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Uranium Exploration Planning, Management and Practice

URANIUM EXPLORATION PLANNING, MANAGEMENT AND PRACTICE

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FOREWORD

This publication is intended to inform IAEA Member States currently engaged in or considering undertaking uranium exploration for peaceful uses (i.e. to discover and mine the uranium resources needed for nuclear fuel to be used in nuclear power plants and research reactors).

Discovering and eventually mining a uranium deposit successfully needs a systematic approach with a good understanding and knowledge of the technical, planning and management aspects of a uranium project. This publication aims to provide practical guidance on managerial and pragmatic practices in mineral exploration to assist the practitioner in making well informed decisions during all phases of a uranium exploration programme.

The IAEA provides a peer review service for Member States called an Integrated Uranium Production Cycle Review. These review missions aim to provide practical guidance to Member States undertaking activities in the uranium production cycle including uranium exploration. This publication may also be used as part of the review basis for Member States that request IAEA support through an Integrated Uranium Production Cycle Review mission and as a basis for training workshops.

The IAEA acknowledges the contributions of the experts who participated in the consultancy meetings for their contributions to this publication. The IAEA officer responsible for this publication was A. Hanly of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

Chapter 1. INTRODUCTION

1.1 BACKGROUND

At least 92 IAEA Member States have historically or are currently exploring for uranium. In the past 30 years,75% or more of the projects in the Uranium Production Cycle that have been supported through the IAEA Technical Cooperation programme were focused on aspects of uranium exploration.

Experience has shown that these projects often required considerable guidance from the IAEA and international experts, not only on the technical aspects, but on the overall management and planning of these projects in the context of mineral exploration. A systematic, phased approach to exploration for uranium utilizing good practices and IAEA guidance is suggested to ensure the sustainability of exploration programmes in Member States as well as to ensure these activities are undertaken in a safe and secure manner.

The document aims to address and support these suggestions by providing guidance based on private industry and government good practices for the practical planning and implementation of mineral exploration programmes. It complements the IAEA Nuclear Energy Series publication, *Milestones in the Development of National Infrastructure for the Uranium Production Cycle* [1.1] and provides additional more detailed information specifically aimed at Member States that are undertaking national uranium exploration programmes for peaceful uses.

Previous IAEA publications covering aspects of uranium exploration were published over 30 years ago including: *Uranium Exploration Methods (Panel Proceedings Series)* [1.2]; *Contractual Arrangements for Uranium Exploration and Mining* [1.3], and *Uranium Exploration Planning and Practice (Report of an Advisory Group Meeting)* [1.4]. This publication provides significant updates and provides a completer and more comprehensive overview on important aspects of uranium exploration.

The Agency provides a peer review service for Member States called an Integrated Uranium Production Cycle Review mission which is aimed at providing guidance to Member States undertaking activities in the Uranium Production Cycle [1.5]. The document may be used as part of the review basis for Member States that request IAEA support through an Integrated Uranium Production Cycle Review mission and as a basis for training workshops.

1.2 OBJECTIVE

This publication is intended to be used by practitioners of uranium mineral exploration. It aims to provide the required guidance to successfully plan, implement and assess mineral exploration projects in a systematic manner utilizing good practices. It is suitable for use by both inexperienced and experienced explorationists.

1.3 SCOPE

The document provides a comprehensive overview of uranium exploration including its role in the nuclear fuel cycle, a summary of uranium deposit models, exploration methods and practical information and guidance on planning and implementation of uranium exploration programmes using the ‘stage gate’ approach.

1.4 STRUCTURE

The document is organized into five chapters based on major key topics in mineral exploration. The chapters are meant to be complementary. Chapter 2 provides an overview of the principles of exploration in the nuclear fuel cycle, exploration business cycles, investment in exploration, understanding prospectivity and explorability (i.e., the practical ability to explore an exploration target), and the exploration management process and understanding the main stakeholders. Chapter 3 includes the basic description and references for the 15 IAEA uranium deposit types including graphical representations of each deposit type. Chapter 4 focuses on the main exploration methods including geology, geochemistry, geophysics and remote sensing, drilling, surveying, and data interpretation. Chapter 5 provides guidance on the five main phases of exploration using the ‘stage gate’ systematic approach.

REFERENCES TO CHAPTER 1

[1.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of National Infrastructure for the Uranium Production Cycle, IAEA Nuclear Energy Series No. NF-G-1.1, IAEA, Vienna (2023).

[1.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium Exploration Methods, Panel Proceedings Series - International Atomic Energy Agency, IAEA, Vienna (1973).

[1.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Contractual Arrangements for Uranium Exploration and Mining, IAEA-TECDOC-468, IAEA, Vienna (1988).

[1.4] INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium Exploration Planning and Practice (Report of an Advisory Group Meeting, Vienna, 13–16 December 1988), IAEA-TECDOC-583, IAEA, Vienna (1991).

[1.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Uranium Production Cycle Review, https://www.iaea.org/sites/default/files/22/11/brochure-iupcr.pdf.

Chapter 2. OVERVIEW OF EXPLORATION MANAGEMENT AND PLANNING

Exploration can involve several stakeholders including governments, geological survey organizations, consultants, researchers, exploration service providers, and exploration company managers and workers. One role of geological survey organizations is the promotion of investment in the mining sector. This can be achieved by developing a favourable environment to conduct business, development of mineral potential assessments, and by generating easily accessible pre-competitive geoscientific data.

The exploration and discovery of economic uranium deposits leading to mining production requires long time frames. Historically, successful uranium exploration programs have relied on prospector-driven and deposit-model-driven approaches. However, the exploration process is relatively inefficient. About fifty percent of significant discoveries progress to mine development due to technical, economic, social, and environmental factors. The exploration process follows several stages from reconnaissance phase exploration to advanced exploration and the definition of resources. Each stage is characterized by specific exploration activities.

Undiscovered economic resources may occur in localities that are under-explored. Technical innovations associated with geochemical, geological, geophysical, drilling, deposit models and mining methods might contribute to the discovery of future economic mineral deposits. Exploration and mining companies consider a variety of investment risk factors. This can include the estimation of economic mineral potential through quantitative and qualitative methods. Data-driven and knowledge-driven assessments of exploration data are typically utilized for prospectivity analysis to focus the strategy on targeting areas and selecting exploration methods.

2.1 URANIUM EXPLORATION AND RESOURCES

Uranium exploration is positioned at the front end of the nuclear fuel cycle. It is a high-risk, high-reward activity that is akin to a research and development process [2.1, 2.2] (Fig. 2.1). Economic mineral resources can be identified through exploration and exploited through mining. Mined and refined uranium is then converted, enriched, and fabricated as fuel for nuclear power generation.

Uranium Resources, Production and Demand also known as the 'Red Book' published by the Nuclear Energy Agency and the International Atomic Energy Agency (IAEA), describes the global distribution of uranium resources at variable production cost categories. Resources are reporting according to four main classifications which includes reasonably assured resources (RAR), inferred resources, prognosticated resources, and speculative resources. Reasonably assured resources have the highest confidence level and include measured and indicated resources. In comparison, inferred resources have a lower degree of confidence while prognosticated resources and speculative resources exhibit the lowest degrees of confidence and can include unreliable and inconsistent information of limited value.

Global identified recoverable resources of uranium, expressed in tons of uranium metal (tU), in the <USD 130 /kgU cost category as of 1 January 2021 amounted to 6 078 500 tU, a decrease of just over 1% compared to 2019. Global annual uranium mine production decreased by nearly 12% from 2018 to 2020, to 47 342 tU. In situ recovery (ISR) remained the dominant production technology throughout the reporting period, accounting for over 58% of total global uranium production in 2020 and approximately 63% in 2021. Continuing a downward trend over several years, worldwide uranium exploration and mine development expenditures have decreased significantly due to depressed uranium prices in recent years. However, exploration expenditures were reported to increase modestly in 2021 [2.3].

