Abstract: The Bayingobi basin is the Mesozoic–Cenozoic basin in North China in which the Tamusu uranium deposit is located. The ore-target layer of the deposit is the Lower Cretaceous Bayingobi Formation, which developed as a fan delta-shallow lacustrine deposit. The distributary channel sand body of the fan delta plain and the underwater distributary channel sand body of the fan delta front formed a favorable uranium reservoir, so the study of sequence stratigraphy is extremely important to understanding the genesis of uranium deposits. On the basis of field investigation and a large number of borehole logs, the high resolution sequence stratigraphy of the Lower Cretaceous is divided and the system tracts of different periods are established. The relationship between deposition, interlayer oxidation and uranium enrichment is discussed. The Lower Cretaceous Bayingobi Formation can be divided into two fourth-order sequences (Sq1 and Sq2). The lower member of the Bayingobi Formation is referred to as Sq1, which is composed of a falling-stage system tract (FSST) on top. On the other hand, the upper member of the Bayingobi Formation is referred to as Sq2, which is composed of a lowstand system tract (LST), transgressive system tract (TST) and highstand system tract (HST). The lowstand system tract forms a favorable stratigraphic structure (mud-sand-mud formation) with the lacustrine mudstone of the overlying transgressive system tract, that is conducive for the migration of uranium-bearing oxygen water. The organic matter and pyrite in the fan delta sand body, as well as the dark mudstone in the distributary bay, provided a reducing medium for uranium mineralization. The ore body mainly occurs in the distributary channel, underwater distributary channel or the mouth bar of the fan delta. As a result of the moderate thickness, high permeability, favorable barrier and rich reducing medium, the rich ore body mainly occurs in the underwater distributary channel and mouth bar sand body of the delta front. Based on study of the sequence stratigraphy, the model of the sequence, sedimentation and mineralization of the uranium deposit is established, which enriches uranium metallogenic theory and provides a reference for exploration of the same type of uranium deposits.

Key words: Bayingobi Formation, sequence stratigraphy, fan delta, uranium mineralization, Tamusu uranium deposit
sedimentology and other methods have been applied to study, explore, evaluate and use for prediction of sandstone type uranium deposits in the northern basins of China. Sequence stratigraphy has been used in the study of the Zhihuo Formation to the north of the Ordos basin and it shows itself to be a powerful tool in explaining the spatial location of uranium ore bodies (Jiao et al., 2015). The sequence C (Xishanyao Formation) in the southeast of the Turpan–Hami basin is classified into lowstand system tract, transgressive system tract and highstand system tract. Uranium mineralization occurs mainly in the lowstand system tract, the highstand system tract and the transgressive system tract is the secondary ore-bearing horizon (Wu et al., 2009). Uranium mineralization occurs mainly in the braided river and distributary channels of the braided delta (Wu et al., 2009). The third-order sequence of the Upper Cretaceous Yaojia Formation in the exploration target layer of the Qianjiadian–Baolongshan area, southwest of the Songliao basin, can be divided into a lowstand system tract, transgressive system tract and highstand system tract. The uranium mineralization occurs mainly in the lowstand system tract and transgressive system tract, which are closely related to the distributary channel of the braided delta (Rong et al., 2019). Different depositional system tracts (vertical and lateral) in the sequence have physical-temporal constraints on the uranium mineralization. Notably, spatial combination of system tracts plays a key role in the uranium mineralization. However, sandstone type uranium mineralization has not received detailed research on the sequence combination, characteristics and distribution of sedimentary construction with system tract, together with their role in uranium mineralization and/or exploration.

The Bayingobi basin in Northern China is a major source of coal, oil-shale, oil-gas and uranium. Studies show that the Tamusu uranium deposit is a fan delta and interlayer oxidation type (Liu et al., 2020). The upper member of the Bayingobi Formation is the main Lower Cretaceous target-layer (Zhang et al., 2015, 2019; Liu et al., 2018, 2020), which developed as a fan delta-shallow lacustrine deposit. Various studies have explored the characteristics of the oxidation zone (Zhang et al., 2015; Liu et al., 2017, 2020), ore-forming fluid (Liu et al., 2017; Zhang et al., 2019), sedimentary facies (Liu et al., 2020) and element geochemistry characteristics of the Tamusu uranium deposit (Liu et al., 2019; Zhang et al., 2019). However, the analysis of the construction elements of the sedimentary facies and high resolution sequence stratigraphy of the Tamusu uranium deposit has yet to be reported.

In the current study on the high resolution sequence stratigraphy of the Tamusu deposit, the authors divided the high resolution (fourth order) sequence of the uranium deposit and reconstructed the sedimentary system tract. This study also discusses the relationship between the sequence and spatial structure of the system tract (vertical and lateral) with the uranium mineralization. The lowstand system tract of the ore body occurrence has been studied, in order to understand the spatio-temporal distribution and controlling factors (e.g., sand body thickness, sand content, reducing medium, porosity and permeability) of the uranium mineralization. The factors have been comprehensively studied through establishing a sequence stratigraphy sedimentary metallogenic model of the fan delta and exploring the regularity of the uranium mineralization. The sequence-metallogenic model explains the vertical color zoning of the sandstone type uranium mineralization (Jin et al., 2019), resulting in the common sequence and post transformation effects (e.g., fluid migration and redox reaction).

2 Geological Setting

The Bayingobi basin is located to the south of the Central Asian Orogenic Belt (CAOB) in Inner Mongolia, China, within the northwest Mengen uplift. It is adjacent to the Langshan uplift in the southeast, the Nuorigiong uplift in the south and the Beishan uplift in the west (Fig. 1b) (Liu et al., 2018). The basin was formed during the extension of the Paleo-Asian Orogenic Belt (Xiao et al., 2018), which has inherited certain basement structure (Zheng et al., 2003) and is located adjacent to the Alxa block in the south (Zhang et al., 2018). The Bayingobi basin can be divided into a southern depression zone and a northern depression zone along the Zongnaishan–Shalazha Mountain uplift (Fig. 1b). The uranium deposits are mainly distributed in the southern depression zone.

The Zongnaishan–Shalazha Mountain uplift is a Paleozoic era island arc. The northern part (bounded by the Engeerwusu ophiolite belt) was the Paleozoic Engeerwusu Ocean, whereas the southern part (bounded by the Chaganchulu ophiolite belt (275 ± 3 Ma)) was the Chaganchulu Ocean (Fig. 1b). The middle Archean–Paleoproterozoic greenschist and amphibolite facies rocks are exposed in the Zongnaishan–Shalazha Mountain uplift (Xiao et al., 2018). During the Paleozoic era, a large volume of magma erupted with the subduction of the Engeerwusu Ocean (Fig. 1b).

The basement of the basin is Carboniferous-Permian marine strata (the Engeerwusu and Chaganchulu oceans), which are composed of greenschist facies rocks, metamorphic glutenite and carbonate rocks. Oil and gas have occurred in the Carboniferous–Permian reservoirs of both the Hari Sag and the Chagan Sag, which has greatly contributed to the oil and gas exploration industry (Lu et al., 2017). In addition, multiple prospecting areas have been predicted in the basin. The Cretaceous formations are the main part of this Mesozo–Cenozoic basin, consisting of the Lower Cretaceous Bayingobi and Suhongtu formations, with the Upper Cretaceous Ulansuhai Formation (Fig. 2) (Zhang et al., 2015; Liu et al., 2017a, b). The upper member of the Bayingobi Formation (late Barremian to early Aptian) mainly consists of clastic rock assemblages of different colors (Fig. 2). The Suhongtu Formation (late Aptian to Albanian) mainly consists of clastic rock and basalt, the basalt age of which is 116.7 ± 1.8 Ma to 105.5 ± 4.03 Ma (Zhang et al., 2014), which erupted during the rift period in the northern depression zone. The Late Cretaceous Ulansuhai Formation mainly consists of red clastic rocks deposited in a meandering river-floodplain setting.
Fig. 1. (a) The location of the Bayingobi basin in China; (b) geological map of the Bayingobi basin, divided into northern and southern depression zones; (c) geological map of the Tamusu uranium deposit.
The Tamusu uranium deposit is located in the Yingejing Sag of the Suhaitu depression in the southern part of the Zongnaishan–Shalazha Mountain (Fig. 1b). The Yingejing Sag is a rift type with the burial depth of the basement ranging from 0 to 2000 m, most of the basement ranging between 300 and 800 m (Fig. 3). The pre-Mesozoic basement rocks of this sag are composed of the Lower Proterozoic Beishan Group, consisting of middle and deep metamorphic rocks, with the Late Carboniferous Amushan Formation medium-acid pyroclastic volcanic rocks, clastic rocks and Jurassic terrigenous sediments. The Zongnaishan–Shalazha Mountain consists of Silurian to Triassic gabbro, diorite, granodiorite and granite rocks, which are characteristic of an island arc environment (Fig. 1c). Shi et al. (2014, 2015) studied the magmatic rocks of Zongnaishan–Shalazha Mountain, which are I-type resulting from depleted mantle, with high Sr and low Y, possibly being related to the CAOB subduction environment. Moreover, the granites, which consist of quasilinear to peraluminous, calc-alkaline to high potassium and calc-alkaline series, are rich in large ion lithophile elements and low in high field strength elements (Shi et al., 2015; Zhang et al., 2018). Uranium concentration in the granites ranges from 6.5 to 50.2 ppm, which is higher than the gabbro and diorite (0.2–1.2 ppm).

