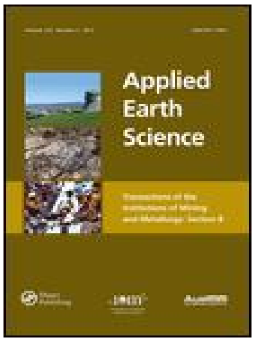

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REVIEW

Sandstone-hosted uranium deposits amenable for exploitation by *in situ* leaching technologies

M. Z. Abzalov*

Sandstone uranium deposits represent uranium concentrations formed by low-temperature hydrothermal processes, usually of diagenetic to epigenetic origin. The deposits are commonly hosted in arkosic sandstone and are therefore referred to as sandstone-type uranium. Globally, this is the most abundant type of uranium mineralisation, containing approximately 28% of the world's uranium resources and including several giant deposits with resources exceeding 100 kt of uranium. The main uranium minerals are pitchblende and coffinite, and uranium is recovered from host rocks by conventional hydrometallurgical technologies using sulphuric acid or alkaline leach. Host sediments were deposited in many different geological environments including continental intracratonic basins, intermontane depressions, coastal-plains and palaeo-river channels. Mineralisation is mostly stratabound and localised in the permeable sandstone at the redox interfaces where oxidised uranium-rich fluids have intersected with relatively reduced basin lithologies. Sandstone-type uranium mineralisation can also be distributed along permeable fault zones cutting sedimentary sequences. Deposits are subdivided into four groups: roll front (roll-type), tabular, basal channel and tectonic-lithologic types. Many sandstone uranium deposits cannot be exploited by conventional mining technologies because of low grade and difficult geotechnical conditions created by the presence of poorly consolidated wallrocks and the location of ore bodies below the water table. However, because of high permeability of the host sediments and the favourable uranium mineralogy, these deposits are well-suited to exploitation by *in situ* leach (ISL) technique. ISL mining is defined as the process of uranium extraction from the host sandstone *in situ* by injecting the chemical leach solutions directly into the ore zone. The pregnant solutions containing leached uranium are transported to the surface through production wells. Uranium is recovered from the solutions to produce yellowcake.

Keywords: Uranium, Sandstone, Roll-type, *in situ* leach, ISL

This paper is part of a special issue on uranium deposits and in-situ leaching

Introduction

Sandstone uranium deposits represent stratabound uranium concentrations in weakly lithified sandstone or unconsolidated sand, and therefore are referred to as sandstone-type uranium (De Voto, 1978).

Globally, this is the most abundant type of uranium mineralisation. According to a database compiled by the International Atomic Energy Agency (IAEA, 2009), 37·5% of world uranium deposits belong to the sandstone-type (Fig. 1*a*) containing approximately 28% of world uranium resources (Fig. 1*b*). This inventory is coupled with presence of large deposits, including several deposits with resources exceeding 100 kt of uranium.

In the past, sandstone uranium deposits have been mined by conventional open pit and underground mining methods (e.g. Crooks Gap mining area; Bailey, 1969). However, in the 1960s a new exploitation technology was developed, known as *in situ* leach (ISL), which allows the direct recovery of uranium by injecting chemical solutions into mineralised strata using specially designed drill holes (IAEA, 2001). The technology was specifically developed for exploitation of sandstone-type uranium deposits hosted in weekly lithified or non-consolidated sands and located below the water table. These deposits cannot be mined by conventional mining techniques, because of their difficult geotechnical conditions. However, the high permeability of the host rocks favours ISL technique for exploitation. This paper describes sandstone-type uranium deposits, their geological features and distribution

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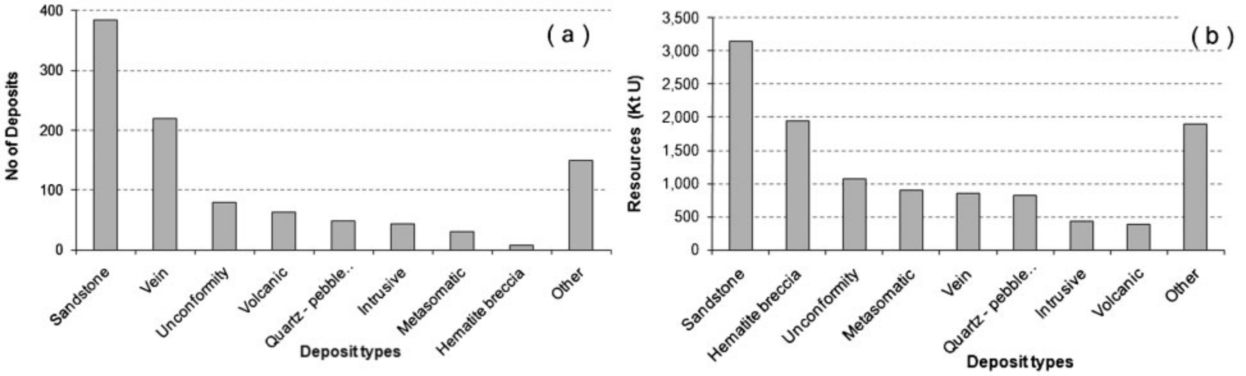


1 Distribution of uranium by deposit types, based on IAEA (2009). ***a*** **number of deposits, and** ***b*** **uranium resources, are shown. Other types include metamorphic, surficial, collapse breccia pipe, phosphorite, lignite associated and black shale hosted**

in the World. Characteristics of the deposits making them favourable for ISL technologies are briefly explained together with technical parameters of ISL operations and their main economic characteristics.

Classification of sandstone-type uranium deposits

Sandstone uranium deposits predominantly occur in reduced facies of fluvial continental sandstone sequences and less commonly in mixed fluvial-marine clastic sedimentary sequences. The main uranium minerals are pitchblende and coffinite which occur as coatings on the sand grains and in the pores of the host sandstones.