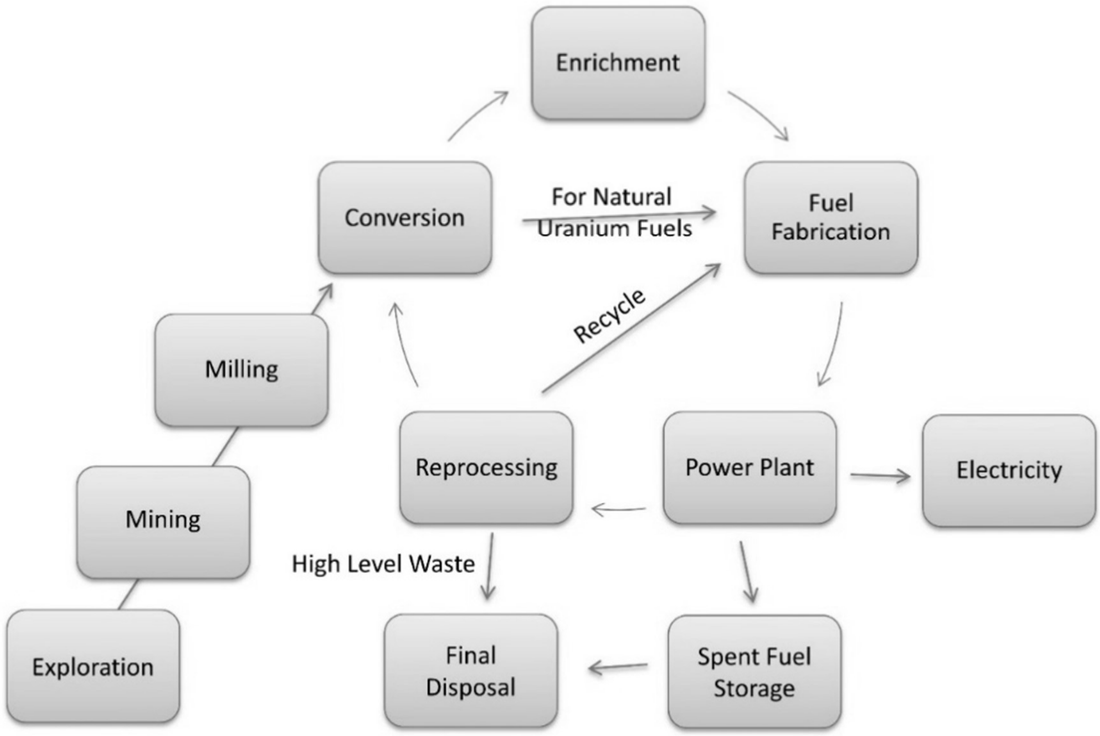

FIG. 2.1. Situating exploration in the nuclear fuel cycle (reproduced from IAEA Ref. [2.2]).

It is anticipated that uranium resources will be adequate to meet the high demand case for nuclear power generation through 2040 [2.3]. However, many factors can impede existing and new production including the requirement of large investments, lack of technical expertise, and adverse risk factors associated with mining, geopolitics, and marketing. Therefore, a shortfall in primary uranium production is already occurring and is being filled by secondary uranium supply [2.3]. In the long term this may not be sustainable as secondary supplies are gradually being consumed and are not forecast to increase in the future [2.4].

Countries hosting significant quantities of RAR are illustrated in Fig. 2.2. Co-product uranium resources from the Olympic Dam breccia complex copper-uranium deposit constitute a significant portion of Australian uranium resources. Global RAR (3 814 384 tU) by production method are illustrated in Fig. 2.3, including open-pit, underground, and low-cost in situ recovery (also known as in situ leach) mining methods. The latter method exploits sandstone uranium deposits. Figure 2.4 exhibits global RAR by processing method. Global RAR by deposit type are identified in Fig. 2.5. Worldwide uranium mine production is illustrated by deposit type relative to long-term uranium price indicators in Fig. 2.6. Low-cost uranium production is sourced from ISR sandstone uranium deposits and Proterozoic unconformity uranium deposits. A global annual uranium production capacity of approximately 80 Mlb U_3O_8 (approximately 30 000 tU) is available at <USD 20 /lb U_3O_8 (USD 52 /kgU), and approximately 150 Mlb U_3O_8 (approximately 60 000 tU) is available at <USD 30 /lb U_3O_8 (USD 78 /kgU). The assessment of the economic feasibility of future mining projects ought to include social and environmental sustainability perspectives. Further information on the sustainable development of uranium resources and mining can be found in IAEA publications [2.5, 2.6].

Dahlkamp [2.7] provides descriptive models for uranium deposits and the IAEA defines a classification scheme for 15 types of uranium deposits [2.8]: 1. Intrusive, 2. Granite-related, 3. Polymetallic iron oxide breccia complex, 4.Volcanic-related, 5.Metasomatite, 6. Metamorphite, 7. Proterozoic unconformity, 8. Collapse breccia pipe, 9. Sandstone, 10. Paleo-quartz pebble conglomerate, 11. Surficial, 12. Coal-lignite, 13. Carbonate, 14. Phosphate, 15. Black shale. Chapter 3 provides more information and references for uranium deposit models.

2.2 EXPLORATION BUSINESS CYCLES, INVESTMENT AND COMPETITORS

Long time frames and adequate funding are required for the exploration, discovery, and development of economic mineral deposits, coupled with the effective use of geoscientific knowledge and exploration technologies. Exploration funding often corresponds to the market price fluctuations of uranium. Price varies with uranium supply and demand and geopolitical factors that can be mapped as business cycles. Participants engaging in the uranium exploration business environment can be motivated by several objectives (Fig. 2.7).

Governmental organizations can focus on securing uranium resources for strategic reasons, in support of domestic nuclear energy programs, and the development of the domestic mining sector. Other benefits may include the generation of royalties from mining production and the creation of employment opportunities.

Successful exploration programmes are conducted over long time frames (decade or longer), starting at regional scales, moving to local scales, and culminating in the drill testing of promising targets.

International entities such as the IAEA, geological survey organizations, university researchers, consultants, and contractors, also participate in the uranium exploration business. These entities can be described as knowledge brokers. They have different motivations including the promotion of peaceful and sustainable use of nuclear energy, attracting investment, technology development, and the provision of expert advice and exploration services.

