



Research insights of argillaceous-based site for high-level radioactive waste disposal in China

Long Xiang^{1,2} · Xiaodong Liu² · Pinghui Liu¹ · Chaocheng Dai³

Received: 5 August 2024 / Accepted: 13 October 2024 / Published online: 28 October 2024
© Akadémiai Kiadó, Budapest, Hungary 2024

Abstract

This article systematically reviews the process and main insights of the argillaceous-based site for high-level radioactive waste (HLW) disposal purpose in China for the first time. In the currently planning and site selection stage, two pre-selected sections in Tamusu pre-selected area in Inner Mongolia and the Tamusu mudstone mainly composited of analcime and dolomite are recommended for HLW and intermediate level long-life radioactive waste disposal purpose. Strengthening international cooperation and detailed evaluations are important to consolidate the foundation of argillaceous-based site selection for China's HLW deep geological repository.

Keywords Argillaceous-based site · High-level radioactive waste disposal · Tamusu

Introduction

A wide spectrum of argillaceous media are being (or were) considered in Nuclear Energy Agency member countries as potential host rocks for deep geological repository (DGR) of high-level radioactive waste (HLW), i.e. from plastic, soft, poorly indurated clays to brittle, hard mudstones or shales [1]. The Boom clay in Belgium, Callovo-Oxfordian clay (COx) in France and Opalinus Clay (OPA clay) in Switzerland are typical clay rocks with high content clay minerals that contributes to advantages over radionuclide retention, slowing radionuclides migration, and self-healing of fractures [2]. The HADES rock laboratory, Meuse Haute Marne underground research laboratory, and the Mont Terri underground laboratory are underground laboratories constructed in clay formations [3]. As one of the most typical representatives of argillaceous media, a wealth of experience

and advanced technologies could be drew from these clay rock cases.

In France, the COx exhibits excellent conditions for the storage of radioactive waste thanks to its significant retention capacity for radionuclides, small molecular diffusion and low permeability [4]. The DGR for intermediate level long-life radioactive waste (ILLW) and HLW called Cigeo project, which has been planned to be constructed in deep COx formation (~150 m thickness). At the start of 2023, Andra, French national radioactive waste management agency, submitted its construction license application for the Cigeo project, according to well-defined design principles and a robust safety demonstration. The construction of Cigeo will be started around 2027 once the project is authorized, indicating the industrial pilot phase. The industrial pilot phase with handling of radioactive waste packages will be around 2035–2040; Continuation of disposal after the industrial pilot phase and authorization of full commissioning by Nuclear Safety Authority will be around 2040–2050. The act to authorize permanent closure of the disposal facility will be around 2150 s [5].

In Switzerland, before the discovery of OPA clay in 1989, Nagra, Switzerland national cooperative for the disposal of radioactive waste, believed that granite was the most suitable host rocks for DGR purposes. With the deepening of Mont Terri underground laboratory program, numerous in-site experiments have confirmed that the OPA clay deep below the surface has the best long-term containment capacity

✉ Xiaodong Liu
liuof99@163.com

¹ Key Laboratory for Digital Land and Resources of Jiangxi Province, East China University of Technology, Nanchang 330013, China

² State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330013, China

³ School of Earth Sciences, East China University of Technology, Nanchang 330013, China

for the radioactive waste. Therefore, Switzerland gradually shifted researches from granite to clay rock [6–8]. Two notable features of clay rocks for HLW considerations could be determined in Switzerland. One is the ongoing Mont Terri Project that has conducted systematic and in-depth research on the characteristics of OPA clay since 1989. The other has been the site selection process since 2008 under the lead of the Swiss Federal Office of Energy. In 2018, Nagra investigated three regions in greater detail: Jura Ost, Nördlich Lägern and Zürich Nordost. In September 2021, Nördlich Lägern had been identified and recommended as the potential site for the construction of DGR. The Nördlich Lägern site is where that the construction of DGR will be started once the general licences have been granted. It is expected that the general licence application will be compiled by 2024–2025 and the construction of the disposal repository will begin in 2045 [8].

In China, as of December 31, 2023, there are a total of 55 commercial nuclear power units in mainland China, and 26

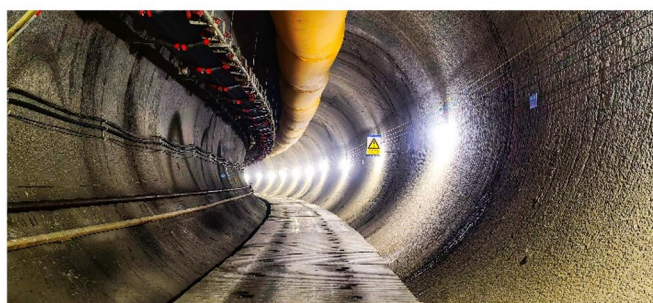
units under construction, the number of commercial nuclear power units under construction ranking first in the world [9]. Also driven by the "carbon peaking and carbon neutrality" goals, the vigorously developing nuclear power will not be changed in China. Therefore, the safe disposal of HLW is a major scientific and technological challenge that must be addressed for the sustainable development of China's nuclear power industry. Granite-based site and argillaceous-based site are the two research routes for disposal of HLW at the national level. Started at the year of 1985 (Table 1), following nearly 40 years of rigorous research on granite-based site, Beishan underground research laboratory (Beishan URL) was approved by China Atomic Energy Authority in May 2019. The Beishan URL was officially started construction in June 2021, which symbolized that China's efforts in geological disposal of HLW entered into a new phase, i.e. the phase of construction of URL and R&D in URL [10–12] (Fig. 1a). Beishan URL categorized as a "third generation" URL for HLW disposal, i.e., area-specific URL, is located in