Host sediments were deposited in many different geological environments, including vast continental (intracratonic) basins, intermontane depressions, coastal-plains and palaeo-river channels deeply incised into basement rocks. Mineralisation can also be distributed along permeable fault zones cutting host sedimentary sequences. Based on the geometry of the uranium accumulations, their relationships with depositional environments and structural characteristics, the sandstone uranium deposits are subdivided into four main groups (Fig. 2): roll-type, which is also known as rollfront; tabular; basal channel; and structurally controlled which is also referred to as the tectonic-lithologic type (Fischer, 1970; De Voto, 1978; Nash *et al.*, 1981; Dahlkamp, 1993; IAEA, 2009). The unifying characteristic of all deposits is the presence of oxidised basin solutions transporting the dissolved uranium through the permeable sedimentary sequences which is then precipitated at the contact with the reducing agents (Adams and Smith, 1981; Barthel and Hahn, 1985; Dahlkamp, 1993; Fischer, 1970; Goldhaber *et al.*, 1983; Nash *et al.*, 1981; Northrop and Goldhaber, 1990; Reynolds and Goldhaber, 1983; Turner-Peterson and Fishman, 1986).

These deposit types have been further subdivided by the age of mineralisation, intensity of post-ore metamorphism, sitting of uranium, associated metals and the nature of reduction factors (Fig. 2). For example, uranium mineralisation of the Great Divide basin in Wyoming USA is referred to as detrital carbon-uranium roll-type which is a special class of Phanerozoic sandstone hosted uranium deposits (Dahlkamp, 1993; Abzalov and Paulson, 2012). Here, the reductant for mineralisation consists of plant fragments dispersed through fluvial facies sand beds. Tabular uranium deposits are further subdivided in to extrinsic carbon-related (Grants region type) and vanadium-uranium (Salt Wash type) types (IAEA, 2009). Uranium deposits of the Oklo district in Gabon are also referred to as Proterozoic sandstone uranium deposits (IAEA, 1996).

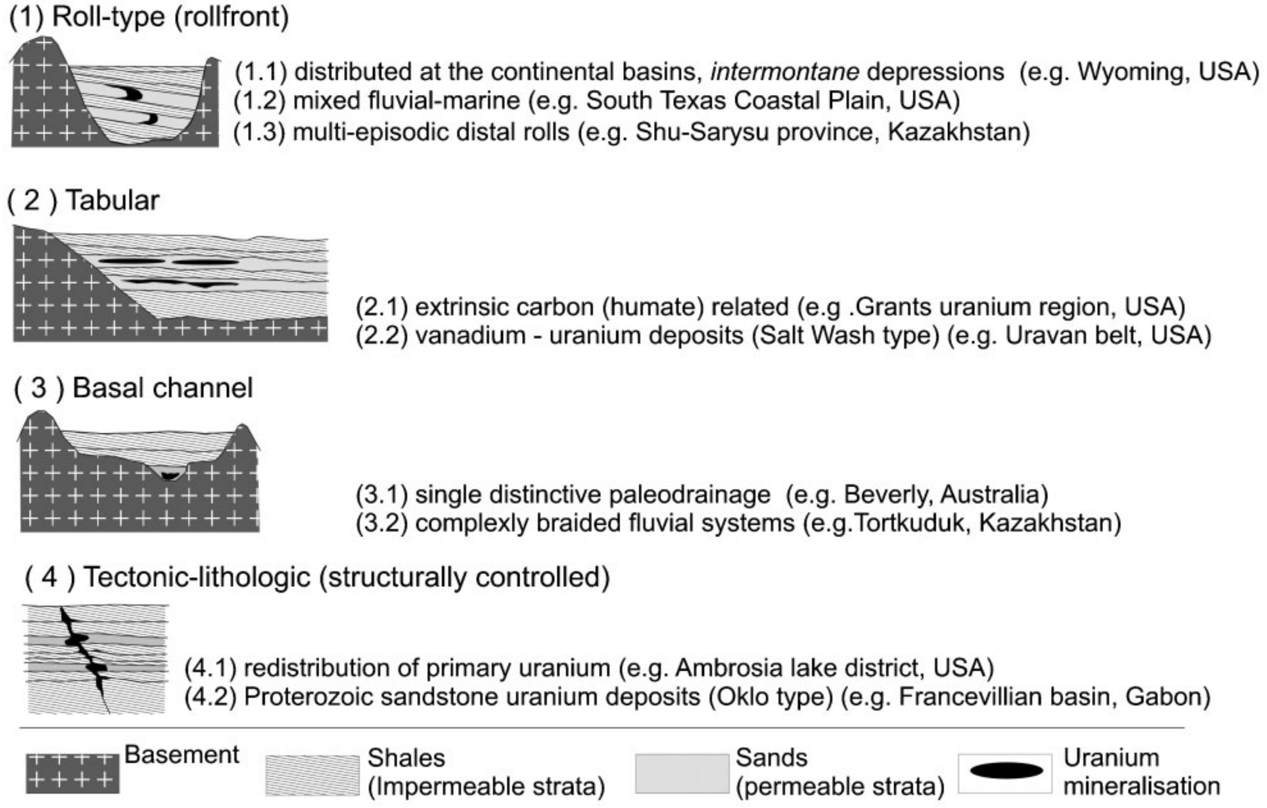
World distribution of sandstone-type uranium deposits

Sandstone hosted uranium deposits are present on all continents (Fig. 3*a*). They typically are distributed in young sedimentary formations, mainly of Cainozoic and Mesozoic age (Fig. 3*a*). Deposits in older host rocks are less common, they include Palaeozoic sandstones that host uranium rollfronts in Europe and Proterozoic sediments in Gabon (Fig. 3*a*).

Approximately 45% of the sandstone uranium deposits registered in the database of International Atomic Energy Agency (IAEA, 2009) have been discovered in central-western USA, mainly in the Colorado Plateau region, Wyoming and Texas (Fig. 3*b*). Another region that hosts significant resources of the sandstone uranium examples is Central Asia and includes the Kyzylkum province in Uzbekistan (Fig. 3*c*) and the Syrdarya and Shu-Sarysu provinces in southern Kazakhstan (Fig. 3*d*). This region contains 58 sandstone deposits (Karimov *et al.*, 1996; Petrov *et al.*, 2008; IAEA, 2009) with estimated uranium endowment in excess of 1500 kt U_3O_8 (M. Abzalov, unpublished data). Sandstone uranium deposits are also common in Africa, in particular in Niger, and also in the Balkan countries, Australia and south-eastern Russia (Fig. 3*a*).

