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Deep-Strata Hydrocarbon Accumulation Mechanisms Driven by Multi-sphere Theory: A Short Review

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Abstract. Deep-strata oil and gas have become the important strategic successor area for global energy exploration, but classical petroleum geology theories face challenges in explaining their accumulation mechanisms. This study systematically reviews the research progress on the deep-strata oil and gas accumulation mechanism driven by the multi-sphere theory. Starting from the evolution of petroleum geology theory, we delve into the multi-sphere interaction framework within the perspective of Earth system science, analyzes the core controlling role of deep-strata fluid activity during the petroleum accumulation, summarizes the orderly symbiotic relationship between coexisting conventional and unconventional resources. Besides, we explore the unique characteristics of accumulation of ultra-deep marine resources. This study also shows that multi-sphere theory breaks through the limitations of the traditional basin perspective, unifying deep dynamic processes with shallow resource effects, and providing theoretical support for deepening the understanding of deep-strata hydrocarbon accumulation mechanisms and expanding new areas of associated resources.

Keywords: Multi-sphere interactions, Deep-strata hydrocarbons, Whole hydrocarbon system, Organic-inorganic interactions, Hydrocarbon accumulation mechanism

1. Introduction

Global hydrocarbon exploration is increasingly extending to deep-strata, deep-marine and unconventional areas. In China, deep-strata resources at the burial depth of >4500 meters account for 34% of the total resources, and the unconventional resources account for over 40% of the total resources [1]. Deep-strata oil and gas have become an important strategic replacement area for ensuring energy security. However, deep-strata hydrocarbon accumulation faces intricate geological settings including high-temperature and high-pressure compaction, multiple tectonic superposition, diverse phases, multi-scale fluid flows, et al. [2,3] which pose a severe challenge to traditional petroleum geological theory.

Classical petroleum geology takes the "source control theory" as its core framework [4], which mainly guides conventional petroleum exploration and is constrained in its ability to explain new phenomena such as the continuous spatial occurrence of unconventional hydrocarbon in deep areas. Traditional oil and gas system theories also only include conventional hydrocarbon, which is a defect [5]. Chinese petroleum geologists have continuously promoted theoretical innovation in their

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long-term exploration practice: from the "source control theory" [4], the "complex oil and gas accumulation zone (zone) theory", the "coal-derived hydrocarbon theory" to the "foreland basin reservoir theory", they have jointly formed a petroleum geology theoretical system with Chinese characteristics.

In the 21st century, breakthroughs in unconventional oil and gas have propelled theoretical innovation into a new stage [6]. At the same time, the development of Earth system science has given rise to the multi-sphere driven theory of hydrocarbon generation and accumulation [7,8]. Its core idea is that the Earth's internal and external systems are linked, multi-spheres form the skeleton, geological melts form the blood, and the cross-sphere migration and redistribution of volatiles such as carbon, hydrogen, oxygen, and sulfur constitute the core process of hydrocarbon resource formation.

This theory, along with studies such as the international subduction zone volatile flux [9], supports each other and jointly promotes the leap of petroleum geology from the basin-scale "hydrocarbon system" to the Earth's sphere-scale "trans-sphere oil and gas system" [10]. The organic-inorganic interaction driven by deep-strata fluid activity is the key to understanding deep oil and gas accumulation [11]. The hydrogen, catalysts and thermal energy carried by mantle-derived fluids significantly affect the hydrocarbon generation process. The orderly symbiotic enrichment of between coexisting conventional and unconventional resources reveals the spatiotemporal order of deep oil and gas resource distribution [12].

2. Multi-sphere interactions from the perspective of earth system science

2.1. Earth system and volatile cycle

Earth system science views the Earth as a coupled system consisting of the core, mantle, crust, hydrosphere, atmosphere, and biosphere, with hydrocarbon formation being an integral part of Earth's evolution. The volatile matter cycle is a core link in understanding the interactions between multiple spheres [13]. The Earth's surface fluid sphere accounts for only about 1% of the total volatile matter, with the vast majority distributed within the solid Earth [13].