The Th/U ratio in granites ranges from 3.3 to 5.4, the uranium leaching rate ranging from 30% to 77.78%, however the most common leaching rates range from 30.00% to 49.20% (Liu et al., 2020).

The cap rocks in the sag consist of the Lower Cretaceous Bayingobi Formation and the Upper Cretaceous Ulansuhai Formation (Figs. 1c, 2), depending on the unconformity surface (Fig. 2). The Bayingobi Formation can be divided into upper and lower members, the sandstone-hosted uranium deposits occurring in the upper member of the Bayingobi Formation (Figs. 2, 3; Zhang et al., 2019; Liu et al., 2020), which is mainly composed of conglomerate, gravel medium-to-coarse grained sandstone, fine- to coarse grained sandstone, sandy siltstone, siltstone, silty mudstone, calcareous mudstone and mudstone (Zhang et al., 2019; Liu et al., 2020). The Ulansuhai Formation lies unconformably on the Bayingobi Formation and consists of meandering river and flooding plain deposits, mainly distributed in the middle of the Yingejing Sag (distributed in a limited scope in the south east) as it is absent/eroded from the south and north of the sag, leaving the Bayingobi Formation directly exposed (Fig. 1c). It is mainly composed of fine sandstone, siltstone and mudstone (Fig. 2). Uranium mineralization mainly occurs in the transition period of
paleoclimate from warm and moist, semi-humid or semi-arid, humid or semi-humid, semi-arid or semi-arid of Lower Cretaceous to the hot and arid of Upper Cretaceous (Zhang et al., 2015, 2019; Liu et al., 2020) (Fig. 2).

3 Materials and Methods

A database of boreholes in the ore deposit was established, based on systematic core observation and well-logging data of 44 boreholes. The third order sequence was divided based on the recognition and interpretation of the stratigraphic reflection interface in seismic section. The lithology, sedimentary structure, paleontological characteristics and uranium mineralization of the strata, as well as the classified sedimentary facies types, have been described through field outcrop investigation and detailed core observation. System tract and strata stacking patterns of the fourth sequence were classified and boundary markers established through core observation, seismic profile, well-logging curve and sedimentary facies research.

Sequence boundary surface and system tract identification, division and correlation, thickness of stratum, sand body, mudstone and sandstone/stratum percentage, as well as a series of isoline maps and depositional system maps were determined using the stratigraphic sequence. The relationship between uranium minerals and associated minerals or clastics was studied using 10 samples of uranium-bearing sandstone samples, collected from drill cores. The samples were made into thin sections without glass covers and analysed using a field emission scanning electron microscope (SEM, Nova NanoSEM 450, FEI Czech Co., Ltd). SEM analysis was carried out in the State Key Laboratory of Nuclear Resources and the Environment, East China University of Technology. SEM and X-MAX electric refrigeration X-ray energy spectrometer (EDS, Oxford Instruments, UK) were used to study the morphology and elemental composition of the uranium and associated minerals or clastics. Prior to analysis, thin-sections were placed into a drying vessel for gold coating using a sputtering coater, the images being captured using a retractable solid-state back-scattered electron detector. The indoor temperature was set at 20 ± 2°C and the humidity was maintained below 80%. A vacuum state was maintained for the bulk of the

Fig. 3. (a–b) A–B seismic profile map of the Tamusu uranium deposit (see Fig. 1c for location); (c) the transgressive system tract (TST) is onlap to the lowstand system tract in the upper member of the Bayingobi Formation; (d) there are obvious offlaps and downlaps in the interface between the lowstand system tract (LST) of the upper member of the Bayingobi Formation and the falling-stage system tract (FSST) of the lower member of the Bayingobi Formation; (e) the basal surface of forced regression (BSFR) at the bottom of the upper member of the Bayingobi Formation can be seen as the offlap surface, the lowstand system tracts of the Bayingobi Formation onlap or downlap the top of the falling-stage system tracts (FSST).

At the top of the profile, a transgressive system tract (TST) and highstand system tract (HST) are denuded at the basin margin. BSFR = basal surface of forced regression; SU = subaerial unconformity; CC = correlative conformity; MRS = maximum regressive surface; TSE = transgressive surface of erosion; MFS = maximum flooding surface.
instruments. The working distance of the SEM-EDS was 1–60 mm with a beam voltage of 30–50 kV, a magnification of 100–600000 being used.

4 Results

4.1 Facies associations

The lake shoreline is an important boundary for sediment transport from land to lake (James and Dalrymple, 2010). Fluvial flows carry terrigenous detritus to the lake for deposition, forming a delta. The fan delta deposits are mainly developed in the Bayingobi Formation at the edge of the depression, the lacustrine facies being developed in the center of the depression. The fan deltas can be classified into fan delta plain subfacies, fan delta front subfacies and prodelta subfacies.

4.1.1 Fan delta facies association

(1) Fan delta plain facies association

The fan delta plain mainly occurs in the middle and lower part of the upper member of the Bayingobi Formation. The lithofacies is composed of Gm, Gp, Gt, Gh, St, Sp, Sl, Sh, Sr, followed by Fl, Fsm, Fm and C (Fig. 4, Table 1). The fan delta plain consists of the distributary channel, natural levee, crevasse fan and the distributary bay. The apparent resistivity curve of the fan delta plain is toothed-bell type, or toothed funnel-shaped, with a thickness of more than 20 m, characterized by upward fining (Fig. 4).

The distributary channel gradually becomes smaller from the edge to the center of the basin, the sediment grain size becoming finer, the lower part is laterally accreting while the upper part vertically accretes (Fig. 4). The distributary channel in the fan delta plain is composed of Gm, Gp, Gt, Gh, St, Sp, Sl, Sh and Sr, the grain size gradually becoming finer towards the basin center, which is composed of Gh, St, Sp, Sl, Sh, Sr, followed by Fl, Fsm, Fm and C (Figs. 4a, b). These observations have indicated that it formed from the upper delta plain to the lower delta plain (Reading, 1996). At the bottom of the distributary channel in the upper delta plain, lenticular conglomerate and glutenite are poor-to-moderately sorted, the grains being sub-angular to sub-rounded shapes, with a thickness of 0.2 to 0.5 m. Massive bedding and weak parallel bedding (Gm) were developed in this part (Figs. 4a, 5a), the pebble imbricate arrangement (Gh) (Fig. 5d), scour surface and gravel retention sedimentation being found at the bottom of the distributary channel (Fig. 5d). The main components of the rocks are quartz, feldspar, granite debris and metamorphic debris, which are distributed discontinuously in a transverse direction and transform into the distributary bay mudstone. At the bottom of the distributary channel, the lenticular conglomerate is mainly composed of sandy conglomerate and sandstone, which are moderate-to-well sorted and 0.05 m to 0.6 m thick. The lenticular conglomerate is characterized by plate cross-bedding (Gp, Sp) (Figs. 4a, 5a, d), trough cross-bedding (Gt, St) (Figs. 5b, d) and parallel bedding (Gh, Sh) (Fig. 5c). There is neither carbon fragment nor pyrite in the distributary channel of the upper delta plain (Fig. 4a).