Roll-type

Deposits of this type are common in the states of Wyoming (Bailey, 1969; Abzalov and Paulson, 2012) and Texas (Adams and Smith, 1981) of the USA and in the Central Asian countries, Kazakhstan (Petrov *et al.*, 2008) and Uzbekistan (Karimov *et al.*, 1996). They also occur in Australia, Russia, and Bulgaria. Mineralisation is called roll-type, or rollfront, because of its specific arch like shape (roll) which cross-cuts the sedimentary bedding (Fig. 4*a*). Uranium mineralisation is distributed at the contact between oxidised (altered) and reduced (non-altered) sediments and usually bounded from the top and bottom by less permeable seams represented by shale or consolidated impermeable sandstone. The arch (roll) is convex in the direction of flow of the solutions



2 Schematic diagram showing main types of the sandstone uranium deposits, based on classifications proposed by Dahlkamp (1993) and IAEA (2009) with modifications by the author

that transported uranium. Uranium is precipitated by redox reaction between oxidised uranium rich solutions and reduced phases in the non-altered sediments. On the concave side of the rolls the uranium mineralisation continues behind the rolls along their upper and lower limbs (Fig. 4*a* and *b*).

Dimensions and resources of uranium rollfronts vary widely, from small deposits in Australia (Penney, 2012) and Wyoming, USA (Bailey, 1969; Fischer, 1970; Abzalov and Paulson, 2012) to giant deposits in Kazakhstan (Petrov *et al.*, 2008). Thickness of the rolls ranges from less than a metre (Fig. 4*a*) to several tens of metres in the apex zone. The width of the rolls usually varies from 10 to 30 metres but can also be hundreds of metres in the giant deposits of Kazakhstan (Petrov *et al.*, 2008; Abzalov, 2010). Strike length varies from a few hundred metres to length aggregate exceeding 150 km in the Shu Sarysu province in Kazakhstan (Petrov *et al.*, 2008).

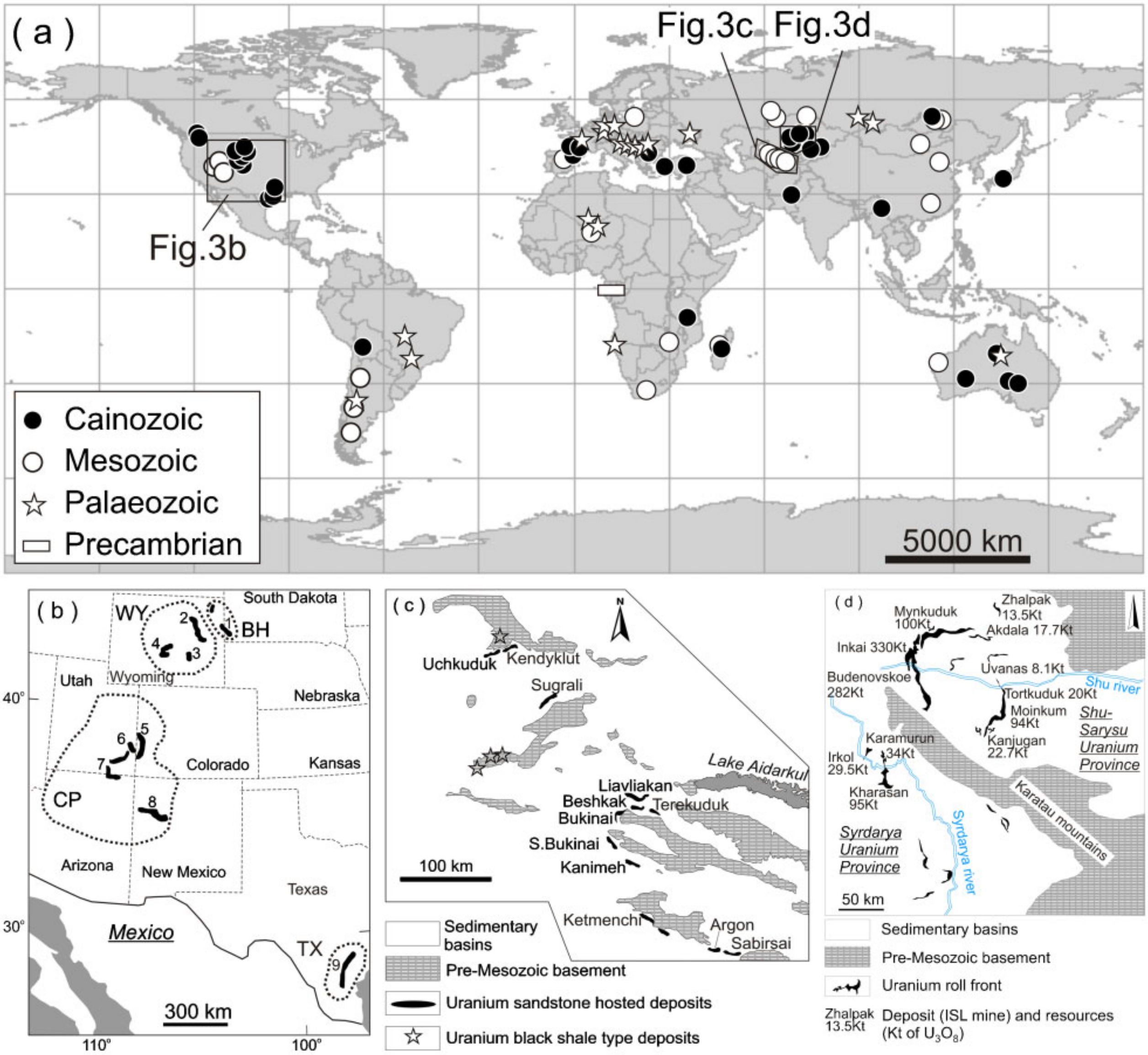
The structure of the rolls reflects the mechanism of uranium deposition from the oxidised solutions descending along permeable sedimentary strata (Fig. 4). The outer contacts of the rolls, located on their convex (front) side, are diffuse (Fig. 4*a*), and often contain narrow uranium stringers penetrating along permeable contacts into the host rocks at the front of the rolls. The rocks distributed in front of the rolls have not been oxidised by uraniferous solutions. They are usually greenish-grey to light grey in colour and are characterised by the presence of reduced chemical material, in particular organic carbon and pyrite. The rear contacts of the rolls on their concave side are sharp (Fig. 4*a*). Rocks distributed behind the rear contacts are oxidised and contain iron-oxides which gives them light brown to yellowish colour. Despite the intense alteration of the rocks by oxidising solutions, the sedimentary bedding textures are commonly well preserved (Fig. 4*a*). The idealised structure of the rolls shown in Fig. 4 may not always be present. It can be complicated and completely destroyed by multiple hydrothermal pulses, in particular, when uranium mineralisation is affected by post-ore reduced solutions.