Volatile elements such as carbon, hydrogen, oxygen, and sulfur were incorporated into the mantle during Earth's accretion and differentiation, and then return to the surface via plate subduction, forming a global-scale cycle. This cycle dictates the evolution of the petroleum system by controlling source rock deposition, the thermal regime driving hydrocarbon generation, and the diagenetic modification of reservoirs post-accumulation. Global carbon cycle studies suggest that subduction zones transport approximately 10^{13} mol of carbon to the mantle annually, roughly equivalent to the annual carbon flux released by volcanoes and mid-ocean ridges, forming a dynamic equilibrium [9].

Regarding the sulfur cycle, the global sulfur output flux from subduction zones is approximately 2.91×10^{12} g/yr, accounting for only 6.3% of the input flux, with most sulfur being carried into the deep mantle [14]. Studies by Chinese scholars on the release of volatiles during the destruction of the North China Craton have further revealed the controlling role of deep processes on the evolution of source rocks in the basin [13]. As the main channel for surface materials to enter the Earth's interior, subduction zones, together with mantle plumes, constitute the most important material and energy cycle pathways in the Earth system. The Earth's volatiles cycle is closely related to the evolution of habitable environments and has a fundamental controlling role in resource formation [13].

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2.2. Tethys geodynamics and hydrocarbon accumulation

The Tethyan tectonic domain is the world's richest region for hydrocarbons. The unidirectional subduction dynamics of the Neo-Tethyan region reveal its evolution from rifting to aggregation: the Indian Plate drifted rapidly northward, and the Neo-Tethyan Ocean Plate rolled back, leading to back-arc extension and the development of passive continental margins, providing a tectonic setting for the deposition of high-quality source rocks [15]. Gravity-driven unidirectional rifting-aggregation dynamics of the Tethyan domain controlled the tectonic evolution of the Tethyan domain. The evolution of the Tethyan domain controlled the spatiotemporal distribution of source rocks. The tectonic evolution of the Neo-Tethyan domain had a decisive influence on the formation of the Persian Gulf super hydrocarbon basin.

2.3. Regional basin response examples

Multi-sphere interactions produce discernible geological signatures in sedimentary basins. The formation of the North Sea Basin is closely associated with the opening of the North Atlantic and the activity of mantle plumes. In the later stage of rifting, thermal subsidence formed thick source rocks, and the continuous supply of mantle heat promoted thermal regime of organic matter. The formation of the giant hydrocarbon field under salt in the Santos Basin of Brazil is closely related to the activity of mantle plumes during the rifting of the South Atlantic. The development of salt layers is controlled by the Cretaceous arid climate and restricted marine environment, and is a typical product of the coupling of deep processes and surface environment [16]. The Southeast Asian multi-island sea tectonic system is located in the intersection of three major plates, and multi-directional subduction leads to a complex multi-island sea pattern. Under this background, several small and deep oil and gas-rich basins have developed, demonstrating the profound control of multi-sphere interactions on basin evolution and oil and gas enrichment.

3. Deep fluid activity and organic-inorganic interactions

3.1. Deep fluid sources and behavior

Deep fluids include mantle degassing fluids, subducting slab dehydration fluids, metamorphic fluids, and magmatic hydrothermal fluids [11]. They carry abundant volatiles and metallic elements and migrate upwards into sedimentary basins under pressure, becoming a medium connecting deep processes and shallow resource effects.

The study of the high-pressure to ultra-high-pressure metamorphic belt in the southwestern Tianshan Mountains was the first to quantitatively analyze the sulfur cycle in the subduction zone from the perspective of the subducting slab [14]. The study found that there is a short-term, highly efficient sulfur release window at the shallow depth of the subducting slab, and sulfur in the fluid mainly exists in the form of reduced HS^- and H_2S. The global sulfur output flux in the subduction zone is about 2.91×10^{12} g/yr, accounting for only 6.3% of the input flux, with most sulfur being carried into the deep mantle by the subducting slab [14]. Significant breakthroughs have been made in deep fluid research in recent years, with natural hydrogen receiving global attention as a potential zero-carbon energy source [17]. This hydrogen can either form reservoirs independently or participate in hydrocarbon generation processes, becoming a bridge between organic and inorganic interactions.