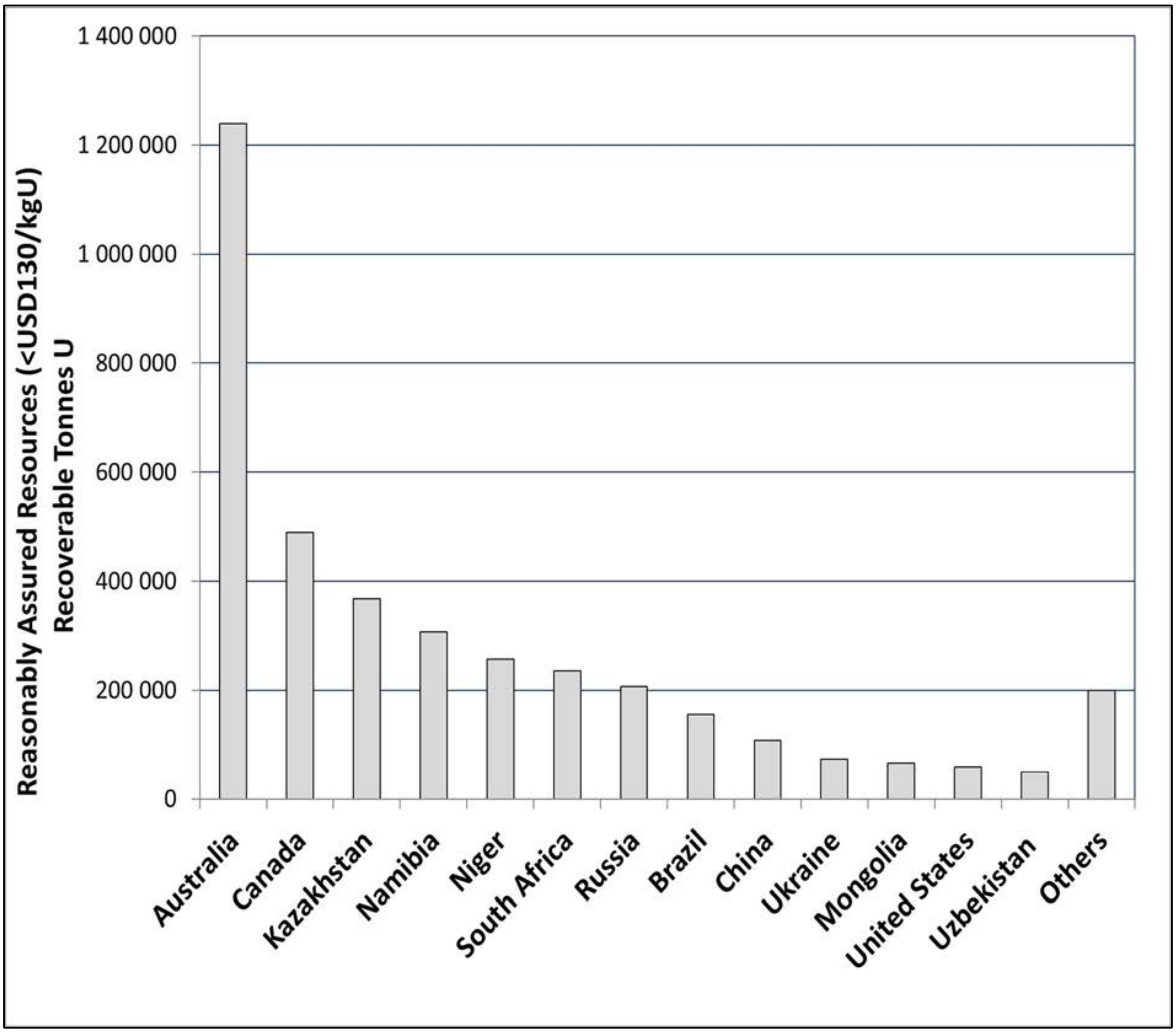

FIG. 2.2. Reasonably assured uranium resources by countries with significant resources. Data source Ref. [2.3].

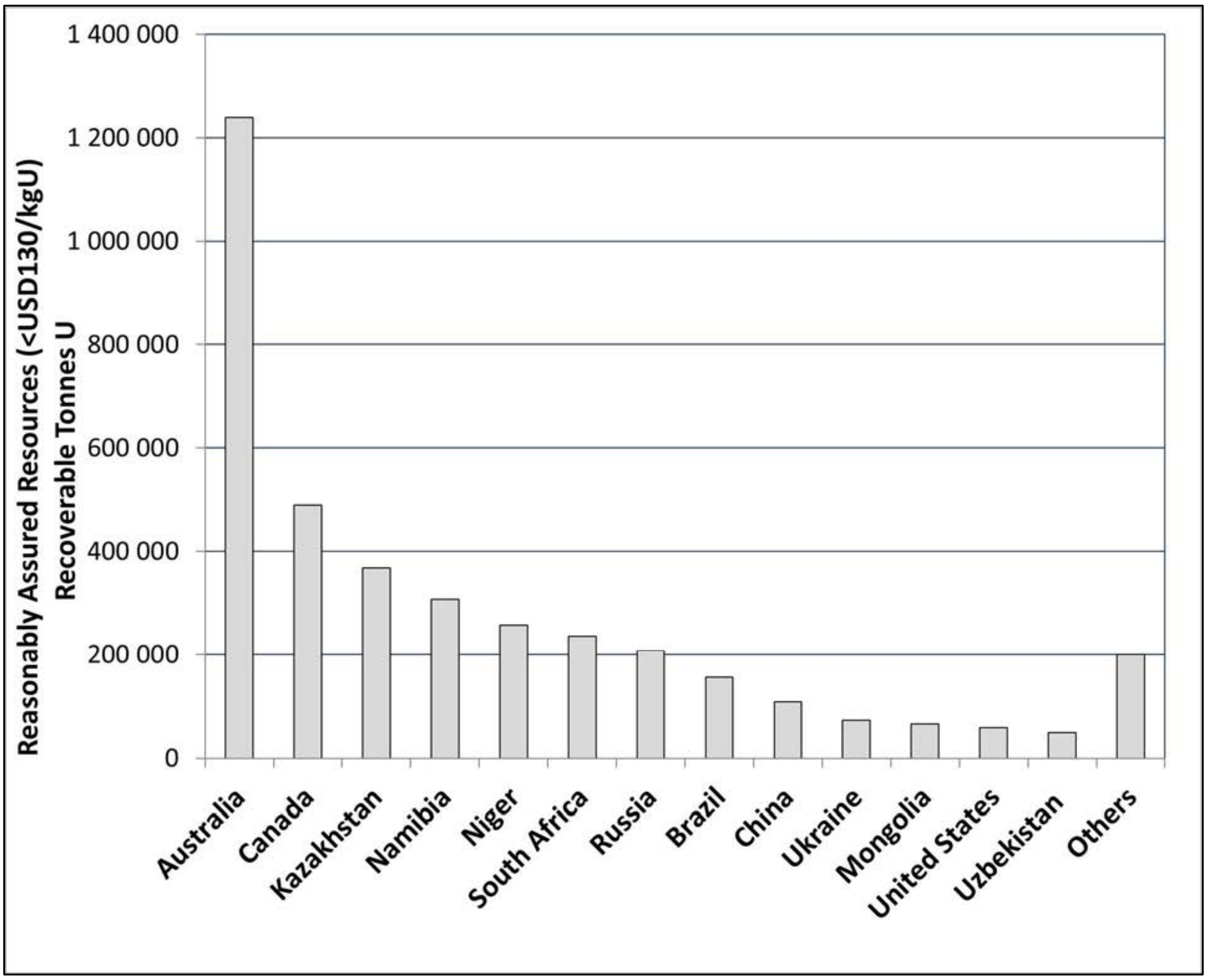

FIG. 2.3. Reasonably assured uranium resources by production method Data source Ref. [2.3].