Uranium minerals, typically pitchblende, uraninite, coffinite and minor brannerite, usually occur in the interstitial pores between sand grains, forming the matrix texture of mineralisation. The grade of uranium rolls decreases from the rear contacts on the concave side toward the roll fronts, on the convex side.

Mineralogical and geochemical characteristics of the roll may change with position in the roll. Selenium, where present in the rolls, is usually distributed along the rear contact of the roll (Fig. 4*b*). Molybdenum, on the contrary, is accumulated at the roll front, closest to the reduced ground. Rhenium, in general, has similar distribution to molybdenum, showing a strong affinity with the reduced ground but extends farther to the rear of the roll, approximately to the rear contact of the economic uranium mineralisation. Vanadium distribution is less consistent; it may be observed in the rear part of the roll where it associates with selenium, or also at the roll fronts (Petrov *et al.*, 2008).

Tabular deposits

Tabular type uranium deposits are defined as deposits that occur as tabular, originally subhorizontal bodies and entirely within reduced fluvial sandstone (Sanford, 1992). This is the most common type of sandstone



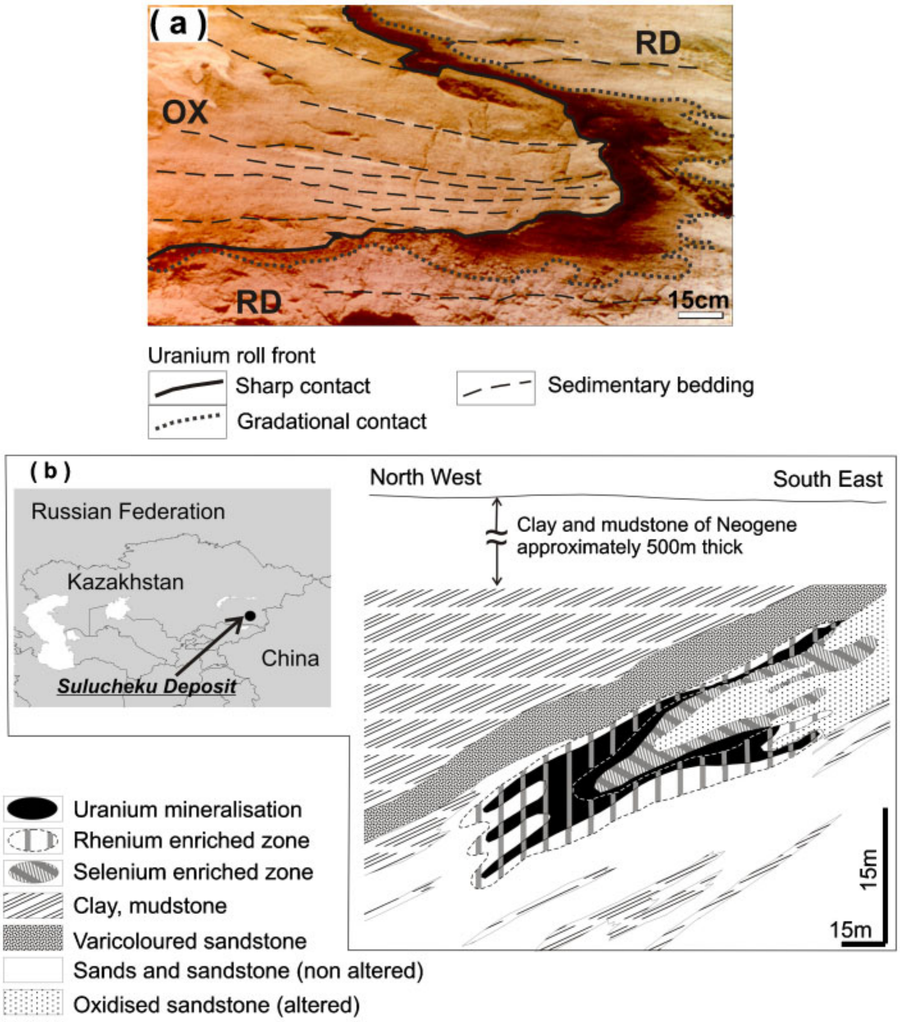
3 **Distribution of sandstone hosted uranium deposits: *a* world map showing the main sandstone type uranium deposits and age of their host rocks (IAEA, 1996, 2009); *b* sandstone hosted uranium deposits in the USA. Regions: BH – Black Hills, WY – Wyoming basins, CP – Colorado Plateau, TX – Texas Coastal region. Numbers denote uranium districts and basins: 1 – Edgement district, 2 – Powder River basin, 3 – Shirley basin, 4 – Great Divide basin, 5 – Uravan belt, 6 – Big Indian district, 7 – Monuments Valley-White Canyon district, 8 – Grants Uranium region (Church Rock, Smith Lake and Ambrosia Lake districts), 9 – Texas Coastal region (Ray Point district, Clay-West Burns district, Rhodes Ranch area and South Duval trend; Fischer, 1970, 1974; Eargle *et al.*, 1975; Fishman *et al.*, 1985; Abzalov and Paulson, 2012); *c* uranium deposits of the Kyzylkum province, Uzbekistan (Karimov *et al.*, 1996); *d* uranium deposits of the Shu-Sarysy and Syrdarya provinces of Kazakhstan (Petrov *et al.*, 2008). Resources as reported by Pool and Wallis (2006b)**

hosted uranium deposits (IAEA, 2009). Most of the tabular deposits in the USA are located in the in the Colorado Plateau region (Fischer, 1970; Northrop and Goldhaber, 1990; Fischer, 1974; Fishman *et al.*, 1985; Turner-Peterson *et al.*, 1986).