Table 1 Laws and strategies for HLW disposal purposes at national level

National laws and regulations		
Time(Year)	Names	Notes
2003	Law of prevention and control of radioactive contamination of the People's Republic of China	The first time in China defined the legal requirements of HLW
2011	Regulations on the Safety Management of Radioactive Waste	
2018	Nuclear Safety Law of the People's Republic of China	Centralized deep geological disposal of HLW
Proposed Granite-based site planning		
Time(Year)	Stages	Notes
1985–2010	Stage I	Site selection and evaluation
2011–2020	Stage II	Site confirmation and underground Laboratory construction
2021–2030	Stage III	In situ experiments and demonstration disposal
2031–2040	Stage IV	Construction of disposal repository



a-Research management zone



b-First turning section of spiral ramp by Tunnel boring machine

Fig. 1 The construction of Beishan granite URL (Provided by Dr. Ju WANG)

Jiuquan City, Gansu Province, Northwest China. The main parts of the Beishan URL include main shaft, spiral ramp, and 2 horizontal tunnels. The shaft and spiral ramp started excavation in May 2022, and the construction of Beishan URL is planned to be completed by 2027. As of December 17, 2023, the spiral ramp and main shaft has reached 2540 m long and 590 m deep, respectively. The horizontal tunnel at the depth of 280 m has been excavated 100 m as well (Fig. 1b). Beishan URL facilities have been appointed as the first HLW geological disposal collaborative center by International Atomic Energy Agency (IAEA), which will promote international academic exchanges and global R&D technology process in HLW disposal field [11, 13].

As early as the year of 2010, the State Administration of Science, Technology and Industry for National Defense clearly stated that granite-based site selection and comparison work should be carried out, with a focus on argillaceous-based site selection in the northwest China. Researches on argillaceous-based site lags behind that of granite-based site, however, some achievements have also been made since the year of 2007. Given the various advantages of argillaceous, especially for the clay rock, research on clay rock are becoming increasingly in-depth and mature. Besides France and Switzerland, other countries such as Germany, Spain, and Canada [7, 14, 15] are also considering storing radioactive waste in clay rocks.

Therefore, introduction China's researches on argillaceous-based site has positive contributions both to recommending China's final DGR site and participating in argillaceous researches worldwide. This paper is the first time to systematically summarize the China's researches on argillaceous-based site for HLW disposal purpose. It includes.

- (1) Reviewing the screening process of argillaceous-based site in mainland China, clarifying the current stage;
- (2) Summarizing main achievements made in the site selection process and in Tamusu pre-selected area;
- (3) Outlooks for subsequent researches on China's argillaceous-based site.

Argillaceous-based site-screening process in mainland China

The safe disposal of HLW attracted the attention of Chinese scientists as early as the 1980s. The acts and planning for HLW disposal purposes at national level (Table 1) emphasizes that the granite-based and argillaceous-based site selection are the two roadmap and focus on the overall strategies for granite-based DGR. Meanwhile, the argillaceous-based site selection, mainly focused on the clay rocks, in mainland China started at the year of 2007. Currently, the site selection is in the stage I.

The project of "Investigation and Research on host Rock of High Level Radioactive Waste Geological Disposal Reservoir-Pre-selected Site of Clay Rock" (2007–2012) is the first project that entirely focus on determining whether there is a geological environment of thick layered argillaceous rock in mainland China, as well as to determine the regional distribution of argillaceous rock. The existence of argillaceous rock that are suitable as the host rock for HLW disposal purposes in mainland China have been demonstrated via this project, existing places such as the eastern coastal region (Shandong, Jiangsu, Zhejiang), the central region (Anhui, Hubei, Jiangxi), the southwest region (Guangxi), the northwest region (Qinghai, Inner Mongolia, Gansu, Xinjiang), and the northeast region (Heilongjiang, Jilin, Liaoning), etc. Considering the relatively developed economy and high population density in the eastern China, which may be the disadvantageous for safety evaluation, it is suggested that the site selection places should focus on the northwest China. Moreover, the screening should revolve around the Mesozoic and Cenozoic sedimentary basins. Three key areas and the corresponding target formations (Fig. 2a, Table 2) for screening argillaceous-based sites have been recommended at the regional level. The "Screening and evaluation of clay rock sections in the northwest region of high-level radioactive waste geological disposal facilities" (2014–2019) considered as the second project. The second project puts forward the basic criteria for argillaceous-based site selection from a technical perspective for the first time.

Based on the two projects funded by State Administration of Science, Technology and Industry for National Defense, PRC, three clay rock pre-selected areas and two pre-selected sections have been selected and recommended in the northwest China. The main achievements will be thoroughly expounded in the following.

Main achievements

Recommended technical guidelines for screening China's argillaceous-based sites

The technical guideline for site selection is one of the most fundamental conditions, serving both as the basic selection guideline and as the basis for safety evaluation by regulatory authorities. According to the recommended safety requirements from IAEA and research experience from France, Sweden, and Switzerland, it could be concluded that different stages of site selection should have specific technical guidelines. It is necessary to have a clear understanding that there are also differences in the technical guidelines for site selection due to differences in geological backgrounds and host rock types. In accordance with the requirements of the "Nuclear Safety Guidelines for Site Selection of