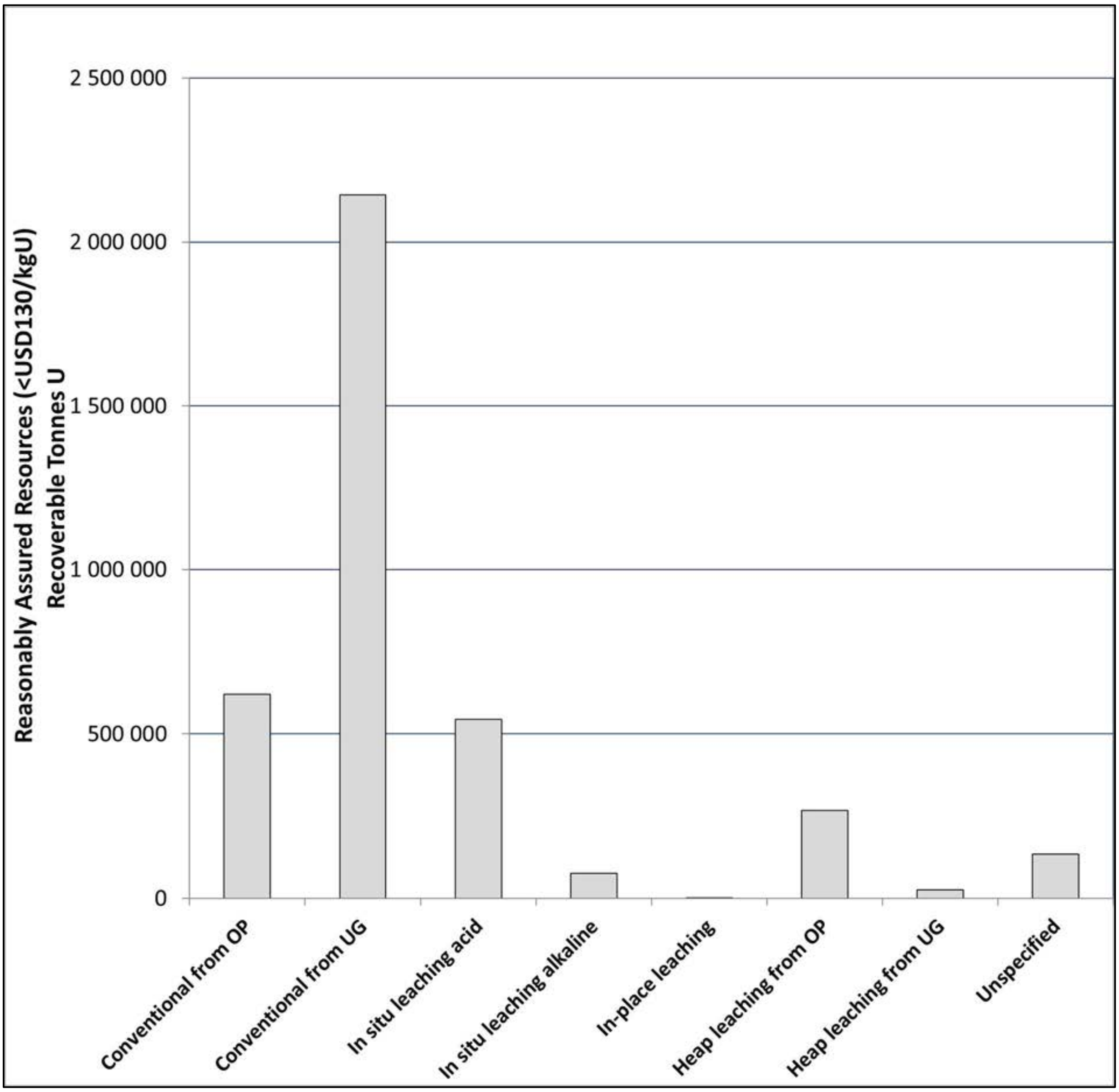

FIG. 2.4. Reasonably assured uranium resources by processing method (OP=open pit; UG=underground). Data source Ref. [2.3].

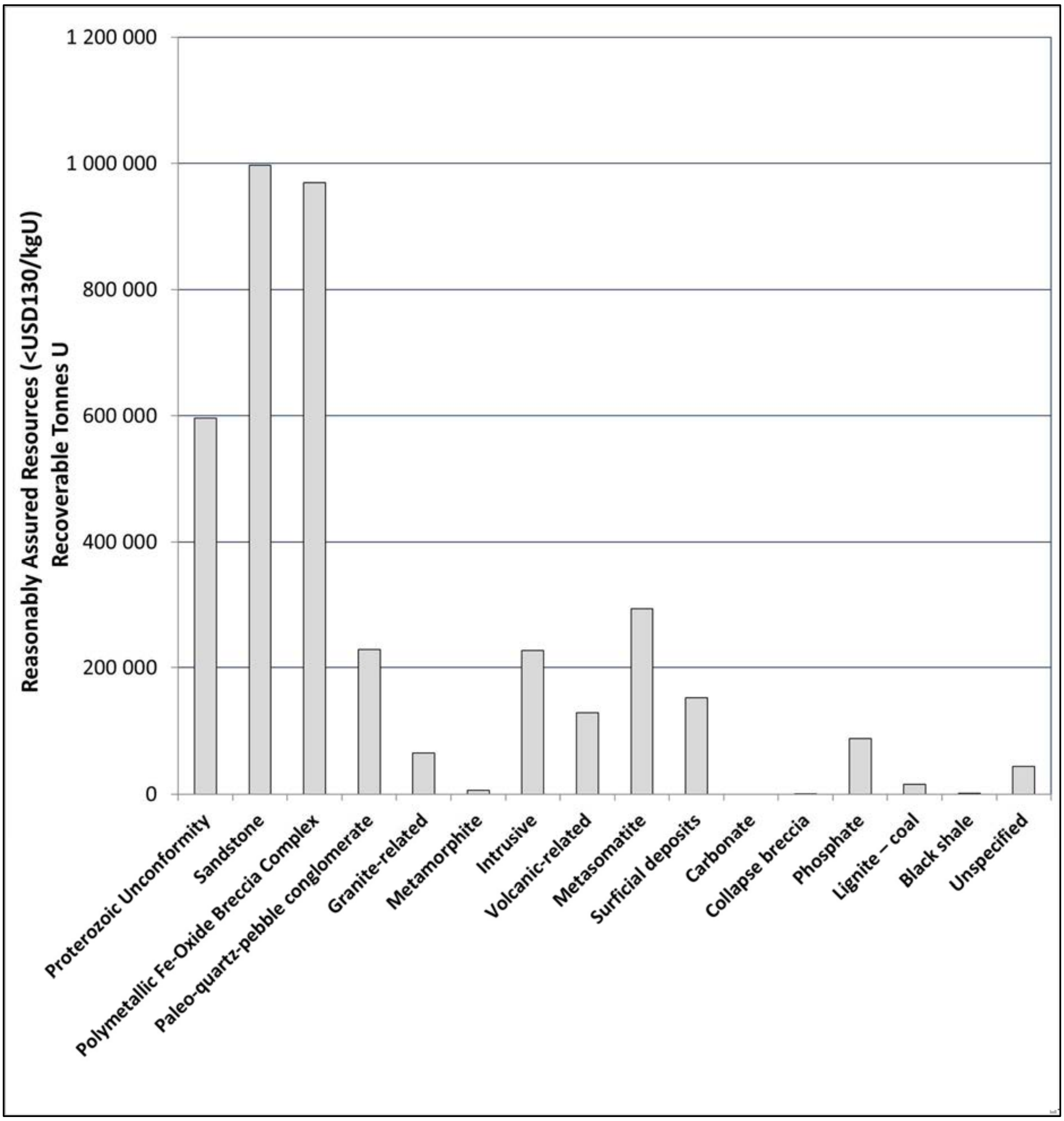

FIG. 2.5. Reasonably assured uranium resources by deposit type. Data source Ref. [2.3].