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3.2. A revolutionary understanding of the hydrocarbon generation effect

The influence of deep fluids on hydrocarbon generation is mainly reflected in two aspects: catalytic hydrogenation and thermal effects. Hydrogen, transition metal catalysts, and thermal energy carried by mantle-derived fluids are transported to the source rock system, which can significantly reduce the activation energy of hydrocarbon generation, increase the conversion rate of hydrocarbon generation, and change the composition of hydrocarbon products [11].

Coupling between different spheres can trigger organic-inorganic composite hydrocarbon generation [10]. Deep tectonic dynamics, crust-mantle coupling, and material and energy exchange promote the upwelling of deep hydrogen-rich fluids into the basin's hydrocarbon accumulation system, thereby triggering inorganic-organic composite hydrocarbon generation and oil and gas accumulation [10].

Alkaline lake environments are typical sites of organic-inorganic interactions. High concentrations of carbonates and alkali metal ions in alkaline lake waters control the formation of high-quality source rocks through multiple mechanisms. Another cutting-edge direction is the generation mechanism of oil and gas in the ancient source reservoirs. The Mesoproterozoic marine biogenic carbon pump model and the new Cambrian marine carbon cycle model extend the timescale of organic-inorganic interactions to the early stages of Earth's evolution.

3.3. Deep transformation of storage space

The effects of deep fluids on reservoirs include three aspects: dissolution and porosimetry, fracture formation, and mineral precipitation [9]. Thermochemical sulfate reduction reaction is an important mechanism for deep dissolution of carbonate reservoirs. The existing studies reveals that hydrocarbons react with sulfates to generate H_2S and CO_2. CO_2 dissolves in water to form carbonic acid, which strongly dissolves carbonate minerals, significantly improves reservoir properties, and guides the exploration breakthrough of reef-shoal gas reservoirs in some formations in Sichuan Basin [18]. Deep fluid activity can also construct fracture systems through mechanisms such as hydraulic fracturing and mineral phase transformation.

Hydraulic fracturing and mineral phase transformation mechanisms together constitute the key dynamic processes by which deep fluids reshape reservoir space. When deep thermal fluid activity causes pore fluid pressure to exceed the rock fracturing threshold, hydraulic fracturing opens a network of microfractures along pre-existing weak surfaces or the direction of maximum principal stress, significantly increasing reservoir permeability anisotropy. Simultaneously, fluid-rock interactions leading to mineral phase transformations, such as the dehydration transformation of gypsum into anhydrite or the illitization of clay minerals, not only alter the mechanical properties of the rock but also induce new microfracture systems accompanied by volume changes. This chain reaction of fluid pressurization-fracturing-phase transformation-re-fracturing allows the originally dense deep reservoir to continuously build effective migration channels and reservoir space within a closed system. From the perspective of hydrocarbon accumulation dynamics, this dual reshaping effect of deep fluids essentially reshapes the fluid potential field and transport framework of the deep basin, controlling the migration direction and accumulation location of hydrocarbons under deep overpressure environments.

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4. Whole hydrocarbon system and orderly symbiotic enrichment

4.1. The connotation of the whole hydrocarbon system theory

The theory of the whole hydrocarbon system is a development of traditional hydrocarbon system [6]. It incorporates conventional and unconventional petroleum resources into a unified system and examines oil and gas accumulation based on the concept of the source-reservoir coupling. Its basic principles include the system's layered structure. The theory of the whole hydrocarbon system echoes the concept of "super basin" proposed by the international petroleum geology community [19]. The latter emphasizes the huge cumulative production, remaining recoverable reserves, and continuous exploration potential of the basin.

As one of the most representative super basins in the 21st century, the Santos Basin in Brazil provides international case support for the theory of the whole hydrocarbon system with its multi-stage charging and multi-type reservoir-seal combination of the subsalt accumulation system [16].