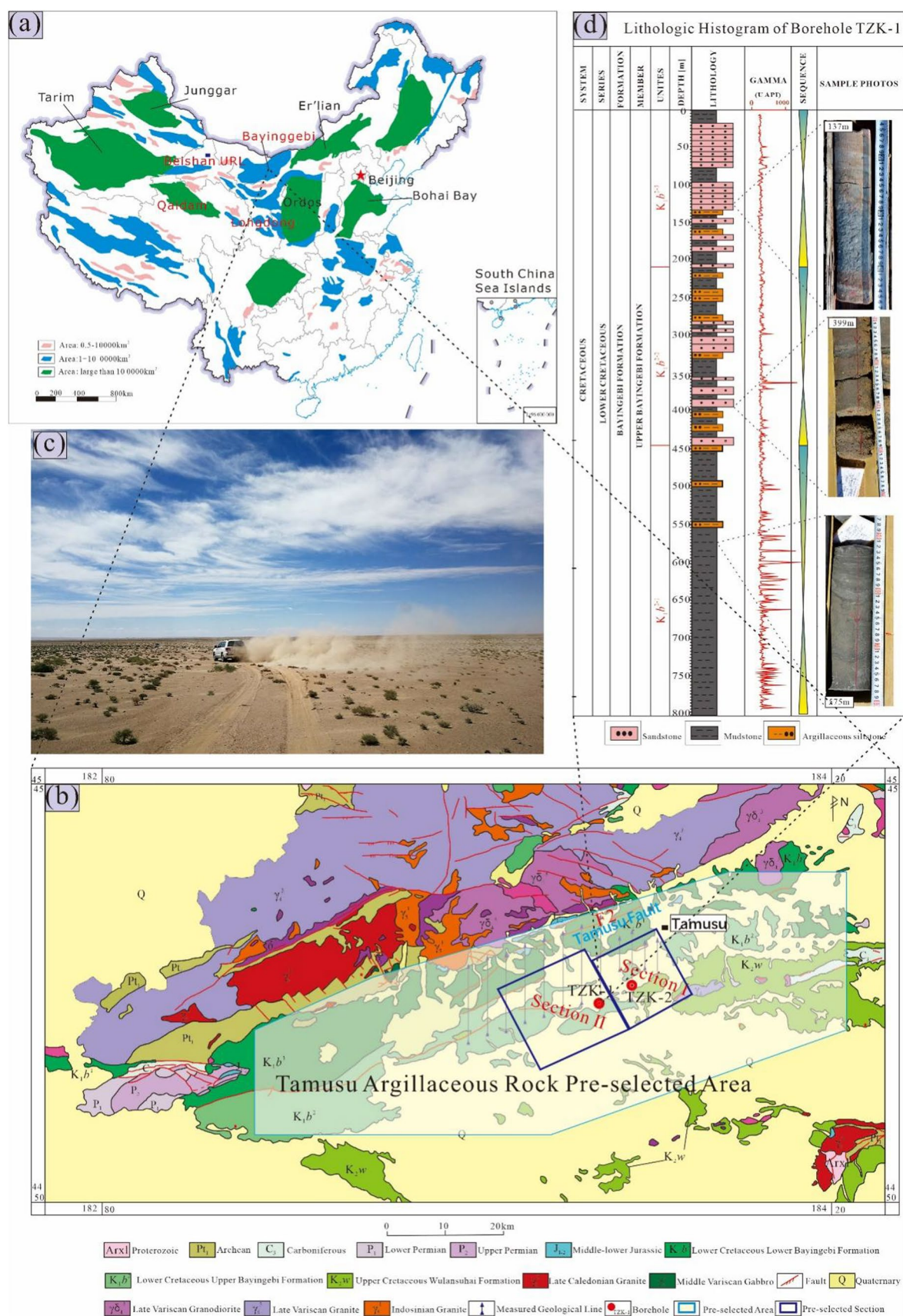


Fig. 2 Basic overview of Tamusu argillaceous rock pre-selected area

Table 2 Key areas and target formations for argillaceous-based site selections in China

Key areas	Target formations
Longdong area (Gansu Province)	The Lower Cretaceous, Huanhehuachi Formation
Nanbaxian area(Qaidam Basin)	The Oligocene Miocene,Ganchaigou Formation; Miocene, Youshashan Formation
Bayingebi basin(Inner Mongolia)	The Lower Cretaceous, Bayingebi Formation(K_1b^2)

Geological Disposal Facilities for Radioactive Waste” issued by the China National Nuclear Safety Administration, a technical guideline outline for argillaceous-based site, specifically targeting the mudstone site selection, in China has been proposed for the first time (Table 3). In view of technical guidelines, a preliminary suitability evaluation model for pre-selected areas has been further constructed to drive the site selection process.

The suitability evaluation index model, taking into account factors such as economic, social, natural geographic, and geological conditions, has been constructed to make comprehensive evaluations among the three pre-selected areas in the northwest region. More evaluation details would be found in literature by Prof. Liu [16]. The evaluation results recommended that the Tamusu pre-selected area would be the most suitable areas for pre-selected site screening.

Basic characteristics of Tamusu mudstone

Tamusu pre-selected area is under the jurisdiction of Tamusu Su Mu in Alxa Right Banner, Alxa League, and Inner Mongolia Autonomous Region. The area of Alxa Right Banner and Tamusu Su Mu are 73443 km² and 24,300 km², respectively. The permanent population of Alxa Right Banner and Tamusu Su Mu are 22,647 people and 900 people by 2020,

respectively, as well as a population density of 0.31 people per km² and 0.037 people per km², respectively. The initial geological and hydrogeological survey of Tamusu pre-selected area is approximately 3000km² (Fig. 2b). It belongs to arid and semi-arid desert areas with underdeveloped surface water systems and groundwater. Tamusu Su Mu belongs to a typical continental arid desert climate, which are characterized by cold winters and hot summers. The annual average temperature and precipitation are 5.8 °C and 85 mm, respectively. Frequent sandstorms from July to August and precipitation mostly concentrated from May to September. Extreme weather is a rare occurrence in this area. Researches on geophysical and crustal structure shows that the Tamusu pre-selected area is characterized by peneplain landforms (Fig. 2c) and a relatively stable tectonic environment [17, 18]. The fault activities in the Tamusu pre-selected area mainly occurred in the Cretaceous and before the Cretaceous. The Quaternary strata has not been dislocated by faults, indicating that there has been almost no obvious fault activity since the Quaternary. Detailed research on the Tamusu Fault (Fig. 2b) indicates that the fault has been in a stable state since (56.8 ± 5.2) ka [18, 19]. According to the classification standards of China earthquake intensity scale of I~XII, the seismic intensity in Tamusu pre-selected area is all classified below VI, and no earthquake with an M_s greater than 5 has ever occurred in that area [20].