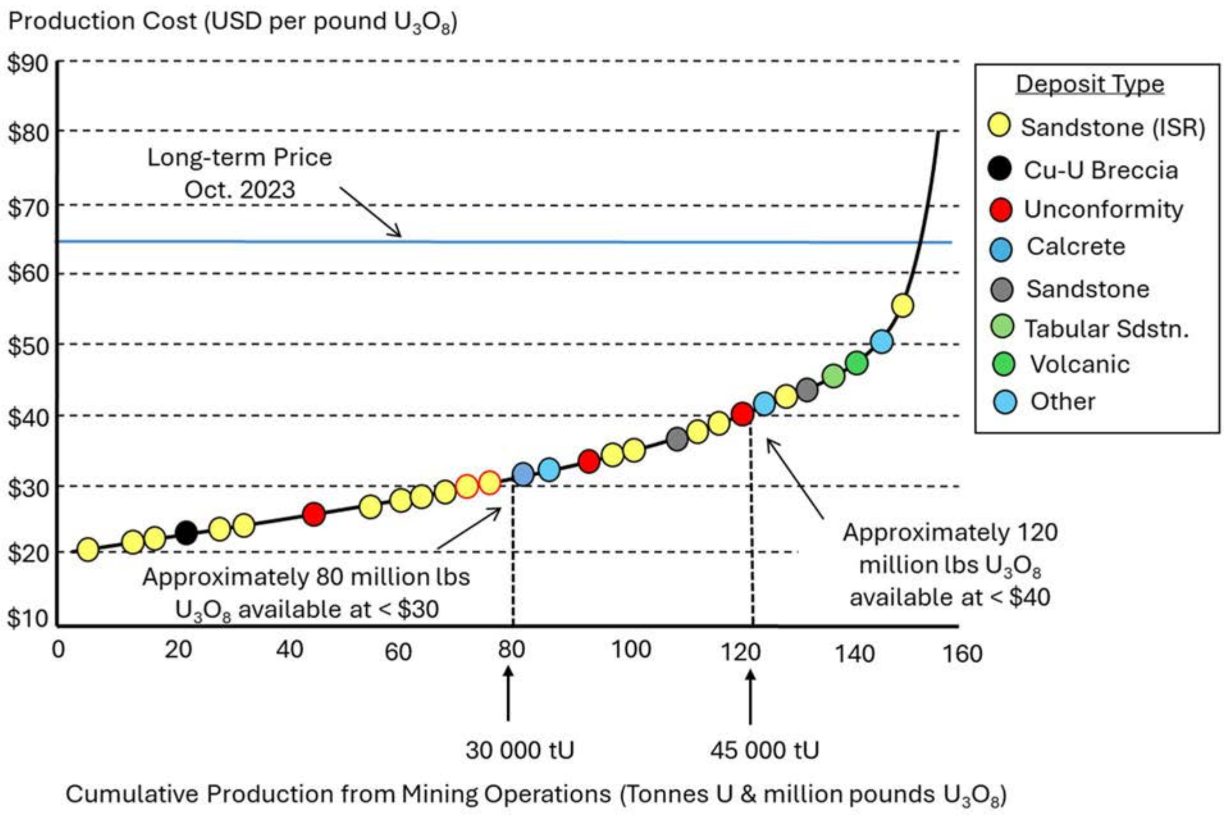

FIG.2.6. Idealized uranium mining production cost curve. Data from Refs.[2.8, 2.9, 2.10].

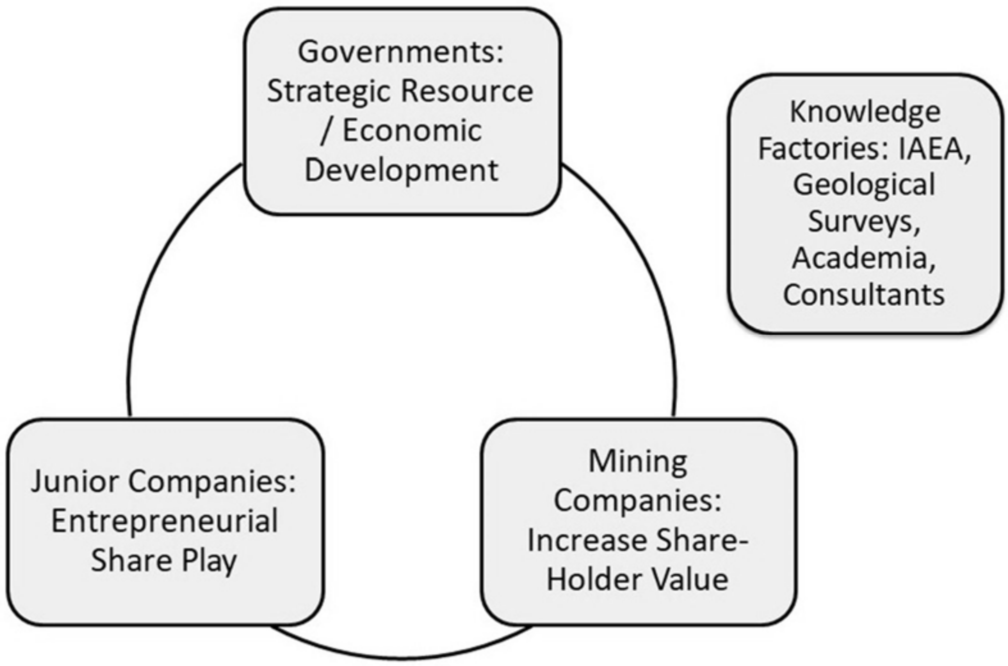

FIG. 2.7. Rationale for uranium exploration (reproduced from IAEA Ref. [2.2]).

Sustained long-term exploration funding is a critical element for discovery success. Junior exploration companies face the challenge of fund raising through private and public sources to sustain their exploration projects. The availability of this funding is generally sympathetic to the price of uranium.

Exploration companies with limited funding often compete in jurisdictions where investment is warranted. Investment decisions are driven by geopolitical factors, the assessment of the economic mineral potential, and the effectiveness of exploration technologies. The economic viability of future mining operations is also considered from the early stage of exploration.

Uranium price shifts are generally in response to a perception of the relationship between uranium supply and demand [2.2]. History demonstrates that the price will not stay below the average production cost for long periods. It will also not exceed the average production costs for long periods, as additional, new production will enter the market in response. This will lead to a drop in price in response to the additional supply.

Changing geopolitical situations can also affect the price of uranium. Price can be impacted by nuclear accidents, damage to nuclear facilities from earthquakes, perceived price impacts related to the introduction of secondary uranium supply and from de-weaponization, financial crises, and consideration of alternative energy sources, among others. Companies react to changes in uranium price in a cyclical fashion responding to market anxiety as illustrated in a model presented in Fig. 2.8.

Companies and other participants engage or withdraw from exploration in response to changes in uranium price. In a market characterized by rising prices, junior company shareholders often focus on share price escalation through promotional announcements about discoveries and rediscoveries, in sympathy with increases in uranium prices. In the competitive exploration environment, geological survey organizations ought to actively promote their jurisdictions to attract investment, considering geopolitical, geoscientific, and technological perspectives.

In a market characterized by falling prices, a lack of funding can disrupt exploration activities due to the decrease (or removal) of venture capital. Exploration budgets are reduced or eliminated, and exploration projects can lapse or become dormant. The demise or pause in activities of junior companies is common.

High-risk frontier exploration (political, physiographic, technological) is also impacted by low prices as companies refocus on historically productive jurisdictions that are lower risk. During periods of severe industry downturns, the irrevocable loss of expertise and knowledge can be associated with staff layoffs. This often includes the reduction or elimination of research and development activities.

The motivations and roles of participants in the uranium exploration business are illustrated in Table 2.1, including factors relevant to investment decisions. One of the roles of governments is to attract companies to the jurisdiction, by the reduction of geopolitical risks including corruption. This can be supported by the development of effective mining policies, and the development of a reliable mineral tenure system so that there is a reliable pathway to mine development [2.11].

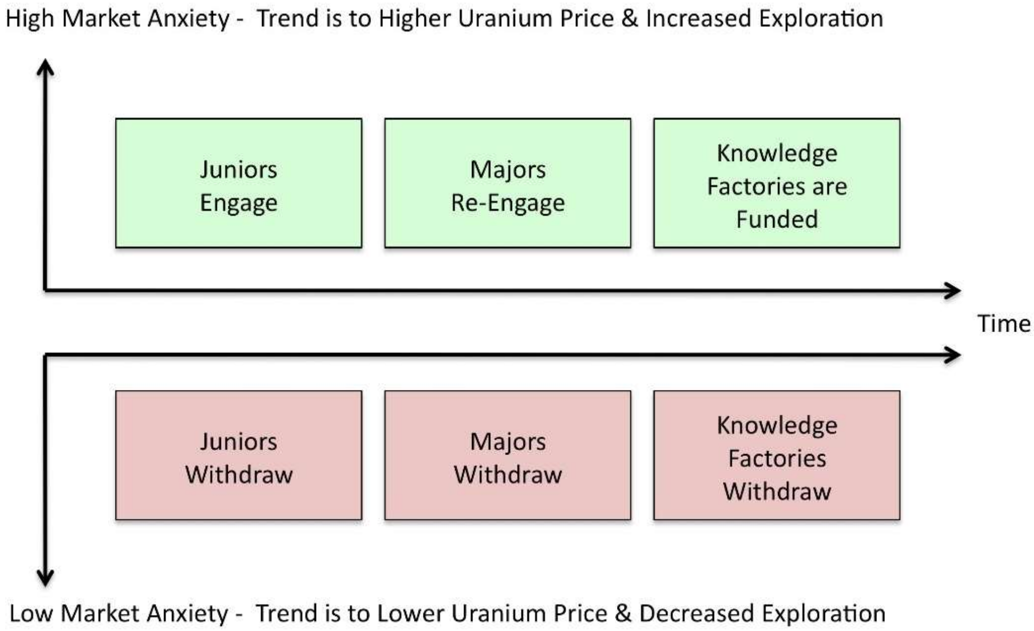

FIG. 2.8. Model of the impact of uranium price on exploration activity.