Fig. 4. Typical facies assemblage of the Bayingobi Formation of the Tamusu uranium deposit. (a) Distributary channel of fan delta plain (upper delta plain); (b) underwater distributary channel of fan delta plain (lower delta plain); (c) mouth bar of fan delta front; (d) underwater distributary channel of fan delta front; (e) lacustrine. The lithofacies symbols refer to table 1.
<table>
<thead>
<tr>
<th>Lithofacies code</th>
<th>Lithofacies</th>
<th>Rock and clastic composition</th>
<th>Sedimentary characteristics</th>
<th>Geometric shape</th>
<th>Fossil</th>
<th>Sedimentary facies association</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gm</td>
<td>Conglomerate and gravelly sandstone</td>
<td>Granite debris, granodiorite debris, metamorphic debris, quartz, feldspar</td>
<td>Weak parallel bedding, eroded basement, sub-angular to sub-round, poor to medium sorting</td>
<td>Lenticular, 0.1-0.5 m thick</td>
<td>Carbonized plant debris, locally</td>
<td>Distributary channel of fan delta plain</td>
</tr>
<tr>
<td>Gp</td>
<td>Conglomerate, gravel sandstone</td>
<td>Granite debris, a small amount of metamorphic debris, quartz, feldspar</td>
<td>Plate cross bedding, channel erosion, sub-angular to sub-round, poor to medium sorting</td>
<td>Plate, 0.05-0.3 m thick</td>
<td>Carbonized plant debris, locally</td>
<td>Distributary channel of fan delta plain</td>
</tr>
<tr>
<td>Gt</td>
<td>Glutinitic conglomerate</td>
<td>Granite debris, a small amount of metamorphic debris, quartz, feldspar</td>
<td>Trough cross bedding, channel filling, sub-angular to sub-round, poor to medium sorting</td>
<td>Plate, 0.05-0.4 m thick</td>
<td>Carbonized plant debris, locally</td>
<td>Distributary channel of fan delta plain</td>
</tr>
<tr>
<td>Gh</td>
<td>Pebble and conglomerate supported by clasts</td>
<td>Granite debris, a small amount of metamorphic debris, quartz, feldspar</td>
<td>Parallel bedding, imbricate structure, sub-angular to sub-round, poor to medium sorting</td>
<td>Layered, 0.1-0.6 m thick</td>
<td>Carbonized plant debris, locally</td>
<td>Distributary channel of fan delta plain</td>
</tr>
<tr>
<td>St</td>
<td>Fine to coarse sandstone, gravel medium to course sandstone</td>
<td>Quartz, feldspar, a small amount of granite debris, metamorphic rock debris</td>
<td>Trough cross bedding, scour surface, wedge bedding, sub-round to round, medium to well sorting</td>
<td>Lenticular, rough, 0.1-0.3 m thick</td>
<td>Carbonized plant debris</td>
<td>Distributary channel of fan delta plain and underwater distributary channel of fan delta front</td>
</tr>
<tr>
<td>Sp</td>
<td>Fine to coarse sandstone, gravel medium to course sandstone</td>
<td>Quartz, feldspar and a small amount of granite debris</td>
<td>Plate cross bedding, wedge bedding, sub-round to round, medium to well sorting</td>
<td>Plate and wedge, 0.1-0.5 m thick</td>
<td>Carbonized plant debris</td>
<td>Distributary channel of fan delta plain and underwater distributary channel of fan delta front</td>
</tr>
<tr>
<td>SI</td>
<td>Fine to coarse sandstone, gravel fine to coarse sandstone</td>
<td>Quartz, feldspar, a small amount of granite debris, a few of heavy minerals</td>
<td>Low angle cross bedding, sub-round to round, medium to well sorting</td>
<td>Layered, lenticular, 0.1-0.3 m thick</td>
<td>Carbonized plant debris</td>
<td>Distributary channel of fan delta plain and underwater distributary channel of fan delta front</td>
</tr>
<tr>
<td>Sh</td>
<td>Fine to course sandstone</td>
<td>Quartz, feldspar, a few of granite debris, a few of heavy minerals, mica</td>
<td>Parallel bedding, sub-round to round, medium to well sorting</td>
<td>Layer and plane, 0.1-0.5 m thick</td>
<td>Carbonized plant debris</td>
<td>Distributary channel of fan delta plain and underwater distributary channel of fan delta front</td>
</tr>
<tr>
<td>Sr</td>
<td>Fine to medium sandstone</td>
<td>Quartz, feldspar and a few of rock debris</td>
<td>Ripple cross bedding, sub-round to round, well sorted</td>
<td>Layered, 0.1-0.3 m thick</td>
<td>Carbonized plant debris</td>
<td>Distributary channel of fan delta front</td>
</tr>
<tr>
<td>Fl</td>
<td>Siltstone with fine sandstone, argillaceous siltstone and mudstone</td>
<td>Quartz, feldspar</td>
<td>Horizontal bedding, ripple bedding, sub-round, well sorting</td>
<td>Layered, 0.05-1 m thick</td>
<td>Carbonized plant debris</td>
<td>Swamp of fan delta plain, crevasse fan, mouth bar, prodelta</td>
</tr>
<tr>
<td>Fsm</td>
<td>Siltstone, argillaceous siltstone</td>
<td>Quartz, feldspar, a few of mica</td>
<td>Massive</td>
<td>Layered, more than 0.1-1 m</td>
<td>Large amount of carbonized plant debris</td>
<td>Swamp of fan delta plain distributary bay, mouth bar, fan delta front</td>
</tr>
<tr>
<td>Fm</td>
<td>Mudstone, siltstone, gravel siltstone</td>
<td>Quartz, feldspar, a few of granite debris, mica</td>
<td>Massive, locally mud crack, gravel is sub-angular sub-round</td>
<td>Layered and lenticular, 0.05-1 m thick</td>
<td>Large amount of carbonized plant debris</td>
<td>Distributary bay of fan delta plain, underwater distributary bay of fan delta front, crevasse fan, prodelta, shallow lake</td>
</tr>
<tr>
<td>C</td>
<td>Carbonaceous mudstone and dark mudstone</td>
<td>Quartz, feldspar, organic carbon, and thin layer pyrite</td>
<td>Horizontal bedding</td>
<td>Layered, 0.05-0.3 m thick</td>
<td>Large amount of carbonized plant debris</td>
<td>Prodelta, shallow lake</td>
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</table>
Fig. 5. The sedimentary structures of the fan delta plain in the upper member of the Bayingobi Formation of the Tamusu uranium deposit.

(a) Distributary channel of fan delta plain with weakly parallel bedding developed (Gm) and plate bedding glutenite (Gp), the clastic composition being quartz, feldspar and debris; (b) distributary channel of fan delta plain with trough cross-bedding glutenite and conglomerate developed (Gt); (c) distributary channel of fan delta plain develops parallel bedding glutenite and conglomerate (Gh); (d) at the bottom of the distributary channel in the fan delta plain, there are imbricated conglomerates (Gh) and parallel-bedded conglomerates (Gh) in the upper part, which are transformed into trough cross-bedding (Gt) and plate cross-bedding (Gp), the gravel consisting of quartz and debris; (e) the fan delta plain with ripple cross-bedding fine sandstone developed (Sr); (f) the Ulansuhai Formation lies on the upper Bayingobi Formation with an unconformable contact; (g) fan delta plain distributary bay is developed with horizontally bedded mudstone (c).
The distributary channel of the lower fan delta plain is mainly composed of Gm, St, Sp, Sl, Sh and Sr (Fig. 4b, Table 1). The bottom of the distributary channel is characterized by detention deposits and channel deposits (Fig. 6a). Scour surfaces and imbricated gravels occur at the bottom of the detention deposits in a directional arrangement (Fig. 6a). The distributary channels in the fan delta plain are stacked vertically by several distributary channels (Fig. 8). The middle and lower parts of the distributary channels were filled with yellow, red and gray, gray-white conglomerate, glutenite, gravel-bearing coarse-to-fine sandstone, coarse sandstone, medium-to-fine sandstone, siltstone and mudstone. The distributary channel sandstones in the basin are well-sorted, sub-rounded and 10 to 30 m thick. These sandstones developed trough cross-bedding (St) (Figs. 6b, d), plate cross-bedding (Sp) (Fig. 6c), graded bedding and parallel bedding (Sh) (Figs. 6e, 7b). The middle and upper parts of the distributary channels were filled with fine sandstone, siltstone and mudstone, with ripple bedding (Sr) (Fig. 7a) and horizontal bedding (Fl) (Fig. 7c). Substantial amounts of carbonated plant detritus and pyrite occur in the distributary channel sand body of the lower delta plain.

The natural levee mainly consists of siltstone, silty mudstone, fine sandstone and a little gravel-bearing sandstone (Fig. 8). The distributary bay is located between the distributary channel, which is mainly composed of dark swamp mudstone, argillaceous siltstone and peat, with a coal line present in some parts (Fig. 6f), characterized by horizontal bedding (Fl) (Fig. 5g). A large quantity of carbonized plant debris has developed in the dark mudstone and silty mudstone, thin layer subdivided scattered pyrites having been found in the local mudstone with developed bioturbation structure, locally (Fig. 4b). The crevasse fan deposit occurred at the edge of the fluvial channel, with reverse graded bedding. They consist of thin
red-brown gravel-bearing siltstone, siltstone, mudstone and fine sandstone.

(2) **Fan delta front facies association**

The delta front is the part between the lake level at the average low water level and the normal wave base during the average low water level period (Jin et al., 2014). The delta front is a process by which the river enters the basin, sediments unloading and interacting with the basin (Reading, 1996). In the upper member of the Bayingobi Formation, the differentiation of the fan delta front facies combination mainly depends on drilling and logging data (the fan delta front is covered by the Ulansuhai Formation of the Upper Cretaceous and Quaternary, without field outcrop). The fan delta front is mainly composed of lithofacies Sp, St, Fl, Sh, Sl, Sr, Fl, followed by Fsm, Fm and C (Fig. 4, Table 1). The apparent resistivity curve occurs as a toothed-funnel shape (Figs. 4, 8). The component facies of this association consists of an underwater distributary channel, underwater distributary bay and underwater natural levee with a mouth bar, with vertically occurring reverse graded bedding (Fig. 4). The underwater distributary channel, mouth bar and underwater distributary bay are the main sedimentary bodies of the fan delta front, whereas the natural levees are mostly reconstructed by the later river channel and so are not developed.