Table 3 Outline of technical guidelines for mudstone site selection

Criteria	Contents
Geological	Screening site area; Target layer burial depth, continuous thickness, extensional width, attitude, mineral content, etc
Future natural changes	Volcanic activity; Fault distribution; Extreme disasters; Earthquake activity, etc
Hydrogeological	Groundwater depth, pH, Eh and age; Permeability coefficient, etc
Geochemistry	Nuclide migration pathways and diffusion coefficients; The quality of active substances contained in the host rock
Social and humanistic	Population density; City level and scale; Gross Domestic Product per Unit Area; Distance to available resources, etc
Construction and engineering	Uniaxial compressive strength; Rock damage stress under temperature and irradiation; Excavation disturbance zone; Rock strength and stress ratio, etc
Waste transportation	Distance from commercial spent fuel reprocessing plants; The distance connected to the road network; Difficulty in transportation routes; Probability of radiation hazards during transportation, etc
Environmental protection	Data and distance of important protected areas, important water bodies, and environmentally sensitive areas
Land use	Land use type; Land use value, etc
Social influence	The proportion of ethnic minority population; The attitude of local governments; Local public attitudes, etc

The Early Cretaceous Bayingebi formation, served as the potential host rock formation, could be divided into the lower Bayingebi formation (K_1b^1) and the upper Bayingebi formation (K_1b^2) [17]. Alluvial fan and fan delta systems developed mostly in the K_1b^1 , consisting of red detrital rocks that underwent a maximum burial depth of ~ 1400 m. The upper Bayingebi formation (K_1b^2), considered as the target formation, consists of a set of grey lacustrine mudstones and identifies at a maximum depth of ~ 911 m. And the target formation is chartered by widely distributed with a gentle attitude and a continuous thickness. The boreholes TZK-1 and TZK-2 were drilled in the Tamusu pre-selected area between June and August 2017. This was the first time that test boreholes were drilled to carry out evaluation of mudstone characteristics for argillaceous-based site selection purposes.

The core lithology from borehole TZK-1 highlights the interbedded mudstone–sandstone–mudstone structure of the target formation (Fig. 2d). In particular, the first unit with a maximum depth of ~ 200 m consists primarily of fine-grained sandstone and silty mudstone with thin argillaceous siltstone beds. The fine-grained sandstone is characterized by a massive structure and parallel bedding with a reddish-brown color. The second unit (200–450 m) is composed mainly of interbedded fine-grained sandstones and argillaceous siltstone. The third unit (450–800 m) consists of dark grey mudstone (Fig. 3). The entire target formation explored by borehole TZK-2 consists of dark grey mudstone, which indicates that borehole TZK-2 was located close to the depositional center of the lacustrine basin. Three layers of gray and dark gray mudstones could be vertically divided from borehole TZK-2: mainly layered mudstones from the surface to a depth of 320 m, continuous and uniform block mudstones from 320 to 540 m, and snowflake shaped mudstones from 540 to 800 m. Taking mudstone samples from TZK-2, the systematic researches on mineral composition, mechanical property, and chemical performance have been systematically carried out.

Mineral composition

Based on the whole-rock mineralogical analysis of 161 samples from TZK-2, the target mudstone formation is mainly composed of three mineral species: carbonates (dolomite and ankerite), albite and analcime. Specifically, three facies could be also distinguished (Fig. 3). The first facies (150–250 m) are mainly composed of analcime, carbonate, and albite, with average mass percentages are 26%, 19%, and 17%, respectively. The second facies (250–540 m) mainly consist of analcime, carbonate minerals and albite, with average mass percentages are 30%, 27% and 13%, respectively. The third facies (540–800.06 m) are mainly composed of carbonate minerals and albite, showing the smallest analcime mass percentages, with average mass percentages are 48%, 21%, and 10%, respectively. In addition, the total mass percentages of clay minerals are less than 10%. The specific clay mineral types and mass percentages are also investigated preliminarily by ethylene glycol solvation. 16 mudstone samples from TZK-2 after extracting clay minerals shows that the main minerals are illite and montmorillonite, with an average mass percentage of 58.6% and 32%, respectively. It could be concluded that there are significant differences in the mineral compositions between Tamusu mudstone and typical clay rock host rocks, such as COX clays and OPA clays. Further comparison indicates that the COX clay and Tamusu mudstone are mainly characterized as mixed mudstones (area D1, Fig. 4), with the clay mineral content being generally higher in OPA clays. The carbonate minerals of Tamusu mudstone are dominated by dolomite and ankerite, whereas calcite dominates in COX and OPA clay. It could be concluded that Tamusu mudstone belongs to one new kind of argillaceous medium for HLW disposal purposes, namely the containing analcime mudstone [21]. Obviously, the Tamusu mudstone has attracted a wide range of monographs due to its stable geological environment, suitable socio-economic conditions, and so on. The basic characteristics and preliminary evaluation on Tamusu