Although in the Colorado Plateau region the tabular uranium deposits are distributed separately from uranium rolls they can also occur in the same sedimentary basin which host uranium rollfronts. Close association of the tabular deposits with uranium rollfronts have been described in the Grants uranium region, New Mexico (Fischer, 1974), Australia (Penney, 2012) and central Kazakhstan (Petrov *et al.*, 2008).

A characteristic feature of this deposit type is their tabular shape created by the distribution of uranium mineralisation in parallel with bedding of the enclosing sediments (Fig. 5*a* and *b*). Ore bodies are horizontally extensive and thin in their vertical dimension (Fig. 5*b*). For example, the Jackpile-Paguate deposit in the Grants uranium region is 1500 m long and 760 m wide whereas its thickness varies from 3 to 7 m (Sanford, 1992). Relationship between oxidised and reduced rocks is more complex than in the rollfront deposits (Figs. 4 and 5*a*).

Petrographic and isotope studies show that uranium mineralisation at the tabular deposits was formed



4 Geometry and structure of uranium rolls: *a* rollfront exposed in the Petrotromics pit, Shirley basin, Wyoming. Dark colour denotes high grade uranium mineralisation. OX – oxidised (altered) sandstone, RD – reduced unaltered) sandstone. Photo: courtesy of O. Paulson; *b* structure of the uranium rollfront at the Sulucheku deposit, Kazakhstan (modified after Petrov *et al.* (2008)

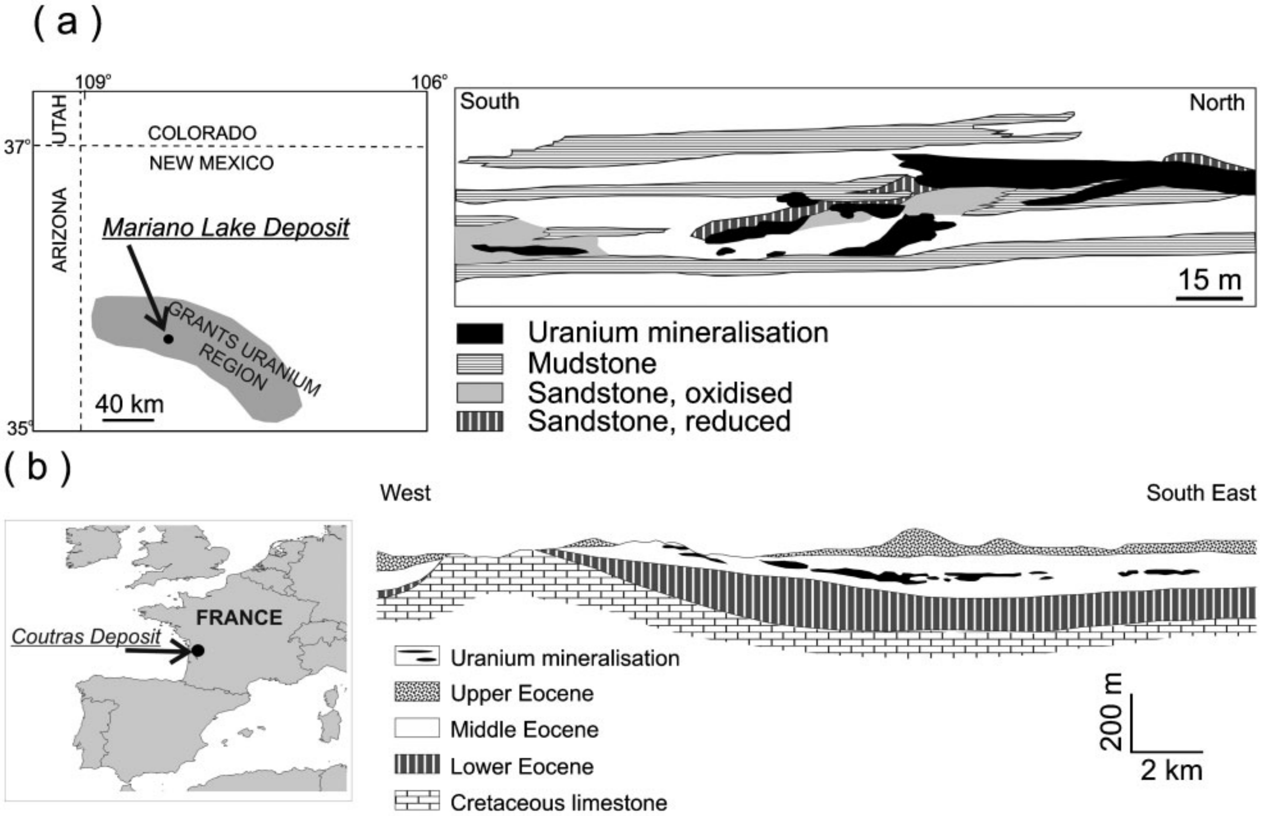
in arkosic fluvial continental sandstone shortly after deposition of these sediments (Ludwig *et al.*, 1984; Sanford, 1992) typically at the early stages of diagenesis (Meunier *et al.*, 1989). Tabular uranium deposits appear to preferentially occur in actively subsiding synclinal structures which create larger and more continuous stream palaeo-channels favourable for accumulation of diagenetically mobilised uranium (Peterson and Turner-Peterson, 1980).

The tabular deposits are divided into sub-types depending on the nature of the carbonaceous matter that acted as the reductant for uranium precipitation. Two main groups are defined; Grants-type and Salt Wash-type tabular deposits. The first group is named after tabular uranium deposits distributed in the Grants district, New Mexico (Peterson and Turner-Peterson, 1980; Fishman *et al.*, 1985, Turner-Peterson and Fishman, 1986). These deposits are characterised by the association of uranium accumulations with carbonaceous matter which itself was redistributed in the host sedimentary sequence after deposition.

Salt Wash-type deposits were named after tabular uranium deposits distributed in the Henry and Uravan districts of the Colorado Plateau, USA. Since the uranium deposits of that area occur in the Salt Wash member of the Morrison Formation of Late Jurassic age they are called Salt Wash-type tabular uranium deposits. These deposits also have high vanadium content and therefore Salt Wash-type is also referred to as vanadium-uranium tabular deposits (Northrop and Goldhaber, 1990; IAEA, 2009). The host rocks of the Salt Wash-type uranium deposits are continental fluvial sandstone which contain carbonaceous debris of the palaeo-plant that acted as a reductant for precipitating uranium from solutions. Uranium mineralisation of the tabular deposits in Niger (Bigotte and Obellianne, 1968; Cazoulat, 1985), Australia (Sanford, 1985), Eastern Europe (Barthel and Hahn, 1985) and France (Meunier *et al.*, 1989) is also associated with carbonaceous debris of palaeo-plants.

