor	Bad
		Water Area		Water		Bad
		Strong Interference Area				Bad

CLASSIFICATION AND EVALUATION OF NEAR-SURFACE FACIES IN YC3D WORK AREA OF THE LONGMEN MOUNTAINS PIEDMONT

Based on the above technical workflow and combined with multi-source geoscience data of the YC work area, this study divides the research area into two major north and south zones with the Guanxian-Anxian Fault as the boundary. A fine evaluation of near-surface facies is carried out from three core dimensions (geomorphology, lithology and sedimentary facies), clarifying the characteristic differences and spatial variation laws of near-surface facies in different zones (Figure 3), which provides important technical support for the optimization of seismic exploration parameters in the study area.

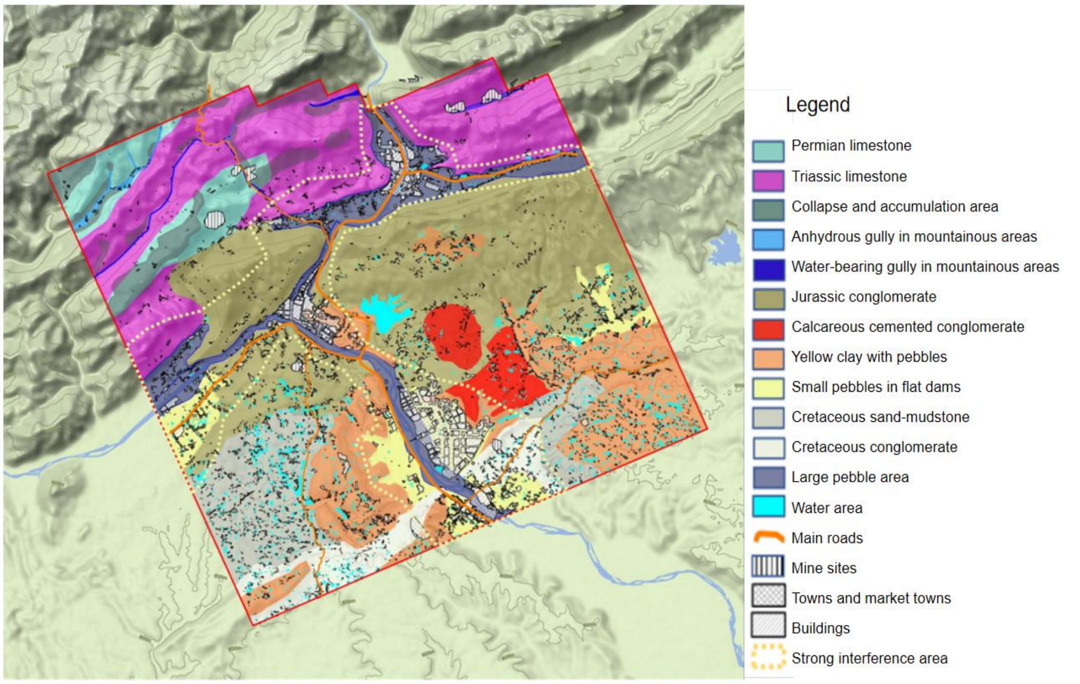

Figure 3: Division Map of Near-Surface Facies in YC3D

Analysis of Near-Surface Facies Characteristics Based on Geomorphic Dimension

The Guanxian-Anxian Fault is the obvious dividing line of the geomorphic pattern in the research area (Figure 1), with significant geomorphic differences on both sides. The northern part is dominated by mountains, presenting an alternating pattern of "mountain-canyon". Marine strata from the Triassic to Cambrian Systems are exposed in this area, with large dip angles and tight tectonic compression. The strata in mountainous areas maintain good integrity, while the strata in canyon areas are severely fractured and weathered. The southern part is dominated by plains, with scattered hills and river valleys and flat terrain.

Continental strata from the Jurassic to Quaternary Systems are exposed here, with gentle dip angles and weak tectonic deformation.

Geomorphological characteristics are closely correlated with the thickness of the near-surface low-velocity layer in the study area: the low-velocity layer is thin in mountainous areas with well-integrated bedrock, thick in canyons, flat dams and river valleys, and the thickest in flat dam areas with thick unconsolidated sediments.

Analysis of Near-Surface Facies Characteristics Based on Lithologic Dimension

Lithologic differences in different zones of the research area are the core geological basis for the classification and evaluation of near-surface facies. According to the lithologic characteristics and spatial distribution, the study area can be divided into three major lithologic units:

(1) The northern segment is dominated by exposed rigid rocks from the Triassic to Devonian Systems (mainly limestone and dolomite). The seismic wave excitation and reception conditions in this area are extremely poor, and the rigid rock mass is prone to causing energy shielding, which significantly reduces the signal-to-noise ratio of seismic data.

(2) The mid-southern segment is composed of clastic rocks from the Jurassic to Quaternary Systems (mainly conglomerate, sandstone and mudstone). The thick conglomerate layers in this area are likely to cause scattering-type energy shielding, which is unfavorable for the propagation of seismic waves and seismic exploration.