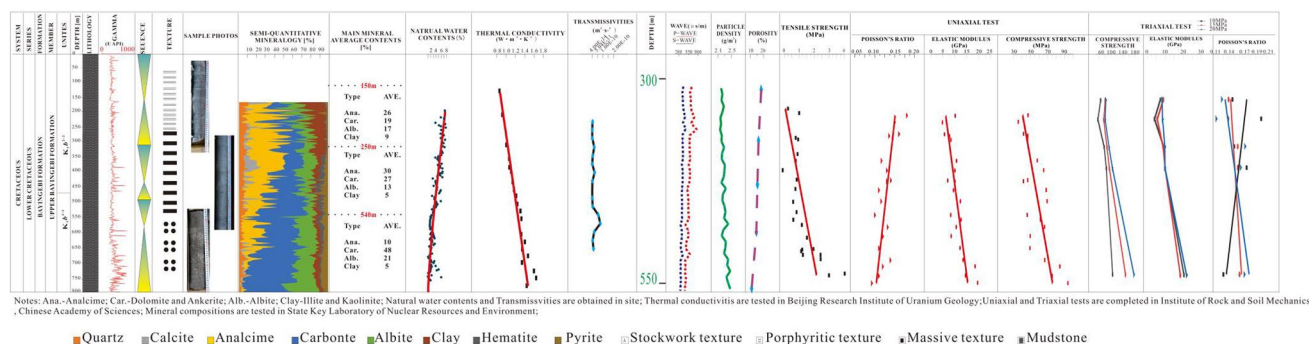
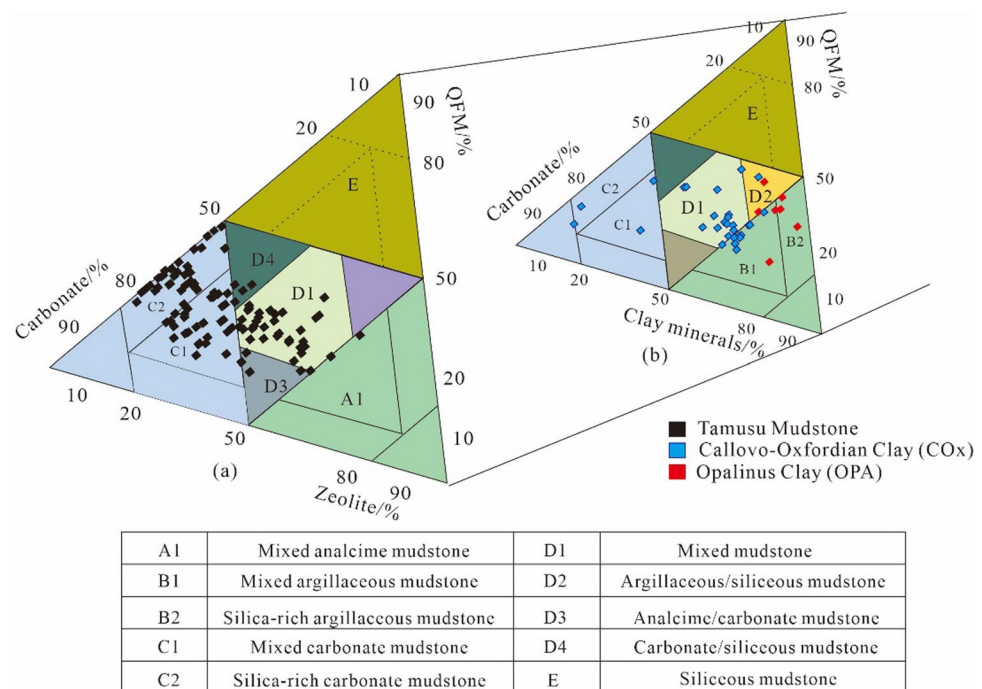


Fig. 3 Basic characteristics of Tamusu mudstones from borehole TZK-2

Fig. 4 Comparison of mineral compositions between Tamusu mudstones and typical foreign clay rocks chemical performance



mudstone in terms of mechanical and chemical properties have been also conducted.

Mechanical properties

Selecting the uniform block mudstones (300–550 m from borehole TZK-2), the systematic researches on mechanical properties, such as the wave, tensile strength, uniaxial, tri-axial tests are conducted (Fig. 3). As depth of tested samples increases, the elastic wave velocity significantly increases. A good correlation between the longitudinal wave velocity and transverse wave velocity could be observed. The average longitudinal wave velocity and transverse wave velocity of the tests samples are 3198.15 m/s and 1905.14 m/s, respectively. Within a depth range of 300 m to 475 m, the increasing in tensile strength is not significant with an average of 1.01Mpa. After the burial depth of tested samples exceeds 475 m, the tensile strength sharply increased with an average of 2.07Mpa. The uniaxial compressive strength and elastic modulus of tested samples show a stepped increasing at depths of 390 m and 510 m. The uniaxial compressive strength is distributed between 36 and 94 MPa, and significantly increased with depth. The uniaxial elastic modulus ranges from 4.35 to 19.56 GPa. The Poisson's ratio of tested samples are distributed between 0.09 and 0.18, showing a stepwise negative correlation with increasing depth. The triaxial compressive strength and elastic modulus of tested samples increase rapidly with depth, showing a two-step positive correlation. Poisson's ratio has no accurate variation

relationship, and the experimental results show a relatively discrete state.

The preliminary comparisons with typical clay rock parameters from abroad are shown in Table 4. It indicates that Tamusu mudstone may has more advantages in engineering construction. In addition, the a creep constitutive model, numerical analysis of Thermo-Hyermo-Mechanical coupling and evaluation on clay rock strata of Tmausu mudstone have been established, respectively by Yu recently [22], Zhang [23] and Gao [24].

In view of functions of analcime channels and molecular sieves, mudstones bearing analcime have advantages over typical host rocks in terms of radionuclide adsorption, water content, thermal stability and permeability [30]. As discussed in the case of the potential Yucca Mountain project [31] and for LLRW in Belgium [32], the function of zeolite has been demonstrated for blocking nuclide migration. Therefore, the preliminary chemical performances that focus on analcime and dolomite should be further analyzed. The adsorption behaviors of Eu(III) and Sr^{2+} on the synthetic dolomite and zeolite show good adsorption behaviors. Meanwhile, the Sr^{2+} adsorption processes are well described by pseudo-second-order kinetics model [33, 34]. Also, the preliminary mechanisms of Tamusu mudstone on redox reactions of U (VI)/ UO_2 and sorption of selenite have been obtained [35, 36]. Researches on the diffusion behaviors of nuclides with higher risk levels, such as HTO, Re(VII) and Se(IV) are systematically conducted and summarized in Table 5 [37].