The underwater distributary channel, which was mainly filled with gray, brown-yellow, maroon-red sandy

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**Table 1**

<table>
<thead>
<tr>
<th>Formation</th>
<th>Apparent resistivity</th>
<th>Depth (m)</th>
<th>Lithology</th>
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**Fig. 8.** Identification of drilling, logging curve, system tract and sequence boundary of the Tamusu uranium deposit.

SU = subaerial unconformity; CC = correlative conformity; MRS = maximum regressive surface; MFS = maximum flooding surface; FSST = falling-stage system tract; LST = lowstand system tract; TST = transgressive system tract.
conglomerate, gravel-bearing sandstone and medium-coarse sandstone, was lenticular with mudstone and argillaceous siltstone occurring at the top (Fig. 4d). It is composed of lithofacies Sp, St, Sh, followed by Fsm, Fm and C (Fig. 4d, Table 1). The main components are quartz, feldspar and a small amount of lithic debris. The sandstone is well-sorted, the grains being sub-round to round in shape. The scour surface occurs at the bottom of the channel sandstone with detrition deposition. Trough cross-bedding (St) and plate cross-bedding (Sp) occurred in the middle and lower sandstone, while ripple bedding (Sr) and massive bedding (Sm) occurred in the upper part. The top is characterized by mudstone and argillaceous siltstone with horizontal bedding. The carbonated plant detritus and pyrite have deposited in the channel sandstone, top mudstone and argillaceous siltstone.

The mouth bar developed in a sheet shape and was mainly composed of gray, yellow and maroon fine sandstone, pebbly-fine sandstone, gravelly medium sandstone and coarse sandstone with inverted graded bedding. Lithofacies in this region are composed of Sm, St, Sh, SI and Fl in inverted grain sequence (Fig. 4c). The main components of the sandstone are quartz, feldspar and small amounts of mica. The sandstone is well-sorted and sub-rounded to rounded in shape, with the occurrence of trough cross-bedding (St), parallel bedding (Sh), low angle cross-stratification (SI), massive bedding (Sm) (Fig. 7a), local drainage structures (Fig. 7e) and deformation bedding (Fig. 7d). In the vertical superposition of the mouth bar, the grain size and the cycle layer gradually become coarser and thicker (Figs. 4, 8).

The underwater distributary bay developed between the underwater distributary channel and the mouth bar, mainly being composed of gray mudstone, siltstone, argillaceous siltstone and fine sandstone (Fig. 8). The lithofacies forming the underwater distributary bay are Fsm, Fm and C with horizontal bedding developed (Figs. 4c, d). Large amounts of carbonated plant debris and thin pyrite have been deposited in the distributary bay.

(3) Prodelta facies association

The front delta is mainly composed of black mudstone (Fm), argillaceous siltstone and siltstone (Fm, Fl) and has horizontal bedding developed (Fl, C) (Fig. 7h, Table 1), as well as local drainage structures and deformation bedding. The fine-grained sediments are rich in organic matter (such as carbonated plant debris) and has a thin layer of pyrite developed.

4.1.2 Shallow lacustrine facies association

Shallow lacustrine deposits mainly occur at the center of the basin, consisting mainly of dark gray, light gray mudstone, siltstone and a thin layer of fine-grained sandstone, characterized by horizontal bedding (Fl, C) (Fig. 4, Table 1). A turbidity sandstone, which is massive, well-sorted and round, was observed in lacustrine mudstone. The mudstone is rich in organic matter and pyrite. A layer of carbonized plant debris and a thin layer of pyrite occurs in the horizontal lamination.

4.2 Sequence stratigraphic characteristics

The Lower Cretaceous Bayingobi Formation third-order sequences can be divided into two fourth-order sequences, namely, the lower member of the Bayingobi Formation (Sq1) and the upper member of the Bayingobi Formation (Sq2), based on interpretation of the seismic section (Fig. 3). The Sq1 can be divided into a lowstand system tract (LST), transgressive system tract (TST), highstand system tract (HST) and falling-stage system tract (FSST), the Sq2 being divisible into lowstand system tract (LST), transgressive system tract (TST) and highstand system tract (HST) (Fig. 3, Table 2).

4.2.1 Stratal stacking patterns

Changes in geometrical trend and depositional trend in the process of shoreline change can be used to describe stratigraphic framework (stratal stacking patterns). Diagnostic stratal stacking patterns reflect the type of shoreline trajectories: forced regression (i.e., progradation and erosion), normal regression (i.e., progradation and aggradation) and transgression (i.e., retrogradation and aggradation) sequences.

In this study, the member of the formation is a fourth-order sequence (10^2–10^3 m), the system tract is a fifth-order sequence (10–10^2 m), whereas the stratal stacking patterns of sedimentological units are the lowest rank system tracts (10^3–10^4 m). The time limit of basic stratal stacking patterns are equivalent to a commonly used ‘coarsening-upwards’ (delta system) or a ‘fining-upwards’ (fluvial system) at different scales (Li et al., 1992). The stratal stacking patterns that define system tracts can be observed at different scales, from high frequency to first order sequence, depending on attainable stratigraphic resolution (i.e. on the data being available). In this study, different stratal stacking patterns were used to define the system tract of the sedimentary environment of different parts of the Tumusur uranium deposit through core observation and well-log interpretation.

Fan delta-shallow lacustrine deposits are the main component of the Lower Cretaceous upper member of the Bayingobi Formation. The fan delta stratal stacking patterns result from a combination of distributary channels, underwater distributary channels and mouth bars formed by the relative rise of the lake level (normal regression). Scour surface at the bottom of the channel (Fig. 8), retained glutenite at the bottom and coarse sandstone forms the bottom boundary of the stratal stacking patterns. The fan delta plain stratal stacking patterns are composed of several upward-thinning cycles, mainly composed of the distributary channel at the bottom and the channel edge at the top. The log resistivity curve is finger-shaped and gradually bell-shaped (Fig. 8). Several upwards-thickening architectures (sequence) form the fan delta front stratal stacking patterns (Figs. 4, 8). Fan delta front mud occurs at the bottom, the top is underwater distributary channel and mouth bar deposit, the apparent log resistivity curve being gradually funnel-shaped. The prodelta and shallow lake consist mainly of gray mudstone, the apparent resistivity curve being finger-shaped and flat (Fig. 8).
Table 2 Characteristics of sequence system tract classification and its relationship with uranium mineralization

<table>
<thead>
<tr>
<th>Fm/Mb</th>
<th>Sequence</th>
<th>System tract</th>
<th>Stratal stacking patterns</th>
<th>Division basis</th>
<th>Facies</th>
<th>Relationship with uranium mineralization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulansuhai Formation</td>
<td>Sq1</td>
<td>FST</td>
<td>Force regression.</td>
<td>The top is the unconformity surface and the corresponding conformity surface, the seismic reflection is internal reflection, forming an offlap surface, and the apparent resistivity curve is a sudden finger funnel shape. The bottom is the forced regression erosion surface.</td>
<td>Fine-grained fan delta-lacustrine facies</td>
<td>Mudstone and siltstone are rich in organic matter, provided reduce material for uranium mineralization, and have high uranium content.</td>
</tr>
<tr>
<td></td>
<td>Sq2</td>
<td>TST</td>
<td>An upward thinning cyclic formed by transgression or retrogradation.</td>
<td>At the bottom is the maximum recession surface and at the top is the maximum flooding surface. At the top is the onlap surface formed by the highstand system tract.</td>
<td>Fine-grained fan delta-lacustrine facies</td>
<td>Forming a favorable regional aquiclude restricted the migration of uranium-bearing oxygen water.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LST</td>
<td>Normal regression, with aggradation and progradation, occurred in coarsening upward cyclic, and the distributary channel showed finer upward deposition. The thickness of sedimentary cyclic increases upward.</td>
<td>The bottom is unconformity. The seismic section shows the downlap surface (in the basin) and the onlap surface (at the edge of the basin) in the early stage of the lowstand system tract, and the apparent resistivity curve is in the shape of finger bell or funnel. The maximum regression surface (MRS) is located at the top of the channel, which is partially eroded by the lake.</td>
<td>Fan delta-lacustrine facies</td>
<td>The distributary channel sand body was developed with obvious vertical superimposition, forming favorable reservoir for uranium mineralization. Meanwhile, the sand body is rich in carbonized plant debris, pyrite, etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HST</td>
<td>Normal recession at highstand coarsening upward deposition formed by progradation and aggradation, and fine upward channel deposition in distributary channel. The thinness of upward sedimentary cyclic became thinner.</td>
<td>Most of HST are eroded at the top and were in unconformity contact with the Ulansuhai Formation of the upper Cretaceous. At the bottom is the maximum flooding surface of transgressive system tract and at the top of the maximum flooding surface is the downlap surface. The apparent resistivity curve is finger funnel or bell shaped.</td>
<td>Fine-grained fan delta-lacustrine facies</td>
<td>Formation of regional aquiclude is beneficial to the migration of uranium-bearing oxygen water.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HAST</td>
<td>A vertical superposition of the meandering river, with several upward thinning sedimentary cyclic.</td>
<td>Unconformity contact between the bottom and the top of Bayingobi Formation.</td>
<td>Meandering river-flood plain deposit</td>
<td>It is favorable for the migration of uranium-bearing oxygen water to the basin.</td>
</tr>
</tbody>
</table>

4.2.2 Sequence boundary

The Lower Cretaceous Bayingobi Formation can be divided into two fourth-order sequences (Sq1 and Sq2), based on classification of system tracts. Core observations indicate that the sequence stratigraphic subaerial surface is mainly composed of sharp changes in lithological surface, lithofacies and unconformity interface. Sq1 consists of calcareous mudstone and silt mudstone at the top of the falling-stage system tract (FSST), to coarse clastic rocks such as glutenite, gravel-sandstone and sandstone in the lowstand system tract of Sq2 (LST) (Fig. 8, Table 2). For example, in the lower part of sequence Sq2 (borehole ZK32-16), prodelta mudstone and small-scale turbidite sand bodies (lowstand fan) were developed (Fig. 9). The top of Sq2 is the unconformity surface between the Lower Cretaceous Bayingobi Formation and the Upper Cretaceous Ulansuhai Formation (Figs. 2, 5f, 8). The Ulansuhai Formation had developed meandering river-flood plain red clastic rocks in the arid and hot climate (Fig. 2).