(3) Conglomerates are well developed and lithologies are severely fractured near the fault zone, resulting in poor seismic excitation and reception conditions. From the fault zone to the south, the lithology gradually becomes fine-grained, the rock mass integrity is improved, and the seismic exploration conditions are gradually optimized.

Analysis of Near-Surface Facies Characteristics Based on Sedimentary Facies Dimension

Different sedimentary environments in the northern and southern parts of the research area have formed distinct sedimentary facies belts, which are important geological basis for the division of near-surface facies. The northern part is characterized by marine sedimentation, presenting a typical distribution feature of "alternating mountain dolomite (or limestone) and canyon dolomite (including limestone)". The strata in this area have a typical double-layer structure of "bedrock + unconsolidated layer", and the near-surface geological characteristics are extremely complex.

The southern part is dominated by continental sedimentation, where the types of sedimentary facies show obvious spatial differentiation laws, with alluvial fan facies, fluvial facies and lacustrine facies distributed in turn from north to south. Areas close to the provenance of the Longmen Mountains (e.g., Yingzuiya) are mainly composed of Jurassic alluvial fan facies, with thick gravel layers and poor sorting, being the most developed area of conglomerates in the study area. Toward the south and far from the provenance, the gravel content gradually decreases, and the sedimentary facies transition to fluvial facies with alternating or intercalated distribution of sandstones and mudstones; Quaternary fluvial facies are sporadically distributed throughout the southern plain area.

Rivers in the northern part have a large drop, fast flow velocity and strong sediment transport capacity, with large gravels and river beach sand and pebbles, forming a typical large pebble zone. Toward the south, the river drop decreases, the flow velocity slows down, and the sedimentary particles become gradually finer. The southern part of the research area is dominated by Cretaceous-Quaternary lacustrine sedimentation, with delta facies developed at the Quaternary river entry into the lake. The strata are mainly composed of fine-grained sand-mudstones with uniform particle size and thick unconsolidated sediments, as well as thick low-velocity and velocity-reduction layers. In this area, the seismic wave energy loss is small during propagation, which is conducive to seismic excitation, and the seismic reception conditions are relatively optimal [10].

Application of Near-Surface Facies in the Optimization of Seismic Exploration Parameters

Based on the fine classification and evaluation results of near-surface facies, targeted optimization suggestions for seismic exploration parameters are put forward for different types of near-surface facies in the YC3D work area, which effectively improve the quality of seismic data:

(1) **Limestone area in the northwestern mountainous region (extremely poor excitation conditions):** The method of small charge and multi-well excitation should be adopted, and the excitation well depth should be optimized to avoid strong reflection interfaces and fractured strata, thus reducing energy shielding and scattering effects. At the same time, special geophone embedding technology should be used to improve the geophone coupling effect with the ground and further optimize the seismic reception quality.

(2) **Conglomerate-developed areas (poor excitation conditions):** The layout density of micro-logging points should be increased to accurately obtain the thickness and velocity parameters of low-velocity and velocity-reduction layers, optimize the static correction processing of seismic data, and reduce the impact of lithologic heterogeneity on seismic data quality. At the same time, the excitation charge and the spacing of excitation points should be appropriately adjusted to improve the energy and resolution of seismic waves.

(3) **Sand-mudstone areas (good excitation conditions):** Conventional seismic excitation and reception parameters can be adopted, with the focus on optimizing the reasonable setting depth and arrangement mode of geophone embedding to give full play to the advantages of favorable near-surface conditions and obtain high-quality seismic data with high signal-to-noise ratio and high resolution.

CONCLUSIONS

The Concept and Core Connotation of Near-Surface Facies are Clarified

Near-surface facies is a comprehensive characterization of the three core attributes (geomorphology, geology and geophysics) of near-surface media in local areas, whose division is based on the spatial differences of the three types of attributes. It has the inherent characteristics of integrity, scale adaptability and practicality, providing a new research perspective for the near-surface study in complex piedmont work areas.

The General Idea of Near-Surface Facies Analysis is Established

The general idea of near-surface facies analysis featuring "multi-method integration, multi-information constraint and 3D modeling" is built. Through the comprehensive investigation methods of combining point and area, electrical and seismic, shallow and deep, ground and airborne, multi-source geoscience data are effectively integrated, and a 3D near-surface geological model with the fusion of various information attributes is constructed, which provides a technical basis for the fine division of near-surface facies.

A Systematic Technical Workflow for the Classification and Evaluation of Near-Surface Facies is Formed

A complete workflow of "initial modeling → multi-source data fusion → attribute extraction and analysis → facies classification and nomenclature → planar mapping and model construction" is developed. Adopting the "class-type" two-level classification system, with "classes" divided mainly by lithology and "types" divided mainly by topographic, physical and hydrological attributes, the fine division of "nine classes and twenty-two types" of near-surface facies in the YC3D of the Longmen Mountains piedmont is realized. The spatial distribution and core characteristics of each near-surface facies are clarified, which provides a reliable geological basis for the optimization of key acquisition and construction parameters (e.g., excitation, reception) in the work area and effectively improves the quality of seismic exploration data.

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