Table 4 Comparison of physical and mechanical parameters between Tamusu mudstone and foreign clay rocks [2, 7, 25–29]

Countries parameters	France (COx clay)	Switzerland (OPA clay)	Belgium (Boom clay)	Chian (Tamusu mudstone)
Era(Ma)	145	180	30	135
Occurrence	Near horizontal	6°	6°	< 6°
Continuous thickness (m)	130	131	100	> 400
Moisture content (%)	2.8–8.7/6.7	5–8.9/6.6	28	0.74–9.97/5.45
Porosity (%)	9–18/14	14–25/17	54(< 2 μm)	13–25
Permeability (m/s)	10 ⁻¹⁴ –10 ⁻¹²	10 ⁻¹⁴ –10 ⁻¹²	2*10 ⁻¹² –4*10 ⁻¹²	10 ⁻¹⁴ –10 ⁻¹²
Block density (g/cm ³)	2.4±0.02	2.4–2.53	2.67	1.94–2.34
Particle density (g/cm ³)	2.7±0.01	2.74–2.79	–	2.61–2.69
Uniaxial compressive (Mpa)	12–49	23.1–28.1	2.0–2.2	36–94
Elastic modulus (GPa)	2.3–11	2.1–3.5	–	3.11–12.28
tensile strength (Mpa)	0.9–5.4	1–2	–	4–16
Poisson's ratio	0.17–0.4/0.3	0.28–0.38	0.4	0.14–0.48
Thermal conductivity(W*m ⁻¹ K ⁻¹)	1.47	1–3.1	level 2.33 vertical 1.77	1.12–1.64

* “–” indicates no data

Table 5 Diffusion parameters for partial nuclides obtained from Tamusu mudstone

Nuclides	Effective diffusion (m ² /s)	Apparent diffusion (m ² /s)	Test methods	Sample notes
HTO	4.49*10 ⁻¹⁰ –5.81*10 ⁻¹⁰	3.38*10 ⁻¹⁰ –4.62*10 ⁻¹⁰	Penetration diffusion	Compacted
R(VII)	10 ⁻¹⁰ –10 ⁻⁹		Penetration diffusion	Irradiated
Se(IV)	10 ⁻¹⁰ –10 ⁻⁹ (C); 10 ⁻¹² –10 ⁻¹³ (P)		Capillary diffusion	Powders

* C, means the Capillary diffusion and P means the Penetration diffusion

In summary, Tamusu mudstone not only has the characteristics of low permeability, strong adsorption and blocking properties that traditional clay rocks have, but also has better rock mechanical properties than traditional clay rocks. It also could effectively avoid and solve the problem of poor construction conditions in traditional clay rock engineering. Tamusu mudstone may be a new type of argillaceous host rock that combines low permeability and good engineering construction conditions. However, the advantages and disadvantages of Tamusu mudstone compared to host rocks remain to be assessed carefully in the future.

Recommended pre-selected sites

Based on the research results of geophysical exploration and connecting-well profiles, the analyses of sedimentary facies in Tamusu pre-selected area have been systematically carried out (Fig. 5a). Moreover, the lake basin evolution and the underground distribution pattern of the target mudstone layer have been preliminarily constructed under the guidance of shallow seismic. It has been verified that the continuous occurrence thickness of the target

layer (K_1b^2) should be greater than 400 m, and two sets of mudstone are vertically developed in the target layer (Fig. 5). The first set (upper layer) is shallower and buried about 450 m below the surface; the second set (lower layer) is buried at a depth of about 500–800 m, and the underground extension range is larger than the upper layer mudstone. Therefore, two pre-selected sections have been recommended in the Tamusu pre-selected area considered from main material components, rock structure and basic property parameters mentioned above. Actually, the two pre-selected sections belong to the upper section of the Bayingebi Formation mudstone. Pre-selected section I: with an area of approximately 220 km² and a depth of 300–550 m of mudstone occurrence; Pre-selected section II: with an area of approximately 245 km², the depth of occurrence of mudstone ranges from 480 to 800 m (Fig. 2b, Fig. 5b). Obviously, the mudstone buried depth of the two recommended sections occurred is different and there are no overlap in the plane. Also, according to disposal requirements, the recommended sections also could be considered as the safe disposal of LLRW purpose.