Different reflection interfaces and their combined characteristics between different system tracts on the seismic section were observed (Fig. 3, Table 2). The base surface of forced regression (BSFR) occurs at the bottom of the falling-stage system tract, the unconformity surface (SU) and its corresponding conformity surface (CC) occur at the top, whereas the onlap surface was formed at the bottom of the lowstand system tract (Fig. 3). The unconformity surface occurs at the bottom of the lowstand system tract, the maximum regressive surface (MRS) occurs at the top. This formed a downlap at the falling-stage system tract at the bottom of the basin and an onlap at the edge of the basin. The transgressive system tract is an onlap and it can be seen from the top that it locally eroded the underlying strata. The downlap surface of the highstand system tract occurs on top of the transgressive system tract (Fig. 3). The well-logging curve is mainly used to divide the sequence boundary (Fig. 8, Table 2). A sharp change is observed at the sequence boundary on the well-logging curve (Sq1 and Sq2).

4.2.3 System tract

The system tract is composed of depositional systems related to each other contemporaneously and controlled by its interface, which is formed from subdivision of a sequence (Zecchin and Catuneanu, 2013; Catuneanu, ...
Fig. 9. Typical profile of line 32 in the Tamusa uranium deposit.
System tracts are interpreted based on stratal stacking patterns, types of bounding surfaces and stratigraphic relations (Catuneanu, 2019). Different system tracts are located in various sedimentary environments and have different boundary division marks. Galloway (2004) defined a system tract as a sediment dispersion system that is composed of sedimentary systems deposited at a certain period.

The fourth-order sequence of Sq2 in the Tamusu uranium deposit can be divided into 3 individual system tracts, based on the 4-component method of high resolution sequence stratigraphy (Zecchin and Catuneanu, 2013; Catuneanu, 2019). The 3 individual system tracts include lowstand system tracts (LST), transgressive system tracts (TST) and highstand system tracts (HST).

The falling-stage system tracts of the lower member of Sq1 (Bayingobi Formation) occur at the bottom of the lowstand system tracts of Sq2 (the upper member of the Bayingobi Formation) (Figs. 3, 8, 9). Different system tracts are composed of different stratal stacking patterns and correspond to different seismic reflection surfaces and well-log curve shapes (Table 2).

Forced regression stacking patterns (progradation and degradation) form the falling-stage system tract (FSST) of Sq1. The falling-stage system tract is bound at its base by the base surface of forced regression (BSFR) (Catuneanu, 2019), eroding the top of the highstand system tract of Sq1 (Fig. 3), and bound at the top by the landward subaerial unconformity and its correlative conformity in the basinward lacustrine deposits (Fig. 3). The base surface of forced regression (BSFR) and unconformity shows strong reflection in the seismic section (landward) whereas the conformity shows weak reflection in the lacustrine facies (basinward). The apparent resistivity curve shows a sharp finger-funnel shape (Fig. 8). At this area, the basin is dominated by fine-grained clastic rocks with high organic matter content. In addition, a large number of the uranium-fertilite rock series (such as granite and metamorphic rock) in the source area are eroded and transported to the center of the basin through weathering. It is worth noting that the uranium concentration in the mudstone is as high as 73.90 ppm (Xiang et al., 2019).

Fan delta stratal stacking patterns of normal regression (progradation and aggradation) mainly occurred in the lowstand system tract (LST) of Sq2 (Martins Neto and Catuneanu, 2010; Li et al., 2018; Catuneanu, 2019). The bottom is mainly composed of subaerial unconformity from the shoreline trajectory to the edge of the basin (landward) and relative conformity of the lacustrine (basinward) (Fig. 3, Table 2). It is characterized by sharp channeled truncations, formed by fan delta distributary channel erosion (Zecchin and Catuneanu, 2013). The apparent resistivity curve has a finger-funnel shape and the scour surface at the bottom of the fan delta distributary channel is visible (Figs. 4, 8). The seismic section shows a downlap surface near the center of the basin (basinward) and an onlap surface at the edge of the basin (landward) (Fig. 3). The upper boundary is the maximum regressive surface (the largest regression surface, MRS) (Helland-Hansen and Martinsen, 1996; Zecchin and Catuneanu, 2013). This surface was modified in part by the lake transgressive surface of erosion, which was shown as the local lack of mudstone at the top of the delta distributary channel (Fig. 8). The upper boundary in the seismic section shows an onlap surface developing at the beginning of lake transgression and the resultant apparent resistivity curve shows a gradual finger-bell shape (Figs. 3, 8). The architecture of the lowstand normal regressions shows an increase in the thickness of fan delta plain (topset) and fan delta front (foreset) sequence, from the bottom to the top (Fig. 8). This implies that the rate of progradation and aggradation following the rate of shoreline upstepping and forestepping (a coarsening-upward and shallowing-upward succession), had increased over time during lowstand normal regressions (Catuneanu, 2019). The lowstand system tracts were prograded into fan delta plain from the early fan delta front and prodelta (Fig. 9). During this period, fan delta sand bodies have developed with apparent vertical superposition. Furthermore, plant detritus and pyrite were deposited in the sand body, that formed a favorable uranium reservoir.

Fan delta-shallow lacustrine deposits and retrogradational stratal stacking patterns of transgression are the main constituents of the transgressive system tract (TST) of Sq2 (Fig. 8). Maximum regression surface (MRS) occurs at the base of the transgressive system tract (TST), whereas maximum flooding surface (MFS) forms the upper boundary (Figs. 8, 9). On the seismic section, an onlap surface shows the bottom of the transgressive system tract (TST), due to the erosion of the top of the lowstand system tract, locally, that formed the lake transgressive surface of erosion (TSE) at the edge of the lake shoreline (Fig. 3). The downlap surface of the highstand system tract (HST) occurs at the top of the transgressive system tract, in addition to the maximum flooding surface (MFS). The transgressive system tract and highstand system tract were denuded (locally absent) in Sq2. The apparent resistivity curve is toothed-bell shape, funnel-shaped locally, turning to toothed-flat shape in the later stage (Fig. 8). In this period, the sediment supply of the basin was less and mainly constituted lacustrine facies deposition. In addition, the retrogradation of fan delta facies with fine-grained terrigenous clastic rock occurred at the edge of the basin (landward), due to the elevation of the relative base level.

Normal regression stacking patterns (progradational and aggradational) are the main constituents of the highstand system tract (HST) of Sq2. The maximum flooding surface (MFS) occurs at the base (Table 2) accompanied by erosion of fan delta distributary channels and a subaerial unconformity surface eroded by forced regression at the top (the top of the upper member of the Bayingobi Formation, Sq2) is denuded and the Ulansuhai Formation rests unconformably upon the Bayingobi Formation) (Fig. 9). At the local core scale, the highstand systems tract is followed by transgression, whereas the maximum regressive surface (MRS) occurred on the upper boundary (Fig. 8). The seismic section shows that the highstand system tract is a downlap on the top of the transgressive system tract (Fig. 3). In addition, the highstand system tract was mostly uplifted and eroded (stratum missing) at the edge of the basin in the later stage.
of sedimentation. The apparent resistivity curve was a toothed-funnel shape. The amplitude of apparent resistivity is higher than that of the transgressive system tract and lower than that of the lowstand system tract (Fig. 8, Table 2).

The fan delta deposits of Sq2 mainly occur in the lowstand system tract. In the period of the lowstand system tract (Early Cretaceous), because the relative base level falls rapidly and there is a large amount of sediment supply (the falling-stage system tract formed accommodation space), a large-scale distributary channel of the fan delta plain, the underwater distributary channel of the fan delta front and mouth bar deposits developed. As a result of the rise of the relative base level, the distributary channel of the fan delta laterally accreted and developed a coarsening-upward trend (shallow upward) deposits. Normal regression (progradation and aggradation) caused vertical superposition of distributary channel deposits in the fan delta plain and developed fining-upwards trending deposits (shallow-water setting). The underwater distributary channel deposits of the fan delta front occurred in the transgressive system tract, locally. The highstand system tracts mainly developed fan delta front deposits with a coarsening-upwards trend in the early stage of the highstand system tracts. The falling-stage system tract mainly developed lacustrine fine grade deposits occurring at the top of the sequence (Sq1) with abrupt lithological (lithofacies) and resistivity curve contacts.