The key to the strong support that the subsalt hydrocarbon accumulation system in this basin provides for the theory of the entire hydrocarbon system lies in its perfect representation of the multi-layered nature of source-reservoir coupling. Subsalt lacustrine carbonate source rocks and microbial reef-shoal reservoirs form a vertically adjacent source-reservoir combination, while the Aptian evaporites, as regional caprocks, create a unique source below generation-source above reservoir-salt layer sealing structure. This spatial configuration allows hydrocarbons generated from the same set of source rocks to form shale oil resources within the source area and to accumulate as conventional hydrocarbons in adjacent reef-shoal bodies, achieving continuous charging during multiple tectonic activities. This characteristic echoes the orderly intra-source-edge-extra-source distribution of source rocks in continental rift basins, demonstrating the universal explanatory power of the theory of the entire hydrocarbon system for hydrocarbon accumulation patterns under different tectonic backgrounds.

4.2. The pattern of ordered symbiotic enrichment

The orderly co-existence and enrichment of conventional and unconventional hydrocarbon is the core characteristic of the entire oil and gas system [12]. Around the main source strata, the distribution of hydrocarbon exhibits a regular three-ring structure: the inner ring consists of continuous unconventional resources such as shale intra-source hydrocarbons, the middle ring consists of quasi-continuous resources such as near-source tight sandstone, and the outer ring consists of discontinuous resources in distant conventional traps [12]. This orderly distribution is controlled by three major factors: the source-reservoir configuration determines secondary migration distance and entrapment mode, the reservoir properties determine fluid transport capability and hydrocarbon enrichment level, and the pressure system determines the reservoir dynamics and preservation conditions [6,7].

4.3. Unique features of ultra-deep marine hydrocarbon accumulation in China

China's marine basins have undergone multiple tectonic transformations and long-term evolution, resulting in distinctive ultra-deep hydrocarbon accumulation. From the perspective of Earth system evolution, the control mechanisms for the formation and enrichment of ultra-deep marine hydrocarbons in China can be revealed [20]. During the synchronous drift of the South China and Tarim blocks, they passed through the tropical convergence zone of the low-latitude Hadley

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circulation twice, forming high-quality source rocks. Deep tectonic activity and surface climate evolution jointly control the tectonic evolution of ultra-deep source-reservoir-seal assemblages in the Sichuan and Tarim basins, forming multiple hydrocarbon systems such as the Ediacaran-Cambrian [20].

The degree of source-reservoir-seal assemblages matching, the type of source rock parent material, the deep thermal system of the basin, and the burial depth-up process across tectonic periods jointly control the full hydrocarbon system evolution. Ultimately, three hydrocarbon enrichment models are formed: near-source charging accumulation in the platform margin zone, high-energy shoal far-source fault connection accumulation, and three-dimensional accumulation in the strike-slip fracture zone [20].

The proposal of these three enrichment models marks a significant leap in China's ultra-deep marine hydrocarbon geological research, moving from phenomenological description to mechanistic explanation. Unlike typical passive continental margin basins abroad, the multi-cycle tectonic evolution of China marine basins results in hydrocarbon accumulation elements exhibiting both diachronic and reconstructive characteristics in space and time: early-formed paleo-uplifts and reef-shoals may be modified or even destroyed by later tectonic movements, while deep hydrothermal activity can reconstruct reservoir space and transport networks under the new tectonic framework. This dialectical unity of destruction-reconstruction allows China's ultra-deep hydrocarbon accumulation to both adhere to the basic principles of the whole hydrocarbon system theory and exhibit unique complexity. In particular, in the three-dimensional hydrocarbon accumulation model of the strike-slip fault zone in the Tarim Basin, faults not only serve as migration channels but also directly participate in the construction of reservoir space through inducing fracture zones and hydrothermal dissolution, becoming a new manifestation of the "source-reservoir coupling" relationship in the context of strike-slip tectonic structures.

5. Technology empowerment and outlook

5.1. Innovation in research methods

Multi-sphere theory research has driven methodological innovation. The development of geochemical tracing technology has made it possible to quantitatively analyze the source and evolution of deep fluids [14]. In-situ sulfur isotope technology has successfully traced the contributions of fluids from different sources in subduction zones [14]. Carbon, hydrogen, oxygen, and helium isotope systems have been widely used to identify mantle-derived fluids, crust-mantle interactions, and fluid-rock reaction processes.