Basal channel type

Basal channel type uranium deposits are common in the USA (Chenoweth and Malan, 1973), Australia (Bush, 2000), Canada (Boyle, 1982), Kazakhstan (Berikbolov *et al.*, 2005; Petrov *et al.*, 2008) and Russia (IAEA, 2009). This type includes uranium mineralisation distributed in palaeodrainages which incise underlying crystalline or sedimentary basement. Palaeo-channels are usually filled with clastic sediments of alluvial-fluvial



5 **Generalised cross-sections of tabular uranium deposits: *a* Mariano Lake deposit, Grants region, New Mexico, modified after Fishman *et al.* (1985); *b* Coutras deposit, France, modified after Meunier *et al.* (1989)**

affinity. Uranium mineralisation occurs as elongated lenses usually several hundreds of metres long and several tens of metres wide (Fig. 6*a* and *b*). The thickness of the lenses is usually small and rarely exceeds 3 metres (Dahlkamp, 1993). In some cases, uranium mineralisation can form rollfronts. Resources of basal channel type of uranium deposits are generally small, in the range of several tonnes to several thousands tonnes of contained U_3O_8 and rarely exceed 20 kt of contained U_3O_8 (e.g. Beverly, Australia). Average grade of basal channel type uranium deposits varies from 0·01 to 0·1% U_3O_8.

In general, uranium lenses are distributed concordantly with the host sedimentary beds and are associated with organic palaeo-plant debris. Palaeo-channels can vary in shape from single distinct palaeodrainage channels (Fig. 6*a*) to complexly braided fluvial systems (Fig. 6*b*). The latter sub-type shares many common features with tabular uranium mineralisation and therefore some geoscientists (Dahlkamp, 1993) consider this mineralisation as a special sub-group of tabular type uranium mineralisation.

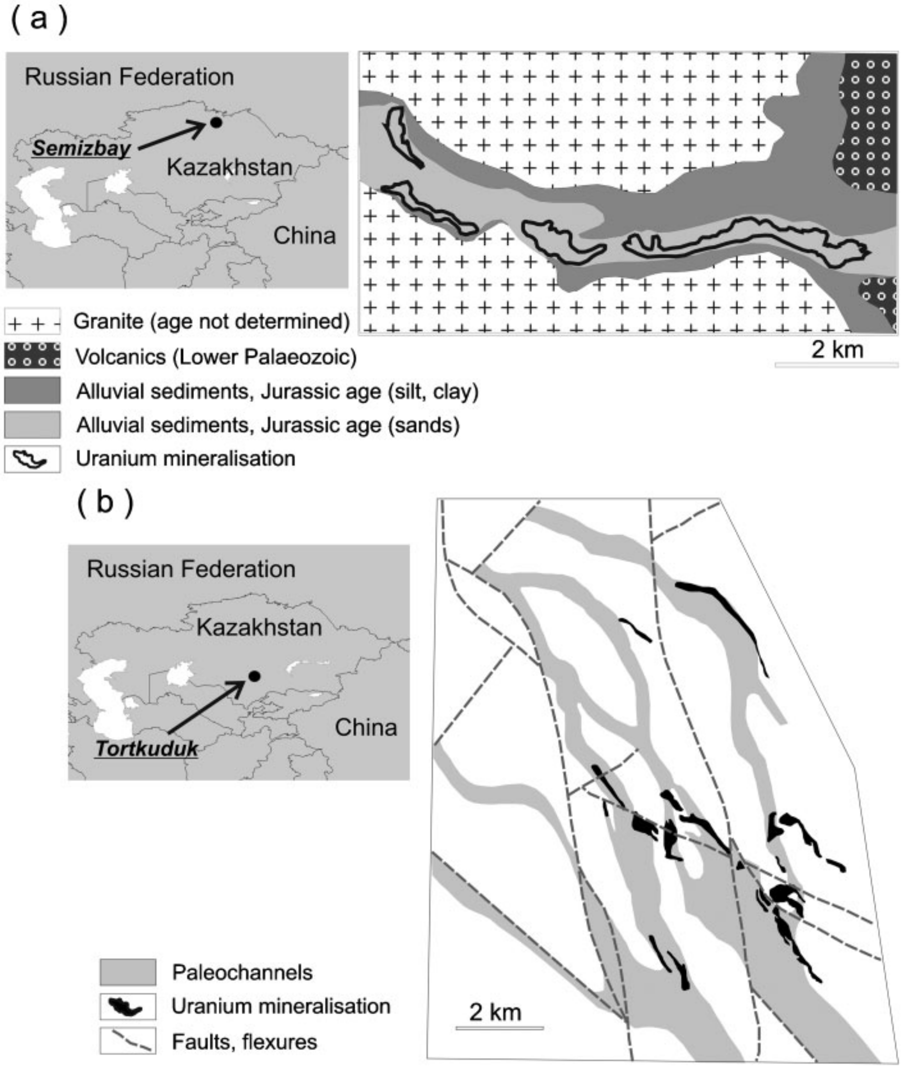
Tectonic-lithologic type

Tectonic-lithologic type of uranium deposits are characterised by strong structural control of mineralisation distributed along high-angle tectonic faults cutting the host sedimentary sequences (Dahlkamp, 1993; IAEA, 2009). Examples of structurally controlled uranium mineralisation are known in France (e.g. Mas Lavayre deposit), Bulgaria (e.g. Dospat deposit), Abrosia Lake district in USA (Dahlkamp, 1993) and the Francevillian basin of Gabon (Gauthier-Lafaye and Weber, 1989). This mineralisation, which occurs discordantly to sedimentary sequences, differs from other types of sandstone hosted uranium which are distributed concordantly with the host sequences as stratabound bodies controlled by sedimentary facies. However, the emplacement of tectonic–lithologic type of uranium mineralisation appears to occur similarly to other types of sandstone uranium deposits from low-temperature oxidising fluids. This is different from the unconformity-type uranium deposits which involve high temperature hydrothermal processes. Because of the genetic similarities, the tectonic–lithologic deposit type is considered as a special type of sandstone-hosted uranium (Dahlkamp, 1993).