4.3 Deposition system and sand body distribution

There are different types of depositional systems in different system tracts of sequence stratigraphy. The fan delta-lacustrine facies of falling-stage system tracts (FSST) mainly occurred on the top of the Sq1 sequence (the top of the lower member of the Bayingobi Formation), whereas the fan delta is mainly composed of the underwater distributary channel of the fan delta front and the fan delta plain is not developed. The thickness of the sand body is in the range from 10 to 25 m, with poor continuity. In the vertical direction of the Sq2 sequence, the fan delta-shallow lacustrine deposits occurred in the lowstand system tract, fine-grade lacustrine facies deposits were developed in the transgressive system tract, whereas small-scale fan delta-lacustrine facies deposits occurred in the highstand system tract.

Uranium mineralization mainly occurred in the fan delta deposits of the lowstand system tract of sequence Sq2 (the upper member of the Bayingobi Formation) (Fig. 10). Fan delta plain, fan delta front and prodelta developed in the fan delta from north to south of the Tamusu uranium deposit (Fig. 11). These composed the early stage progradation type to the late stage aggradation type of of the lowstand system tract (Fig. 9). The distributary channel of the fan delta plain, the underwater distributary channel of the fan delta front and the sand body of the mouth bar have developed. The sand body occurs as a lobate shape with a decrease in thickness from east to west (Fig. 10a). The sand body changes from thick to thin and gradually transitions to the prodelta and lacustrine facies mudstone along the direction of delta development (from north to south). The distributary channel sand body of the fan delta plain, underwater distributary channel sand body of the fan delta front and mouth bar sand body are the main constituents of the uranium reservoir, the uranium mineralization being limited at the channel edge and distributary bay (only a small amount of uranium mineralization occurring).
4.4 Interlayer oxidation zone and environmental geochemical characteristics

The interlayer oxidation zone has developed from north to south and can be divided into oxidation zone (intense oxidation zone, weak oxidation zone), oxidation-reduction transition zone and reduction zone (Zhang et al., 2019; Fig. 11). The uranium ore bodies mainly occur in the oxidation-reduction transition zone and are controlled by the front of the oxidation zone. Environmental index samples were collected from the intense oxidation zone (red oxidation zone), weak oxidation zone (yellow oxidation zone), oxidation-reduction transition zone, reduction zone, mudstone ore zone and non-ore bearing mudstone (Liu et al., 2020) (Supp. Table 1).

The main rocks in the red oxidation zone are maroon argillaceous siltstone, fine sandstone to coarse sandstone and gravel sandstone. In these samples, Fe$^{2+}$ content was 0.25 to 2.47%, averaging 0.92%; Fe$^{3+}$ content was 0.19 to 3.84%, averaging 1.88%; TOC content was 0.02 to 6.30%, averaging 0.73%; CO$_2$ content was 0.16 to 19.82%, averaging 3.89%; S$^2-$ content was 0.01 to 0.42%, averaging 0.17% and S$_{total}$ content was 0.01 to 8.38%, averaging 1.52%. The content of ΔEh was 13 to 41 mv, with an average of 23 mv (Fig. 12).

The main rocks in the oxidation-reduction transition zone are dark gray to gray, fine sandstone to coarse sandstone, including gravelly medium sandstone and coarse sandstone. Samples collected from this zone showed Fe$^{2+}$ content of 0.26 to 1.99%, averaging 1.00%; Fe$^{3+}$ content of 0.25 to 3.30%, averaging 1.55%; TOC content of 0.01 to 7.94%, averaging 1.53%; CO$_2$ content of 0.19 to 11.57%, averaging 5.03%; S$^2-$ content of 0.01 to 2.16%, averaging 0.93%; S$_{total}$ content of 0.01 to 3.49%, averaging 2.16%. The content of ΔEh was 41 to 64 mv with an average of 57 mv. The content of uranium was 0.01 to 0.33%, with an average of 0.10% (Fig. 12).

The main rocks in the reduction zone are gray siltstone, fine sandstone to coarse sandstone, including gravel medium to coarse sandstone and glutenite. Samples collected from this zone showed Fe$^{2+}$ content of 0.54 to 2.22%, with an average of 1.49% (Fig. 12); Fe$^{3+}$ content of 0.19 to 3.20%, with an average of 1.45%; TOC content of 0.06 to 1.49%, with an average of 0.57%; CO$_2$ content of 1.94 to 19.05%, with an average of 6.14%; S$^2-$ content of 0.02 to 1.46%, with an average of 0.48%; S$_{total}$ content of 0.05 to 0.99%, with an average of 0.05 to 0.99%. The content of ΔEh was 62 to 81 mv, with an average of 71 mv.

The main rocks of the ore-bearing mudstone are dark-gray to gray mudstone, calcareous mudstone, calcareous siltite.
mudstone and silty mudstone. Fe$^{2+}$ content of samples from this zone was 0.43 to 3.50%, with an average of 1.51%; Fe$^{3+}$ content was 0.05 to 4.65% (Fig. 12), with an average of 2.29%; TOC content was 0.02 to 13.96%, with an average of 2.82%; CO$_2$ content was 0.68 to 25.48%, with an average of 13.29%; $S^2-$ content was 0.01 to 5.56%, with an average of 1.24%; $S_{\text{total}}$ content was 0.01 to 6.72%, with an average of 1.58%; $\Delta$Eh content was 49 to 86 mv, with an average value of 61 mv and uranium content was 0.01 to 0.53%, with an average value of 0.16%.

The main rocks of the non-ore-bearing mudstone were gray to dark gray mudstone, calcareous mudstone, calcareous silty mudstone and silty mudstone. These rocks...
had Fe\(^{2+}\) content of 1.39 to 2.19%, with an average of 1.76%; Fe\(^{3+}\) content was 0.32 to 4.01%, with an average of 2.65%; TOC content was 0.29 to 2.68%, with an average of 1.60%; CO\(_2\) content was 3.87 to 26.36%, with an average of 12.98%; S\(^2\) content was 0.06 to 2.90%, with an average of 0.48% and S\(_{\text{total}}\) content was 2.06%.

5 Discussion

Based on analysis of the sequence stratigraphy and sedimentary filling of the Tamusu uranium deposit, the sequence, sedimentary characteristics and uranium mineralization characteristics of the deposit were statistically analyzed and discussed.

5.1 Sequence stratigraphy and uranium mineralization

The Lower Cretaceous Bayingobi Formation is the main uranium-bearing layer of the Tamusu uranium deposit, which lies on the angular unconformity of the Carboniferous–Permian basement (Fig. 3). The falling-stage system tract (FSST) mainly occurred on top of sequence Sq1. The forced recession caused erosion of the basin margin and a large amount of uranium-enriched granites and siliciclastic rocks in the source area (Zongnaishan–Shalazha Mountain) were transported to the basin. The FSST mainly developed lacustrine dark mudstone and argillaceous siltstone with high organic content, the uranium content of the fine clastic rocks being up to 73 ppm (Xiang et al., 2019). The organic-rich fine clastic rocks in the falling-stage system tracts provided an indirect reducing medium for uranium mineralization. The pore fluid in the fine-grained sediments was gradually released due to compression, the uranium-rich pore fluid migrating to the lowstand system tract sand body providing a partial uranium source for uranium mineralization (Table 2).

After the deposition of the falling-stage system tract of Sq1 in the Early Cretaceous (unconformable contact with Sq2, the upper member of the Bayingobi Formation), the Zongnaishan–Shalazha Mountain was rapidly uplifted. As a result of the rapid uplift, the basin deposited the lowstand fan delta sedimentation of Sq2 (Fig. 3). The fan delta distributary channel is the main part of the fan delta deposit and the distributary channel sand body forms a favorable uranium reservoir sand body with an average of 3.30 ppm, which provides a source of uranium for uranium mineralization (Liu et al., 2020) (Fig. 14, Table 2). The distributary channel sand bodies are mainly composed of glutenite, medium to coarse sandstone and fine sandstone with good permeability. The sandbodies are characterized by their large scale, stable thickness and good connectivity, which provide a channel for the migration of uranium-bearing oxygenated water and a place for uranium precipitation (Table 2). The transgressive system tract (TST) occurs above the lowstand system tract. It mainly consists of shallow lacustrine fine-grained sediments (silty mudstone and mudstone), which developed with the rise of the relative base level and formed a favorable aquiclude at the top (Table 2). In addition, the transgressive system tracts formed prodelta lenticular sand bodies and/or lacustrine turbidite sand bodies, locally. The fine-grained sediments restricted the migration of uranium-bearing oxygenated water, migrating along the sand bodies. During this period (TST), the enriched-uranium granites and sedimentary rocks that came from the Zongnaishan–Shalazha Mountain uplift were transported by fluvial means (distributary channel) and trapped in organic-rich dark mudstone in the basin. This is favorable for the formation of synsedimentary type uranium mineralization. Due to uplift of the Zongnaishan–Shalazha Mountain in the Early Cretaceous, the transgressive system tracts were eroded in the northern part of the basin. As a result of the erosion of the TST, the LST was exposed to the subsurface and formed erosion windows. This provided favorable conditions for the migration of uranium-bearing oxygenated water into the basin (Fig. 1c).