In helium resource research, helium isotopes have become a key indicator for distinguishing between crust-derived and mantle-derived helium [21]. Numerical simulation technology has been extended from the basin scale to the lithosphere scale, realizing the quantitative coupling of deep processes and shallow responses.

The introduction of artificial intelligence technology has greatly improved data processing and pattern recognition capabilities. Machine learning shows broad prospects in source rock evaluation, reservoir prediction, and sweet spot identification. High-temperature and high-pressure experimental simulation provides direct evidence for understanding deep processes and can establish a bridge between theoretical models and geological realities.

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5.2. Energy strategic significance

From a global perspective, deep-burial and ultra-deep hydrocarbon systems have become the main battleground for petroleum reserves growth. From 2004 to 2024, a total of 898 petroleum reservoirs were discovered globally in deep and ultra-deep reservoirs assemblages, with a cumulative recoverable 2P reserve of 9.04 billion tons of oil equivalent, an increase of about 17 times in 2024 compared to 2004 [1]. China and the United States account for 79.8% of global deep-strata georeserves, leading global onshore and offshore deep-strata oil and gas exploration respectively [1]. This dominance stems not only from substantial energy demand and sustained technological investment but also from the guidance of innovative concepts like the multi-sphere and whole petroleum system theories advanced by Chinese scholars. In terms of resource type, unconventional resources accounted for an average of 54.3% of the newly added global reserves in the past decade, rising to 71.1% in 2024 [1].

In addition to conventional petroleum, the whole hydrocarbon system includes various types such as coalbed methane [6]. Meanwhile, helium, hydrogen and other associated resources are becoming new exploration hotspots. Recently, the Da Tan 1 well in the Sichuan Basin obtained a high-yield industrial gas flow in the Dengying Formation of the Sinian System, with a helium content of 0.1% in the natural gas, which confirms the helium enrichment model with the underlying granite basement as the main helium source and the source fault as the migration channel [21].

6. Conclusions

The multi-sphere theory places hydrocarbon formation within the framework of Earth system science, emphasizing the unity of volatile matter cross-sphere circulation, deep dynamic processes, and shallow resource effects. The Earth's multi-sphere structure forms the skeleton, while geological melt flows form the blood. The cross-sphere migration and redistribution of volatiles such as carbon, hydrogen, oxygen, and sulfur are the core processes of hydrocarbon resource formation.

The Tethys geodynamic evolution controlled the formation of the world's richest hydrocarbon regions, and the development of basins such as the North Sea, Santos, and Southeast Asia is a regional response to sphere interactions. Deep fluids are the core carriers of organic-inorganic interactions. Processes such as fluid release from subduction zones and mantle degassing carry hydrogen, catalysts, and heat energy into the basins, profoundly affecting hydrocarbon generation processes by lowering activation energy, widening the hydrocarbon generation window, and altering product composition. Coupling effects of different spheres can trigger organic-inorganic hydrocarbon synthesis. Fluid modification effects such as thermochemical sulfate reduction reaction dissolution and hydraulic fracturing can significantly improve the properties of deep reservoirs. The theory of the whole hydrocarbon system establishes a new paradigm of orderly co-existence and enrichment of conventional and unconventional petroleum. The petroleum around the main source strata exhibits a sphere distribution pattern of unconventional within the source, tight near the source, and conventional far from the source. This distribution is controlled by three major factors: source-reservoir configuration, reservoir properties, and pressure system. The marine ultra-deep petroleum in China are products of long-term evolution and multi-phase tectonic overprinting. The evolution of the Earth system controls the source-reservoir-cap configuration and temperature and pressure system, forming a variety of oil and gas enrichment patterns. Multi-sphere theory research has driven innovations in geochemical tracing, numerical simulation, and artificial intelligence, providing theoretical support for deep-ultra-deep and unconventional oil and gas exploration, while also expanding new directions for the exploration of associated resources such as helium, hydrogen,

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and geothermal energy. In the future, it is necessary to further focus on the cross-sphere material-energy exchange mechanism and construct a more complete multi-sphere coupled oil and gas accumulation theory system.

References

[1] Lu R Q, Yu G M, Li X G, et al. Review of global oil and gas exploration and development in 2024 [J]. World Petroleum Industry, 2025, 31(1): 1-14.