Genetic concepts

Sandstone uranium deposits occur in continental fluvial and, less commonly, in mixed fluvial marine sandstone. Despite a wide variety of modes of their distribution they have many common characteristics:

- their host environment is represented by weakly consolidated sandstone, usually medium to coarse grain size, often interbedded with pebble conglomerate
- host sandstone is commonly of arkosic composition. Although composition of the sandstone may have no direct implication for uranium mineralisation, immature lithologies possibly indicate closer proximity to felsic volcanic or granitic sources from which the uranium may have been derived
- permeable sandstone is interbedded with and usually bounded by impermeable strata, mainly siltstone and mudstone beds
- uranium mineralisation is distributed at the contacts between oxidised (altered) and reduced (non-altered) rocks.



6 Basal channel type uranium deposits: *a* geological map of the Semizbai deposit, Kazakhstan. Generalised after Berikbolov *et al.* (2005); *b* braided channels at the Tortkuduk deposit, Kazakhstan. Based on the written communications by Cherniakov, V. M. (Volkovgeologiia)

The common characteristics of these deposits appear to reflect their genetic similarities, mainly that sandstone uranium deposits have been formed in low-temperature regimes related to diagenetic–epigenetic processes at the host sedimentary sequences (Dahlkamp, 1993). The different genetic models proposed for sandstone uranium deposits are in general consistent in that uranium concentrations in the permeable sandstone were formed by low-temperature oxidised solutions which leached uranium from the source rocks and precipitated it at a chemical interface with the reducing agents (Adams and Smith, 1981; Harshman and Adams, 1981; Goldhaber *et al.*, 1983; Sanford, 1985, 1992, 1994; Turner-Peterson and Fishman, 1986; Gauthier-Lafaye and Weber, 1989; Northrop and Goldhaber, 1990; Jaireth *et al.*, 2008). The main differences in the proposed models concern the suggested source of uranium, nature of the ground water, transportation mechanisms and nature of the reducing agents which caused precipitation of the uranium minerals.

The most frequently proposed source of uranium in sandstone deposits is uraniferous granitic provenance (Stuckless and Nkomo, 1978; Stuckless and Miesch, 1981; Boyle, 1982; Meunier *et al.*, 1989). In some cases, contribution of pre-existing uranium deposits has been proposed to explain uranium rolls or basal channel deposits. For example, some sandstone deposits in Kazakhstan appear to have a spatial association with uraniferous quartz veins in Palaeozoic volcano-sedimentary sequences (e.g. Nizhne Ili province in Kazakhstan; Petrov *et al.*, 2008). In Uzbekistan black shale hosted uranium mineralisation in Early Palaeozoic sedimentary formations is considered as one of the main sources of the uranium in rollfronts occurring along the foothills of the exposed Palaeozoic basement (e.g. Uchkuduk; Karimov *et al.*, 1996). Adams and Smith (1981) have suggested that uranium in the roll-type deposits of south Texas have been derived from uranium rich shales overlying and adjacent to permeable sands. Mobilisation of uranium from shales is interpreted to have occurred during their early diagenesis by connate waters generated by compaction of the sedimentary sequence (Adams and Smith, 1981). Another commonly considered source of uranium is felsic volcaniclastic material (e.g. Dolmatovskoe, Russia; IAEA, 2009) either directly distributed in the host sandstone sequence or separately in underlying or overlying sediment packages.

The nature of the ground water and transportation mechanisms are other crucial parameters. In general, there is agreement that roll-type deposits were formed in a dynamic fluid regime by the gravity-driven ground waters moving in the down-dip direction along permeable strata. The gravity gradient that controls continuous flux of ground water is considered to be related to uplifts of the basement rocks exposed at the basin margins (Dahlkamp, 1993). For the tabular deposits, nature of the ground water and transportation mechanisms are controversial. Geometry of the tabular uranium mineralisation and the distribution of ore bodies in districts suggest that uranium precipitation occurred in almost stationary hydrogeologic regimes, in locally reduced zones within oxidised sandstone units (Dahlkamp, 1993). Some workers (Fishman *et al.*, 1985; Turner-Peterson and Fishman, 1986) advocate for a lacustrine-humate model for the formation of tabular deposits. According to this model uranium mineralisation is related to a fluid generated by the compaction of the mud beds overlying the permeable sandstone. The alternative proposal is a brine interface model in which two fluids reacted along a density stratified interface. The upper, oxidised fluid was gravity driven in the down-dip direction and then spread horizontally as it encountered the underlying strata (Northrop and Goldhaber, 1990; Sanford, 1992). According to the brine interface model (Sanford, 1994), precipitation of uranium at the district scale occurs preferentially in zones of mixing of local and regional ground water discharges. Sanford (1994) has studied the tabular deposits at the San Juan basin and suggested that gravity driven flow was concentrated along the palaeoshore line or playa margin.

In oxidised fluids, uranium is transported in the hexavalent state and it must be reduced to the tetravalent state needed for precipitation of pitchblende and coffinite, the main uranium minerals in sandstone deposits. Reducing agents (reductants) are subdivided into intrinsic, introduced contemporaneously with sedimentation, and extrinsic, post-dating the sedimentation (IAEA, 2009). Examples of intrinsic reductants include organic debris at the Wyoming deposits (Abzalov and Paulson, 2012). Extrinsic reductants include oil and gas reservoirs, proposed as reductants for giant deposits in Kazakhstan (Jaireth *et al.*, 2008). Uranium rolls in the Texas coastal plain deposits are associated with authigenic pyrite which apparently was the only available reductant in the system (Goldhaber *et al.*, 1983). Formation of pyrite in the Texas sandstone was caused by hydrogen sulphide (extrinsic reductant) introduced into sandstone along the faults (Goldhaber *et al.*, 1983; Reynolds and Goldhaber, 1983).