The provision of access to free or low-cost, high-quality, pre-competitive geoscientific datasets by geological survey organizations can also promote exploration investments. This type of information can assist the exploration company with mineral potential evaluations at an early stage in support of investment decisions.

Perceptions of the effectiveness of mining policy, corruption, sovereign risk, prospectivity, explorability, and other factors impact the investment decisions of exploration and mining companies [2.3]. Competitive benchmarks available to governments and geological survey organizations include those provided by the Fraser Institute annual country rankings survey of investment attractiveness, and Transparency International's anti-corruption index, among others (Table 2.2, [2.12]).

2.3 THE EXPLORATION PROCESS

The objective of uranium exploration is the identification of concentrations of mineralization that can be eventually exploited through mining. The exploration process starts with the selection of a geographical area and an evaluation of the investment worth of the exploration project. Initial work includes the desktop study of historical geoscientific and other technical information by experts, with a focus on understanding the economic potential for the occurrence of uranium within the geological environment. Another objective is the identification of effective exploration methods. Field programmes rely on a variety of geological, geochemical and geophysical exploration methods. A description of exploration methods is presented in Chapter 4.

TABLE 2.1. FACTORS INFLUENCING URANIUM EXPLORATION AND MINING INVESTMENT DECISIONS

Factors Influencing Investment Decisions in Various Jurisdictions	Role of Governments & Ministries	Role of Agencies, & Geological Survey Organizations	Role & Needs of Consultants / Academics Involved in Supporting Uranium Exploration	Needs of Junior Uranium Exploration Companies	Needs of Uranium Exploration & Mining Companies	Needs of Multi-Commodity Exploration & Mining Companies
Motivation of Organizations, Consultants & Academics	Attract Investors	Provide Information and Expertise	Provide Specialist Expertise	Share Price Escalation	Increase Shareholder Value	Increase Shareholder Value
Exploration Investment Risk	Risk Mitigation Role	Risk Mitigation Role	Technical Risk Mitigation Role	Higher	Moderate	Lower
At the Exploration Stage						
Higher level of security	x				?	x
Favourable uranium exploration & mining policies	x	x		x	x	x
Lower level of corruption	x	x		?	?	x
Advocate for good practice	x	x				x
Availability of local logistical experts		x		x	x	
Safe working conditions				?	x	x
Access to senior government officials	x	x		x	x	x
Easy/free access to high-quality geoscientific databases	x	x	x	x	?	?
Availability of local geoscientific experts/consultants/academics		x	x	x	?	
Advice on uranium prospectivity and explorability		x	x	x		
Certainty around the application of regulations*	x	x		?	x	
Cost effective land tenure and reporting system*	x	x		x	x	

TABLE 2.1. (cont.) FACTORS INFLUENCING URANIUM EXPLORATION AND MINING INVESTMENT DECISIONS

Factors Influencing Investment Decisions in Various Jurisdictions	Role of Governments & Ministries	Role of Agencies, & Geological Survey Organizations	Role & Needs of Consultants / Academics Involved in Supporting Uranium Exploration	Needs of Junior Uranium Exploration Companies	Needs of Uranium Exploration & Mining Companies	Needs of Multi-Commodity Exploration & Mining Companies
Motivation of Organizations, Consultants & Academics	Attract Investors	Provide Information and Expertise	Provide Specialist Expertise	Share Price Escalation	Increase Shareholder Value	Increase Shareholder Value
Exploration Investment Risk	Risk Mitigation Role	Risk Mitigation Role	Technical Risk Mitigation Role	Higher	Moderate	Lower
			At the Exploration Stage			
Timely granting of exploration land holdings	x	x		x	x	
Ability to import scientific equipment	x	x	x	x	x	
Ability to export rock, soil, vegetation, water and other samples	x	x	x	x	x	
Reporting on the status of mineral resources (e.g., NI 43–101)			x			
Exploration agreements with consultants, experts, & academics				?	?	x
Exploration agreements with junior exploration companies					x	x
Development of stakeholder relationships	x	x	x	x	x	x
			At the Mining Stage			
Higher level of security	x			A common strategy is to develop a resource and sell the company to a major mining	x	x
Lower level of corruption	x				x	x

TABLE 2.1. (cont.) FACTORS INFLUENCING URANIUM EXPLORATION AND MINING INVESTMENT DECISIONS

Factors Influencing Investment Decisions in Various Jurisdictions	Role of Governments & Ministries	Role of Agencies, & Geological Survey Organizations	Role & Needs of Consultants / Academics Involved in Supporting Uranium Exploration	Needs of Junior Uranium Exploration Companies	Needs of Uranium Exploration & Mining Companies	Needs of Multi-Commodity Exploration & Mining Companies
Motivation of Organizations, Consultants & Academics	Attract Investors	Provide Information and Expertise	Provide Specialist Expertise	Share Price Escalation	Increase Shareholder Value	Increase Shareholder Value
Exploration Investment Risk	Risk Mitigation Role	Risk Mitigation Role	Technical Risk Mitigation Role	Higher	Moderate	Lower
At the Mining Stage						
Political stability*	x			A common strategy is to develop a resource and sell the company to a major mining company	x	x
Fair legal system*	x				x	x
Understanding trade barriers*	x				x	x
Certainty around the application of regulations*	x	x			x	x
Minimal regulatory duplication and inconsistency*	x	x			x	x
Certainty around environmental regulations*	x	x			x	x
Clear understanding of socioeconomic stakeholder agreements*	x	x			x	x
Clear land claim dispute mechanism*	x	x			x	x
Infrastructure to support mining development*	x				x	x
Understanding labour regulations*	x				x	x
Availability of labour/skills*	x				x	x
Worker health & safety	x				x	x

* Factors adapted from the Fraser Institute Annual Survey of Mining Companies [2.11].