[2] Chen F B, Zong Z Y, Yin X Y. Acoustothermoelasticity for joint effects of stress and thermal fields on wave dispersion and attenuation [J]. Journal of Geophysical Research: Solid Earth, 2022, 127(4): e2021JB023671.

[3] Chen F B, Zong Z Y, Yin X Y, Alexey S. Stress dependence of elastic wave dispersion and attenuation in fluid-saturated porous layered media [J]. Science China Earth Science, 2023, 66: 2622-2634.

[4] Hu C Y. Source bed controls hydrocarbon habitat in continental basins, East China [J]. Acta Petrolei Sinica, 1982(2): 9-16.

[5] Jia C Z. Breakthrough and significance of unconventional oil and gas to classical petroleum geology theory [J]. Petroleum Exploration and Development, 2017, 44(1): 1-11.

[6] Jia C Z, Zhao W Z, Zou C N, et al. Basic principles of whole petroleum system theory [J]. Acta Petrolei Sinica, 2024, 45(7): 1-14.

[7] Zhao X Z, Zhou L H, Zhao C Y, et al. Spherical structure and ordered hydrocarbon accumulation of whole petroleum system in continental rift basin: A case study of Cangdong sag, Bohai Bay Basin [J]. Acta Petrolei Sinica, 2025, 46(2): 1-16.

[8] Zhu R X, Zhang S C, Wang H J, et al. Theory of hydrocarbon formation and enrichment driven by multi-sphere interactions [J]. Science China Earth Sciences, 2025, 55(8): 2603-2620.

[9] Plank T, Manning C E. Subducting carbon [J]. Nature, 2004, 431: 680-683.

[10] Tao S Z, Yang Y Q, Zhang G C, et al. Cross-sphere petroleum systems and new directions in petroleum geology [J]. Earth Science Frontiers, 2025, 32(5): 205-219.

[] [11 Liu Q Y, Zhu D Y, Meng Q Q, et al. Hydrocarbon accumulation mechanism under the action of deep fluids [J]. Earth Science Frontiers, 2022, 29(6): 87-101.

[12] Yang Z, Zou C N. Ordered "symbiotic enrichment" of conventional and unconventional oil and gas: Discussion on theory and technology of conventional and unconventional petroleum geology [J]. Acta Geologica Sinica, 2022, 96(5): 1635-1653.

[13] Ji W Q, Wu F Y. Volatile cycles in the Earth and evolution of habitable environment [J]. Acta Petrologica Sinica, 2022, 38(5): 1329-1344.

[14] Li J L, Gao J, John T, et al. Geochemical behavior of sulfur and sulfur cycle in subduction zones [J]. Acta Petrologica Sinica, 2022, 38(5): 1389-1404.

[15] Zhu R X, Zhang W, Wang H J, et al. Dynamic mechanism of the unidirectional subduction of the Neo-Tethys Ocean [J]. Science China Earth Sciences, 2023, 53(8): 1721-1736.

[16] Baptista R J, Ferraz A E, Sombra C, et al. The presalt Santos Basin, a super basin of the twenty-first century [J]. AAPG Bulletin, 2023, 107(8): 1369-1389.

[17] Ellis G S, Gelman S E. Model predictions of global geologic hydrogen resources [J]. Science Advances, 2024, 10: eado0955.

[18] Ma Y S, Guo X S, Guo T L, et al. Discovery of the large-scale Puguang gas field in the Sichuan Basin and its exploration enlightenment [J]. Geological Review, 2005, 51(4): 476-480.

[19] Fryklund B, Stark P P. Super basins—New paradigm for oil and gas supply [J]. AAPG Bulletin, 2020, 104(12): 2507-2519.

[20] Zhang S C, Wang H J, Su J, et al. Control of Earth system evolution on the formation and enrichment of marine ultra-deep oil and gas in China [J]. Petroleum Exploration and Development, 2024, 51(4): 759-773.

[21] Liu X B, Tao S Z, Yang D L, et al. Exploration breakthrough and main controlling factors of helium-rich natural gas accumulation in Well Datan 1, Sichuan Basin [J]. Earth Science Frontiers, 2025, 32(5): 258-277.