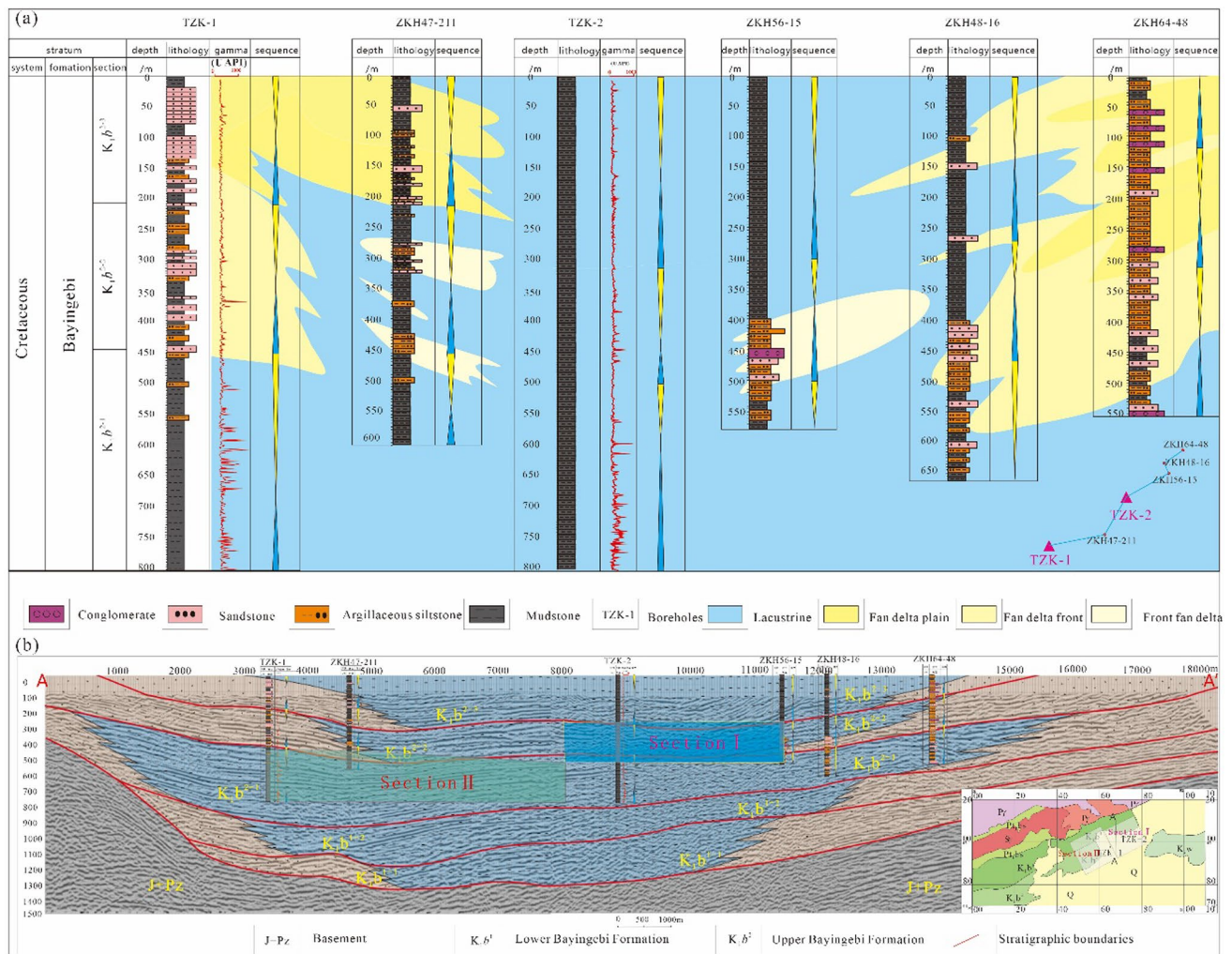


Fig. 5 Spatial distribution characteristics of Tamusu mudstones

R&D outlooks

The safe disposal of HLW are related to the sustainable development of the nuclear industry and must rely on one's own efforts to solve the problem within China's territory. After nearly 40 years of research and development, China officially began the construction of the Beishan granite URL, marking a new milestone in the research and development of geological disposal of HLW in China.

The initial strategy for argillaceous-based site selection aims at clay rock host rock, however, the mentioned two projects confirmed and demonstrated that Tamusu mudstone and Tamusu pre-selected area both have advantages for HLW disposal purposes. Experts from IAEA taking the Expert's Mission of IAEA TC-CPR9049/9050 program to Tamusu pre-selected area in 2017 and 2018 drew preliminary conclusions: "This is a potential new host rock formation for radioactive waste disposal, and the experience and results gained from European clay formations cannot

automatically be transferred to this new rock type. Hence, a comprehensive evaluation of this potential host rock and its specific characteristics with regard to rock suitability for final disposal of radioactive waste are of paramount importance" [38]. Meanwhile, a suitable roadmap and criteria for mudstone site selection has been established and has become the fundamental basis. Accelerating the mudstone site selection progress and then to provide host rock comparison basis are also requirements for future review and management decisions at the national level.

Therefore, follow-up projects for screening mudstone site at the national level would be approved as soon as possible. The follow-up projects are contributed to continuously making full use of the established multidisciplinary team to promote the evaluation of mudstone sites. Meanwhile, relying on in-depth geological, natural geographic, social, and economic surveys, the technical criteria system should be further improved to establish testing methods for safety evaluation. The safety of the disposal repository needs to

reach a scale of over ten thousand years, and more safety evaluations need to be conducted simultaneously. To sum, an underground research facility (URF) within the mudstone host rock in China should be first constructed and then to recommend at least two candidate sites for further comparative research.

Actually, seeking the application of the IAEA technical cooperation and to obtain sustained support from the IAEA are essential parts in the field of geological disposal of HLW. Especially, focus on further strengthening international cooperation and drawing on the research and development experience from French clay rock projects.

Conclusions

The research and development of geological disposal of HLW in China has entered a new milestone in terms of the construction of Beishan granite URL, while the screening of clay rock sites is still in the planning and site selection stage. A type of argillaceous media containing analcime (Tamusu mudstone) has been discovered and its suitability on mineral composition and mechanical properties have been preliminarily demonstrated. The preliminary evaluation system and indicators for Tamusu mudstone also have been constructed. Two pre-selected sites have been recommended in the Tamusu pre-selection area. Continuous project researches, even constructing a URF and enhancing international cooperation are essential to promote the development of argillaceous-based geological disposal of HLW in China.