In situ leach (ISL) uranium exploitation technique

ISL is not a mining technology *senso stricto* as it is based on dissolving uranium minerals directly in their host rocks (*in situ*) by reactive solutions injected through specially drilled holes (IAEA, 2001). Solutions dissolve uranium and are then pumped to the surface through discharge drill holes (production wells), where they are collected and supplied to the processing plant located at the surface; here the uranium is extracted from the pregnant solutions (Bush, 2000; IAEA, 2001; McKay *et al.*, 2007). Usually the end product at ISL facilities is ammonium or sodium polyuranate which is transported to a hydrometallurgical plant for further processing (IAEA, 2001).

ISL technologies allow access to lower grade deposits than conventional mining techniques and permit the exploitation of uranium ore bodies hosted in weakly lithified sand at depths up to 600 m below surface (Table 1). Such deposits, because of their low grade and difficult geotechnical conditions caused by unconsolidated sand located below the water table, cannot be exploited safely by conventional mining methods. Another economic advantage of ISL operations over conventional mining is their low capital costs, short development time and high cash flow starting from the commissioning of the project which leads to rapid payback of investments (IAEA, 2001).

Table 1 Technical and economic characteristics of the selected ISL projects*

		Resources			Acid consumption		Operating cost	
Deposit	**Country**	**Tonnage (Mt)/grade (U_3O_8%)**	**Depth below surface/m**	**Leach reagent**	**(acid tonnes per 1 t uranium)**	**Uranium recovery/%**	**US$/lb U**	**References**
Akdala	Kazakhstan	30·3 Mt at 0·06%	200–250	Sulphuric acid (92%)	35	90	7·34	Pool and Wallis (2006a), Petrov *et al.* (2008)
Kharassan	Kazakhstan	38·6 Mt at 0·11%	560–680	Sulphuric acid (92%)	90–140	93	8·70	Pool and Wallis (2006b), Petrov *et al.* (2008)
South Inkai	Kazakhstan	32·7 Mt @ 0·043%	350–510	Sulphuric acid (92%)	50	90	8·49	Pool and Wallis (2006c), Petrov *et al.* (2008)
Honeymoon	Australia	1·2 Mt at 0·24%	100–120	Sulphuric acid	7·7	70	N/A	Bush (2000), McKay *et al.* (2007)
Uchkuduk	Uzbekistan	25 Mt at 0·2%	10–280	Sulphuric acid	20–40	N/A	N/A	Karimov *et al.* (1996), IAEA (2001, 2009)

*N/A: not available.

The main uranium minerals of the sandstone type uranium deposits are pitchblende and coffinite. These are relatively easily recoverable from host rocks by sulphuric acid or alkaline leach. This factor is highly favourable for application ISL techniques to exploitation of sandstone uranium deposits.

Two chemical leaching systems are used in ISL techniques: acid (IAEA, 2001) and alkaline (McMurray, 1998). Acid leaching was developed in the USSR, and was first applied to exploitation of sandstone deposits in the Ukraine and Uzbekistan (IAEA, 2001). The method is faster and produces better recovery of uranium than alkaline leach. At the Honeymoon mine, Australia, direct comparison of the two approaches has shown that acid leach achieves 80% recovery of the *in situ* resources approximately 4 times faster than using alkaline leach method (Bush, 2000). Acid leaching also allows recovery of some by-product metals (Karimov *et al.*, 1996). However, the acid leaching approach becomes inefficient when host rocks contain carbonates because of excessively high acid consumption. In general, when the CO_2 content of the host rocks exceeds 2%, acid leaching becomes economically non-viable for exploitation of the deposit.

An alternative approach is alkaline (sodium carbonate) leach, first developed in the USA. The alkaline leach method is successfully used for the exploitation of sandstone deposits containing carbonate (McMurray, 1998). The alkaline leach method is also characterised by a high selectivity for uranium with a minimal attack on most gangue minerals. Therefore alkaline solutions in general are less corrosive and contain less impurities than sulphuric acid leach. These characteristics partially compensate for lower kinetics, less aggressiveness and the higher energy consumption of the alkaline leach method.

In general, amenability of sandstone deposits to ISL exploitation techniques depends on the following factors:

- permeability of the host sediments
- grade and tonnage of uranium resources
- geometry of uranium mineralisation
- depth below surface
- groundwater flow
- aquifer salinity
- uranium mineralogy
- deleterious components.

Permeability of host rocks and location of the uranium mineralisation below the water table are the main criteria for assessing amenability of uranium deposits for ISL technique (IAEA, 2001). Permeability should be at least 0·5 to 1 m/day. It is also important that the permeability of the uranium mineralisation should be higher or at least the same as that of the barren sediments. ISL mining is favoured when permeability of mineralisation is higher than that of the enclosing sediments. Opposite relationships lead to excessive losses and dilution of leach solutions, significantly decreasing the economic efficiency of the ISL operation.

The grade of uranium reserves at ISL operations usually varies from 0·04 to 0·2% U_3O_8 which is sufficient for exploitation of uranium ore at depths up to 600 m (Table 1). These grades are in general too low for conventional underground mining. The product of grade by thickness of uranium mineralisation (m*% U_3O_8) is commonly used parameter for definition of ore boundaries. At the Kazakhstan operations (Pool and Wallis, 2006a, 2006b, 2006c) economic mineralisation is commonly delineated at 0·06 m*% U_3O_8 cut off value. At the Australian ISL mines this parameter is higher. Average grade-thickness parameter of the mineralised layers at the Honeymoon mine varies from 0·18 to 0·51 m*% U_3O_8 with a global average of 0·42 m*% U_3O_8 (McKay *et al.*, 2007).

Conclusions

Sandstone uranium deposits represent stratabound uranium concentrations in weakly lithified sandstone or unconsolidated sand, usually of fluvial continental affinity. Some of the deposits occur in mixed fluvial-marine clastic sedimentary sequences and also can be distributed along the high-angle faults cutting the sedimentary sequences. Sandstone uranium deposits are subdivided into four main groups: rollfront (roll-type), tabular, basal channel, and tectonic-lithologic types. This type of uranium mineralisation contains approximately 28% of the world uranium resources including several giant deposits with resources exceeding 100 kt of uranium.

Many sandstone uranium deposits cannot be exploited by conventional mining technologies because of low grade and difficult geotechnical conditions, created by the presence of unconsolidated sands and the location of the ore bodies below the water table. However, because of the high permeability of the water saturated host sediments and the simple uranium mineralogy these deposits are particularly suited to exploitation by ISL techniques.

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