The highstand system tract is mainly composed of a highstand normal regression sand body, locally, along with lacustrine fine-grained sediments such as mudstone and argillaceous siltstone. The highstand sand body is small in scale and poor in connectivity. In the late Early Cretaceous, with the uplifting of the Zongnaishan–Shalazha Mountain, the top cover of the highstand system tract underwent long-term erosion, which, as it was in unconformable contact with the Ulansuhai Formation, lacked a favorable barrier. Due to the lack of a favorable uranium reservoir sand body, barrier and uranium source conditions, it was difficult for uranium mineralization to occur (Table 2).

5.2 Deposition and uranium mineralization

5.2.1 Depositional system

Uranium ore bodies occur in the fan delta plain, fan delta front and some lacustrine mudstone. A series of sand body thickness, sand content (sandstone/stratum percentage) and mudstone thickness maps were compiled, based on the statistics from 44 boreholes. Based on this data and other parameters, the depositional system map of the lowstand system tract of Sq2 was compiled. The results showed that the large-scale distributary channels of the delta plain and delta front are developed in the lowstand system tract (LST). In addition, the distributary channels are distributed NW and NNW to the SSE, the fan delta distributary bay occurring between the distributary channels overlapping vertically and locally migrating laterally. Statistics of the uranium mineralization data (Table 3) show that uranium ore bodies were mainly located in the fan delta distributary channel of the lowstand system tract, partly in the redox transition zone of the underwater distributary channel of the fan delta front, with a few in the delta distributary bay. Uranium ore bodies are mainly distributed at the junction formed by distributary channel and bay (the thickness of the mudstone is 50 to 175 m, mostly between 100 and 150 m) (Fig. 10c) and the overlapping part of the distributary channel and prodelta mudstone (the thickness of the mudstone is 175 to 375 m, mostly between 150 and 175 m). This indicates that the organic matter directly or indirectly developed in the dark mudstone of the distributary channel and a limnetic deposit provided a reducing medium for uranium mineralization (Fig. 10c).
5.2.2 Stability and thickness of the sand body
The stability and thickness of the sand bodies significantly affects uranium mineralization (Hu et al., 2019). Uranium mineralization mainly occurs in the distributary channel of the fan delta plain and partly in the underwater distributary channel sand body of the fan delta front, rarely in the lacustrine mudstone. The thickness and sand content in the distributary channel sand bodies were stable and high, respectively. Through analysis of the sand thickness/content of the lowstand system tract of Sq2, it was demonstrated that the mineralization mainly occurred in the sand bodies with a thickness of 140 to 260 m (Fig. 10a) and a sand content of 0.45 to 0.80 (Fig. 10b). In addition, the highest grade uranium mineralization mainly formed with a sand content of 0.55 to 0.65. The thick sand body of the distributary channel has good connectivity. This is conducive to the formation of high-grade uranium mineralization, when the uranium-bearing oxygenated water migrated in the sand body, under the action of a certain thickness of distributary bay mudstone (the mudstone at the top of the distributary channel).

5.2.3 Porosity and permeability of the sand body
The sand body porosity and permeability affects uranium mineralization. The main ore-bearing sand bodies are distributary channels of the fan delta plain and underwater distributary channel sand bodies of the fan delta front (LST), which are generally homogeneous. They mainly consist of medium-coarse sandstone, medium sandstone and fine sandstone. It is difficult to get a complete succession of porosity and permeability data from the sand body because of the core recovery rate and sampling discontinuity. However, we can get obtain the sequence of porosity and permeability of the strata through interpretation of the geophysical logging curves (Hu et al., 2019), which suggests that the porosity and permeability differ in the different sedimentary facies (Fig. 13).

The underwater distributary channel sandstone (fan delta front) has better porosity (0.37) and permeability (0.85) than the distributary channel sandstone of the fan delta plain, with a maximum porosity of 0.30 and permeability of 0.75 (Fig. 13). The sample tested also showed that the porosity and permeability of the underwater distributary channel sand body were better than the distributary channel sand body (Yao et al., 2015). This is consistent with the interpretation of the logging curves. Uranium ore bodies mostly occurred in the redox transition zone of the fan delta plain and the fan delta front. It suggests that the uranium-bearing fluid migrated along the sand body of the channel with better porosity and permeability in the lowstand system tract. As a result of the reduction of the thin mudstone and the carbon fragments in the sand body at the distributary channel in the lowstand fan delta, the uranium in the ore-bearing fluid was gradually unloaded and formed the tabular orebody (between the redox transition zone and the redox front line).

5.2.4 Characteristics of the reducing medium of the sand body
The main uranium minerals in the sand body are pitchblende, uraninite and a few titanium-bearing uranium minerals (Zhang et al., 2019). The uranium minerals mainly occur in the interior and margin of rock-forming minerals, cement and plant debris (Fig. 14). The precipitation of uranium minerals is mainly influenced by the organic matter (e.g., carbon, plant debris), pyrite and clay minerals in the sand body. The organic matter is an important reducing medium and adsorbent for uranium. Abundant terrigenous plant detritus brought by the channels during the sedimentary period provided a good reducing environment for uranium mineralization (Figs. 14a, f). In addition, pores, formed by clayification of feldspar and other minerals in sandstone, provide space for the formation of pyrite and the precipitation of uranium minerals, as well as the adsorption of uranium on to the surface.

Pyrite is the most common and important mineral in sandstone type uranium deposits, as it provides a reducing medium for uranium precipitation. It can provide a direct reducing medium for uranium precipitation, in addition to enhancing the reducing ability of the reservoir. Fine-grained and agglomerated pyrite occurs in the channel sand body of the fan delta, locally (Fig. 14b). Pyrite in the channel sand body mainly occurs in the pores of the feldspar surface and micro-cracks of minerals (Figs. 14c, d), plant clastic cracks and plant cell cavities (pyrite metasomatically grows in the plant cells) (Fig. 14e). The pitchblende, uraninite and titanium-bearing uranium minerals are closely associated with pyrite and organic matter (Fig. 14f).

Comparing the Fe$^{3+}$, Fe$^{2+}$, TOC, CO$_2$, S$^{2-}$, S$_{min}$, ΔEh and U content of the ore in the intense red oxidized sandstone, yellow oxidized sandstone, transition zone (ore-bearing sandstone), reduction zone sandstone, ore-bearing mudstone and non-ore mineralization mudstone, it could be seen that the Fe$^{2+}$, CO$_2$ contents are highest in the oxidation zone (Fig. 12, Supp Table. 1) and the contents of Fe$^{3+}$, S$^{2-}$ and U in the yellow oxidation zone are slightly higher than those in the red oxidation zone. This implied that the pyrite in the gray sandstone was oxidized from the edge of the basin to the inner basin and the Fe$^{2+}$ was gradually oxidized to Fe$^{3+}$ (the rock was oxidized to red) during the process of groundwater infiltration. In addition, part of the iron, which provided the iron element for the deep sand body, was lost and formed pyrite in the

<table>
<thead>
<tr>
<th>Sequence</th>
<th>System tract</th>
<th>Number of industrial hole</th>
<th>Number of mineralized hole</th>
<th>Number of abnormal hole</th>
<th>Number of non-mineralized hole</th>
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</thead>
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<tr>
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<td>0</td>
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<td>44</td>
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<tr>
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<td>2</td>
<td>40</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>44</td>
</tr>
</tbody>
</table>
oxidation-reduction transition zone, whereas part of the Fe$^{2+}$ formed iron dolomite (Zhang et al., 2016). The sulfur in the meteoric water and pyrite in the grey sandstone were oxidized (the rocks were oxidized to red) to SO$_4^{2-}$ and migrated to the basin. The SO$_4^{2-}$ ions were reduced to pyrite in the oxidation-reduction transition zone (Zhang et al., 2016, 2019). The redox transition zone (ore zone) has higher Fe$^{2+}$, Fe$^{2+}$/Fe$^{3+}$, TOC, S$_{total}$, S$_2^-$, $\Delta$Eh and U content and the Fe$^{3+}$ and CO$_2$ contents are relatively low. This indicates that pyrite and carbonated plant debris in the sandstone provided an important reducing medium for uranium mineralization. The uranium in the basin is primarily transported as [UO$_2$(CO$_3$)$_2$]$^{2-}$ (Zhang et al., 2019). During the process of uranium precipitation, the [UO$_2$(CO$_3$)$_2$]$^{2-}$ gradually decomposes, releasing a large amount of CO$_2$, which results in an increase of CO$_2$ content.