TABLE 2.2. A COMPARISON OF URANIUM EXPLORATION AND MINING INVESTMENT ATTRACTIVENESS BY COUNTRY*

Country	State / Province	Economic Deposit Models	Economic Uranium Prospectivity Ranking	Transparency International Corruption Index (2021)	Fraser Institute Investment Attractiveness Index (2021) [not specific to uranium]	Fraser Institute Policy Perception Index (2021) [not specific to uranium]	Factors impacting Uranium Exploration and Mining Investment Decisions
Uzbekistan		Sandstone (ISR)	Moderate	28	?	?	
Russian Federation		Volcanic-related, metasomatic, sandstone	Moderate	29	64	65	
Niger		Sandstone	High	31	45	64	Threat of terrorism
Gabon		Unconformity-related?	Low	31	?	?	Under-cover exploration in a tropical environment
Ukraine		Sandstone (ISR)	Low (depleted)	32	?	?	
Mongolia		Sandstone	Low	35	51	37	
Kazakhstan		Sandstone (ISR)	High	37	49	60	State controlled; acid leach permitted
Brazil		Metasomatic, phosphate (by-product)	Moderate	38	56	48	
Guyana		Unconformity-related?	Low (under-explored)	39	44	48	Permitting timelines
South Africa		Paleo-quartz-pebble conglomerate (by-product)	Low	44	38	50	Permitting challenges; no new discoveries
China		Sandstone (ISR)	Moderate	45	35	44	State controlled

TABLE 2.2. (cont.) A COMPARISON OF URANIUM EXPLORATION AND MINING INVESTMENT ATTRACTIVENESS BY COUNTRY*

Country	State / Province	Economic Deposit Models	Economic Uranium Prospectivity Ranking	Transparency International Corruption Index (2021)	Fraser Institute Investment Attractiveness Index (2021) [not specific to uranium]	Fraser Institute Policy Perception Index (2021) [not specific to uranium]	Factors impacting Uranium Exploration and Mining Investment Decisions
Namibia		Surficial (calcrete), sandstone	Moderate	49	53	75	Namibian state lifted the 10-year moratorium on new applications for U exploration licences
USA	Wyoming	Sandstone (ISR)	Moderate	67	72	87	Acid leach prohibited
USA	New Mexico	Sandstone (ISR)	Low	67	73	80	Permitting challenges
Australia	Queensland	Volcanic-related	Low	73	77	80	History of back-flipping on uranium mining policy/ Uranium exploration permitted but mining is not
Australia	Northern Territory	Unconformity-related	Moderate	73	78	76	Koongarra deposit incorporated into Kakadu National Park; Jabiluka mine on care and maintenance; NT government opposes Angela-Pamela uranium mine
Australia	South Australia	Sandstone (ISR), polymetallic iron oxide breccia complex (by-product)	High	73	82	83	High level of government support. Excellent pre-competitive databases
Australia	Western Australia	Surficial (calcrete)	High	73	90	93	History of back-flipping on uranium mining policy

TABLE 2.2. (cont.) A COMPARISON OF URANIUM EXPLORATION AND MINING INVESTMENT ATTRACTIVENESS BY COUNTRY*

Country	State / Province	Economic Deposit Models	Economic Uranium Prospectivity Ranking	Transparency International Corruption Index (2021)	Fraser Institute Investment Attractiveness Index (2021) [not specific to uranium]	Fraser Institute Policy Perception Index (2021) [not specific to uranium]	Factors impacting Uranium Exploration and Mining Investment Decisions
Canada	Northwest Territories	Unconformity-related	Low	74	66	58	Remote, expensive, exploration, and permitting challenges
Canada	Nunavut	Unconformity-related?	Low	74	71	70	Uranium mining developments impeded by licensing process
Canada	Quebec	Sandstone (mafic dykes sills)	Low	74	83	93	Uranium exploration and mining prohibited
Canada	Saskatchewan	Unconformity-related	Hight	74	88	91	Economic deposits are taking longer to find
Finland		Metamorphite	Low	88	79	89	Uranium-specific permitting requirements

*Rankings after the Fraser Institute [2.10] and Transparency International [2.11] (higher values are more favourable).

The general stages of mineral exploration are depicted in Fig. 2.9. The process starts with the definition of the type of deposit model to be explored for considering economic potential and establishment of the operational and technical framework. The target area is selected, and exploration proceeds from regional to prospect scales, including the drill testing of mineralized occurrences. Additional information on the 'stage gate' approach is covered in Chapter 5. Approximately one in 1000 exploration projects lead to the discovery of an economic uranium deposit and only one in three of these deposit definition projects will advance through the economic feasibility study to the mining stage [2.3].

Increasing levels of expenditures and decreasing levels of investment risk occur as the exploration process advances. Lead times can be decades long before the identification of an economic deposit, mine development, and realizing a return on investment after production starts.

At the mining stage, many factors can impact the economic viability of a uranium deposit, including risks related to ore reserves, geopolitical risk, environmental and social risks, price, and mining operation costs. Uranium grade and tonnage are the most significant factors in determining economic viability. Additional costs incurred at the end-of-mine-life are related to reclamation and environmental monitoring (Fig. 2.11) [2.14].

The general stages of mineral exploration are depicted in Fig. 2.9. The process starts with the definition of the type of deposit model to be explored for considering economic potential and establishment of the operational and technical framework. The target area is selected, and exploration proceeds from regional to prospect scales, including the drill testing of mineralized occurrences. Additional information on the 'stage gate' approach is covered in Chapter 5. Approximately one in 1000 exploration projects lead to the discovery of an economic uranium deposit. Only one in three of these deposit definition projects will advance through the economic feasibility study to the mining stage.

Expenditures increase from the exploration to the mining stage. Larger investments are required to assess economic and environmental feasibility, predevelop, develop, and ultimately decommission the mine (Fig. 2.10).

The capitalistic objective of exploration and major mining companies is the sustainable generation of profits and increasing shareholder value. The focus of junior exploration companies is on increasing stock market share prices through entrepreneurial and promotional activities. Junior companies may seek the identification of an economic deposit or advanced project to develop or sell to a major mining company. They can have short time frames and be willing to take on riskier strategies. They often enter exploration joint ventures and strategic alliances, with major companies funding the exploration activities of the junior company, as their surrogate.

As an illustration, the distribution of primary Australian and Canadian uranium deposits by contained tonnes of uranium, is presented in Fig. 2.12 [2.2, 2.16]. Many deposits that have been discovered may never meet an economic threshold. For example, the Kintyre and Millennium deposits appear to be sub-economic at 2022 prices, based upon public announcements. The Rabbit Lake mine is closed due to low uranium prices. The Ranger mine has closed in the absence of extensions of mining agreements.

Examples of jurisdiction policy and location risks include the effective prohibition of the development of the Koongarra and Jabiluka uranium deposits in Australia, and the further development at the Ranger Mine, due to socio-political factors. The moratorium on uranium mine development imposed by the Quebec government in the province of Quebec, Canada is another example.

Long time frames are typically required from the discovery of an economic deposit to production. Examples for selected Canadian and Australian uranium deposits are illustrated in Fig. 2.13. The time to production ranges to over 30 years from discovery to production. Some sub-economic deposits, and potentially economic deposits such as Jabiluka, have remained inventoried for more than 30 to 60 years. Less than one half of the significant deposits that have been discovered in Canada and Australia have been brought into production (Fig. 2.14) [2.15].

An inventory of the global distribution of uranium deposits is presented in the IAEA World Distribution of Uranium Deposits Database (UDEPO) [2.8]. A size threshold for these deposits was used as a rough estimate of the number of economic uranium deposits suggested by this inventory as shown Fig. 2.15. More than 100 'economic' deposits are postulated from this inventory using a rule-of-thumb resource threshold of 50 000 tU and about 50 of these deposits could lead to production, amounting to roughly 1% of the total inventory of global deposits.

The probability of the discovery of an economic deposit is estimated at one economic discovery for every 100 uranium prospects assessed, or one economic discovery for every 1 000 reconnaissance drill holes completed. These rates are similar to those identified for other research and development activities in other sectors such as manufacturing (Refer to Table 2.3).