Acknowledgements The authors gratefully acknowledge to Dr. Ju Wang (Beijing Research Institute of Uranium Geology) and Geological Team No.208, CNNC, for providing photos and the field data collection. This manuscript is financially supported by the National Natural Science Foundation of China (Grant No. 42302044), the State Key Laboratory of Nuclear Resources and Environment, East China University of Technology (2022NRE-LH-01), Key Laboratory for Digital Land and Resources of Jiangxi Province, East China University of Technology (DLLJ202210), and the Doctoral Program of East China University of Technology (DHBK2020017).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- IAEA TECHNICAL REPORTS SERIFS No. 413 (2003) Scientific and technical basis for geological disposal of radioactive wastes
- Witherspoon PA, Bodvarsson GS (2001) Geological challenges in radioactive waste isolation: Third worldwide review. Lawrence Berkeley National Laboratory. University of California, Berkeley, USA
- OECD (2013) Underground Research Laboratories (URL). Radioactive waste management, NEA/RWM/R (2013)2, p. 53. Cooperation and Organization for Economic Development, Paris, France
- Wang C (2024) Self-sealing of pre-cracked Callovo-oxfordian claystone: Implications for geological disposal of nuclear waste. *Int J Rock Mech Min Sci*. <https://doi.org/10.1016/j.ijrmms.2024.105678>
- Andra (2023) Submission of the construction licence application for Cigeo. ISSN: 2265–8467
- Nagra (2002) Project Opalinus Clay. Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste. Technical Report No. NTB 02–05. Nagra, Wettingen
- Bossart P (2017) Mont Terri rock laboratory, 20 years of research: introduction, site characteristics and overview of experiments. *Swiss J Geosci* 110:322
- Nagra (2022) The site for the deep geological repository. National Cooperative for the Disposal of Radioactive Waste
- China Nuclear Energy Association (2024) The report on the development of China's nuclear energy
- Wang J (2018) The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests. *J Rock Mech Geotech Eng* 10:411–435
- Wang J (2022) Site selection of underground research laboratory for geological disposal of high-level radioactive waste in China world nuclear geoscience. <https://doi.org/10.3969/j.issn.1672-0636.2022.01.001>
- Chen L (2023) Progress on rock mechanics research of Beishan granite for geological disposal of high-level radioactive waste in China. *Rock Mech Bullet* 2:100046
- Wang J (2023) Beishan underground research laboratory for geological disposal of high level radioactive waste in China-update 2023. *World Nucl Geosci*. <https://doi.org/10.3969/j.issn.1672-0636.2023.S1.001>
- Di Nucci M (2017) From the “right to know” to the “right to object” and “decide”. A comparative perspective on participation in siting procedures for high level radioactive waste repositories. *Prog Nucl Energy* 100:316–325
- Jobmann M (2017) Safety assessment methodology for a German high-level waste repository in clay formations. *J Rock Mech Geotech Eng* 9:856–876
- Liu P (2022) Investigation and screening of clay rock pre-selected area for high-level radioactive waste geological disposal repository. Science Press, Beijing
- Zhang C (2019) Characterization of ore-forming fluids in the Tamusu sandstone-type uranium deposit, Bayingobi Basin, China: constraints from trace elements, fluid inclusions and C-O-S isotopes. *Ore Geol Rev* 111:102999
- Gao H (2023) Geology of the Tamusu clay site for high level waste. *J Radioanal Nucl Chem*. <https://doi.org/10.1007/s10967-023-09228-1>
- Rao Z (2021) Fault activity in clay rock site candidate of high level radioactive waste repository. *Tamusu Inner Mongolia Minerals* 11(9):941
- Du J (2017) Estimation of the present-day stress field using in-situ stress measurements in the Alxa area, Inner Mongolia for China's HLW disposal. *Eng Geol* 220:76–84. <https://doi.org/10.1016/j.enggeo.2017.01.020>
- Xiang L (2020) Mineralogical and hydraulic characteristics of mudstone in the Tamusu candidate area in northwest China for high-level radioactive waste geological disposal purposes. *Clay Miner*. <https://doi.org/10.1180/clm>

22. Yu H (2023) Experimental and theoretical study on the creep behavior of Tamusu mudstone. *Chin J Rock Mech Eng.* <https://doi.org/10.13722/j.cnki.jrme.2023.1031>
23. Zhang J (2023) Numerical analysis of Thermo-Hyermo-Mechanical coupling of clay surrounding rock for high-level radioactive waste disposal repository. *Safety Environ Eng* 30:64–77
24. Gao H (2022) Evaluation of the suitability of clay rock sites for geological disposal of high-level radioactive waste in the Tamusu area, Inner Mongolia, China. *J Radioanal Nucl Chem.* <https://doi.org/10.1007/s10967-022-08654-x>
25. Distinguin M, Lavanchy J (2007) Determination of hydraulic properties of the Callovo-Oxfordian argillite at the Bure site: Synthesis of the results obtained in deep boreholes using several in situ investigation techniques. *Phys Chem Earth* 32:379–392
26. Bernier F, Li X, Bastiaens W, (2007) Twenty-five years' geotechnical observation and testing in the Tertiary Boom Clay formation. *Géotechnique* 57(2):229–237
27. Boulila S, Hinnov L, Huret E (2008) Astronomical calibration of the Early Oxfordian (Vocontian and Paris basins, France): consequences of revising the Late Jurassic time scale. *Earth Planet Sci Lett* 276:40–51
28. Yven B (2007) Mineralogy, texture and porosity of Callovo-Oxfordian argillites of the Meuse/Haute-Marne region (eastern Paris Basin). *Bull Soc Geol Fr* 178:73–90
29. Xiang L (2023) Genesis of host rock in the Tamusu Mudstone pre-selected area in Northwest China for high-level radioactive waste geological disposal purposes. *Swiss J Geosci* 116:6. <https://doi.org/10.1186/s00015-023-00434-3>
30. Yu H (2021) Permeability changes in fractured Tamusu mudstone in the context of radioactive waste disposal. *Bull Eng Geol Env* 80(10):7945–7957
31. Bish D (1999) Natural zeolites and nuclear-waste management: the case of Yucca mountain, Nevada, USA. Natural microporous materials in environmental technology. Springer, Netherlands, Dordrecht, pp 177–191
32. Misaelides P (2019) Clay minerals and zeolites for radioactive waste immobilization and containment. Modified clay and zeolite nanocomposite materials. Elsevier, Amsterdam, pp 243–274
33. Dong Y (2018) Adsorption of Sr^{2+} on dolomite and analcime. *Atom Energy Sci Technol* 52:1942–1948
34. Zhang H (2021) Sorption behavior of Eu (III) on dolomite. *J Nucl Radiochem* 43(5):418–425
35. He H (2019) Sorption of selenite on Tamusu clay in simulated groundwater with high salinity under aerobic/anaerobic conditions. *J Environ Radioact* 203:210–219
36. Kang M (2024) The redox reactions of U(VI)/UO_2 on Tamusu claystone: Effects of $\text{Fe}^{2+}/\text{Fe}^{3+}$ and organic matters. *Chemosphere* 348:140754
37. Xiao L (2023) Study on diffusion behavior of tritium, rhenium (technetium) and selenium in Tamusu clay rock in Inner Mongolia. Doctoral dissertation, East China University of Technology. <https://doi.org/10.27145/d.cnki.ghddc.2023.000005>
38. Landais P, Zhang C, Bossart P (2018) Siting of clay formation as the host rocks for high-level radioactive waste disposal repository. End-of-Mission Report, IAEA TC program CPR9050

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Reproduced with permission of copyright owner. Further reproduction
prohibited without permission.