5.3 Sequence and sedimentary metallogenic model

A metallogenic model was established in the Tamusu uranium deposit, based on analysis of the common controlling factors of sequence and sedimentary filling related to uranium mineralization.

In the period of the falling-stage system tract (FSST) of Sq1, the basement rocks (granites and ancient strata) were eroded and transported from the source area to the basin, forming an unconformity surface at the basin margin and a relatively conformable surface in the basin (Fig. 15a), mainly developing lacustrine dark organic-rich mudstone. Furthermore, the lacustrine facies organic-rich mudstone was in direct contact with the fan delta distributary channel sand body of the lowstand system tract (LST) (Fig. 15a).

In the late Early Cretaceous (140–128 Ma), as a result
of the closing and collisional orogeny of the Mongolia–Okhotsk Ocean (Han et al., 2015; Zuo et al., 2015; Liu et al., 2017), the northern part of the Suhongtu depression became extensional and erupted basalt-andesite rocks. The U-Pb dating of the zircons from the basalt-andesite rocks gave isochron ages of 131.8 ± 5.9 Ma to 132 ± 0.7 Ma, indicating that significant faulting occurred along the Engeerwusu fault (Wang et al., 2016; Chen et al., 2019). Furthermore, because the Siberian plate moved rapidly southwards from 70°N, the basin rose rapidly from north to south (the rate of uplift was 40–55 m/Ma) and the Permian oil and gas system was damaged in the southern depression zone (vertical asphalt veinlets were found in the mudstone) (Han et al., 2015). In addition, the regional unconformity surface (SU) of Yingejing Sag was formed at the top of the falling-stage system tract of Sq1 (Figs. 3, 15a). As a result of the deposition and compaction of the lacustrine mudstones, the reducing pore fluid in the dark mudstone migrated upwards, providing a reducing medium for uranium mineralization.

The distributary channel and underwater distributary channel sand bodies of the fan delta were developed in the lowstand system tract (LST) (Fig. 16a), which had better permeability and porosity, reasonable sand body
thickness, a rich reducing medium (e.g., plant debris, reducing S) and a regional aquiclude layer. The transgressive system tract (TST) and highstand system tract (HST) mainly formed the regional aquiclude and a few fan delta distributary channel sand bodies, in which it is difficult to form uranium mineralization.

During the late Early Cretaceous (115 Ma–105 Ma) (Figs. 2, 15b, 16b) period, there was an obvious regional extension in the basin, due to it being compressed by the Pacific Ocean Plate (SW–NE) and the Siberian Plate (NW–SE) (Zuo et al., 2015). The eruption of basalt (sedimentary Suhongtu Formation) (Zhong et al., 2014; Zhang et al., 2019) occurred in the middle and late Early Cretaceous (115 ± 1.5 Ma–109.7 ± 1.5 Ma) (Figs. 1, 2, 15). Furthermore, intense rifting occurred in the northern basin, while the Zongnaishan–Shalazha Mountain uplifted (Liu et al., 2020). Due to the intense extension and lithospheric thinning, the upwelling mantle material generated a lot of heat and the temperature gradient in the basin reached a maximum (Zuo et al., 2015). In addition, a 20 Ma hiatus occurred in the south depression from 115 Ma to 95 Ma, before the Ulansuhai Formation was deposited from 95 Ma to 70 Ma (Zuo et al., 2015) (Fig. 15). The uranium-bearing pore fluid of the dark mudstone in the deep part of the basin percolated to the edge of the basin, the saturated water gradually increased from the
Fig. 16. Sequence and sedimentary metallogenic model of the Lower Cretaceous Tamusu uranium deposit.

(a) From 128 Ma to 115 Ma, the lowstand system tract (LST), transgressive system tract (TST) and highstand system tract (HST) of Sq2 (upper member of the Bayingobi Formation) were developed on the basis of the falling-stage system tract (FSST) of Sq1 (top of the lower member of the Bayingobi Formation), uranium becoming preconcentrated; (b) from 115 Ma to 95 Ma, with the influence of the Siberian plate compression, Engeerwusu fault activity (accompanied by basalt eruption) and the uplift of Zongnaishan-Shalazha Mountain in the northern depression zone led to the erosion of the highstand system tract and the transgression system tract at the top of Sq2 (upper member of the Bayingobi Formation) at the edge of the depression, forming the erosion window. The uranium-bearing oxygenated water migrated to the basin and reacted (redox reaction) with the reducing medium in the fan delta sand body in the sag, which formed uranium mineralization; (c) from 95 Ma to 70 Ma, the depression developed thermal subsidence, developing the meandering and floodplain deposits of the Upper Cretaceous Ulansuhai Formation. (d) from 45 Ma to the present, because of the effect of the remote compression of the Indian Plate and the Pacific Plate, tectonic inversion and uplift occurred in the Upper Cretaceous Ulansuhai Formation, which formed the erosion windows, the uranium-bearing oxygenated water migrated into the basin and reacted with the reducing medium (oxidation-reduction reaction) in the fan delta sand body, which formed uranium mineralization. BSFR = basal surface of forced regression; SU = subaerial unconformity; CC = correlative conformity; MRS = maximum regressive surface; TSE = transgressive surface of erosion; MFS = maximum flooding surface; HST = highstand systems tract; FSST = falling-stage systems tract; LST = lowstand systems tract; TST = transgressive systems tract.
bottom to the top of the falling-stage system tract, due to the uplift and heat increase of the basin (Liu et al., 2019). In addition, the mudstone at the top of the FSST had a high gamma anomaly, indicating that the uranium might come from the pore fluid. The uranium mineralization occurred through the oxidation-reduction reaction between the oxygen-bearing water infiltrating into the basin and the reducing medium (e.g., carbonized plant debris, pyrite) in the sand body, with the mudstone at the bottom or the escaping reducing pore fluid.

In the Late Cretaceous (95–70 Ma), depression and thermal gravity subsidence took place in the basin (Figs. 2, 15), resulting in the deposition of the meandering river and floodplain deposits of the Upper Cretaceous Ulansuhai Formation. These deposits covered the Early Cretaceous erosion window (Figs. 15, 16c), preventing the migration of uranium-bearing oxygenated water into the basin and ultimately stopped uranium mineralization.

In the Late Cretaceous–Paleogene (45.4 ± 0.6 Ma–70.9 ± 1.0 Ma), with the subduction of the Indian Ocean Plate and the Pacific Plate, the whole basin was uplifted and reversal faults were developed at the margin of the basin. This resulted in the Ulansuhai Formation (95–70 Ma) of the Late Cretaceous (Zuo et al., 2015), the highstand system tract and the transgression system tract of Sq2 being partially denuded (Figs. 15, 16d). As a result, a large erosion window was formed in the north of the Ying'ejing Sag and the uranium-bearing oxygenated water migrated into the basin along the erosion window and reacted with the reducing medium in the sand body and/or the deep reducing medium that formed uranium mineralization under the arid climate. In the Neogene (12.3 ± 0.2 Ma–2.5 ± 0 Ma), accompanied by the north east compression of the Indian Ocean Plate, the basin uplifted and the uranium mineralization continued (Liu et al., 2020). The whole rock U-Pb isochron age is 10.5 ± 0.1 Ma and 2.5 Ma (Zhang et al., 2019; Liu et al., 2020).

6 Conclusions

(1) The upper member of the Bayingobi Formation in the Lower Cretaceous mainly developed fan delta-shore shallow lacustrine deposits, which can be divided into three subfacies and a series of microfacies. Uranium ore bodies are mainly located in the distributary channel of the fan delta plain, the underwater distributary channel and the mouth bar of the fan delta front and underwater distributary bay. The distributary channel sand body has a high sand content (0.45 to 0.80), favorable metallogenic sand body thickness (140 to 260 m), porosity and permeability (up to 15.5% and 13.5 md) and forms a favorable uranium reservoir.

(2) The Bayingobi Formation can be divided into two fourth-order sequences (Sq1 and Sq2). Each fourth-order sequence consists of a lowstand system tract, transgressive system tract, highstand system tract and falling-stage system tract. The lowstand system tract forms a good uranium reservoir, whereas the transgressive system tract forms a barrier, which is favorable for uranium mineralization.

(3) Organic matter and pyrite play important roles in uranium mineralization. The carbon debris from the distributary channel in the fan delta plain and the underwater distributary channel in the fan delta front provided an important reducing medium for uranium mineralization. Pyrite is associated with the carbon debris in the distributary channel sand body and the dark mudstone in the distributary bay.

(4) Uranium mineralization is mainly developed in 3 stages, based on the sequence-sedimentary metallogenic model: Early Cretaceous, Late Cretaceous and Paleogene. The vertical structure of the Bayingobi Formation (FSST + LST + TST + HST) forms a favorable combination of reduction construction + favorable sand body + aquiclude construction. Furthermore, the later structural inversion formed an erosion window connecting the source area and the basin, thus laying a foundation for the migration of uranium-bearing oxygenated water into the basin for mineralization to occur.

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