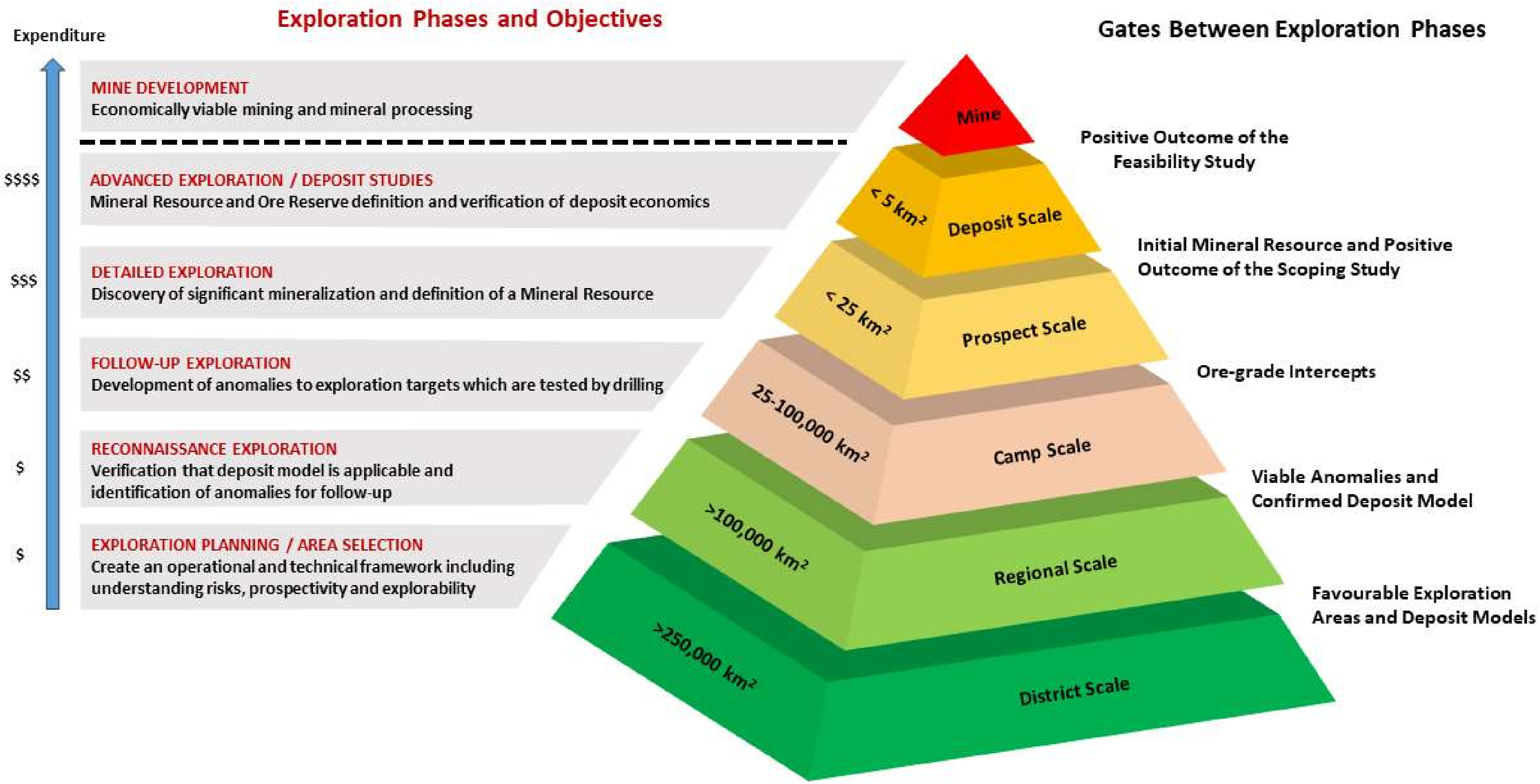

FIG. 2.9. Simplified illustration of the stage-gate approach showing the main exploration phases, their objectives, and gates between exploration phases.

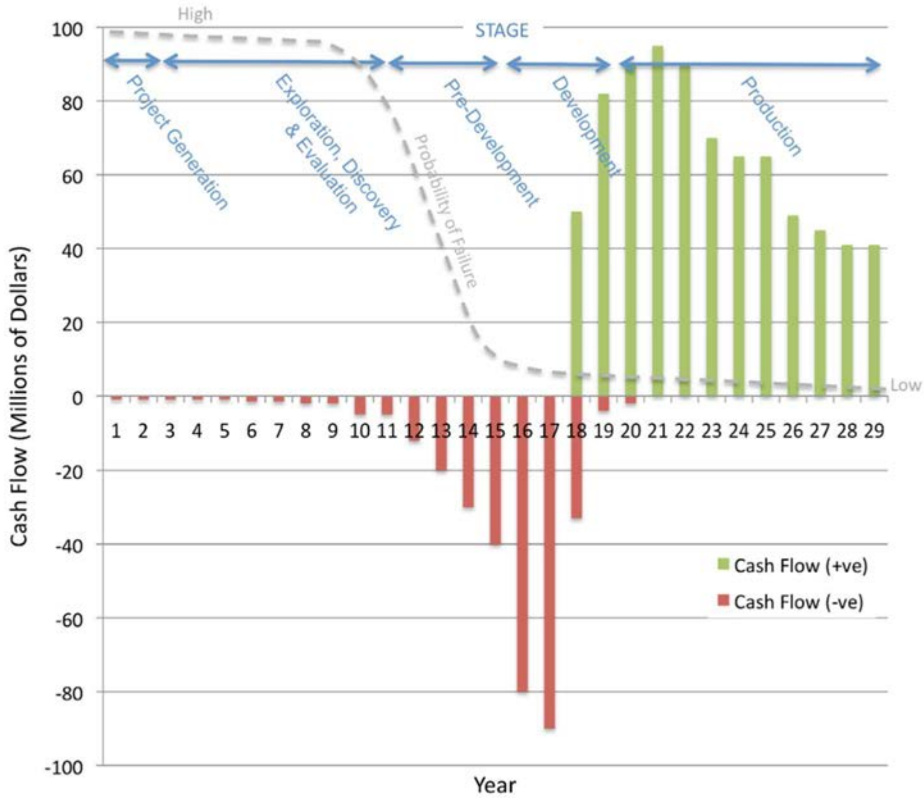

FIG. 2.10. Hypothetical cash flow associated with exploration and mining development (reproduced from IAEA Ref. [2.2] and adapted from Ref. [2.13]).

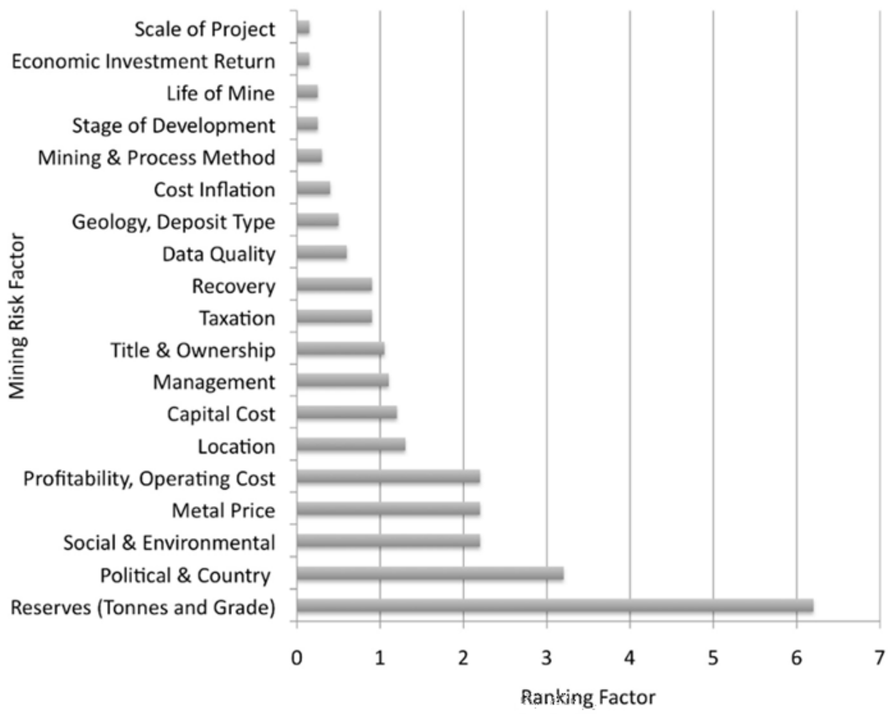

FIG. 2.11. Ranking of principal mining project risks (reproduced from IAEA Ref. [2.2]).

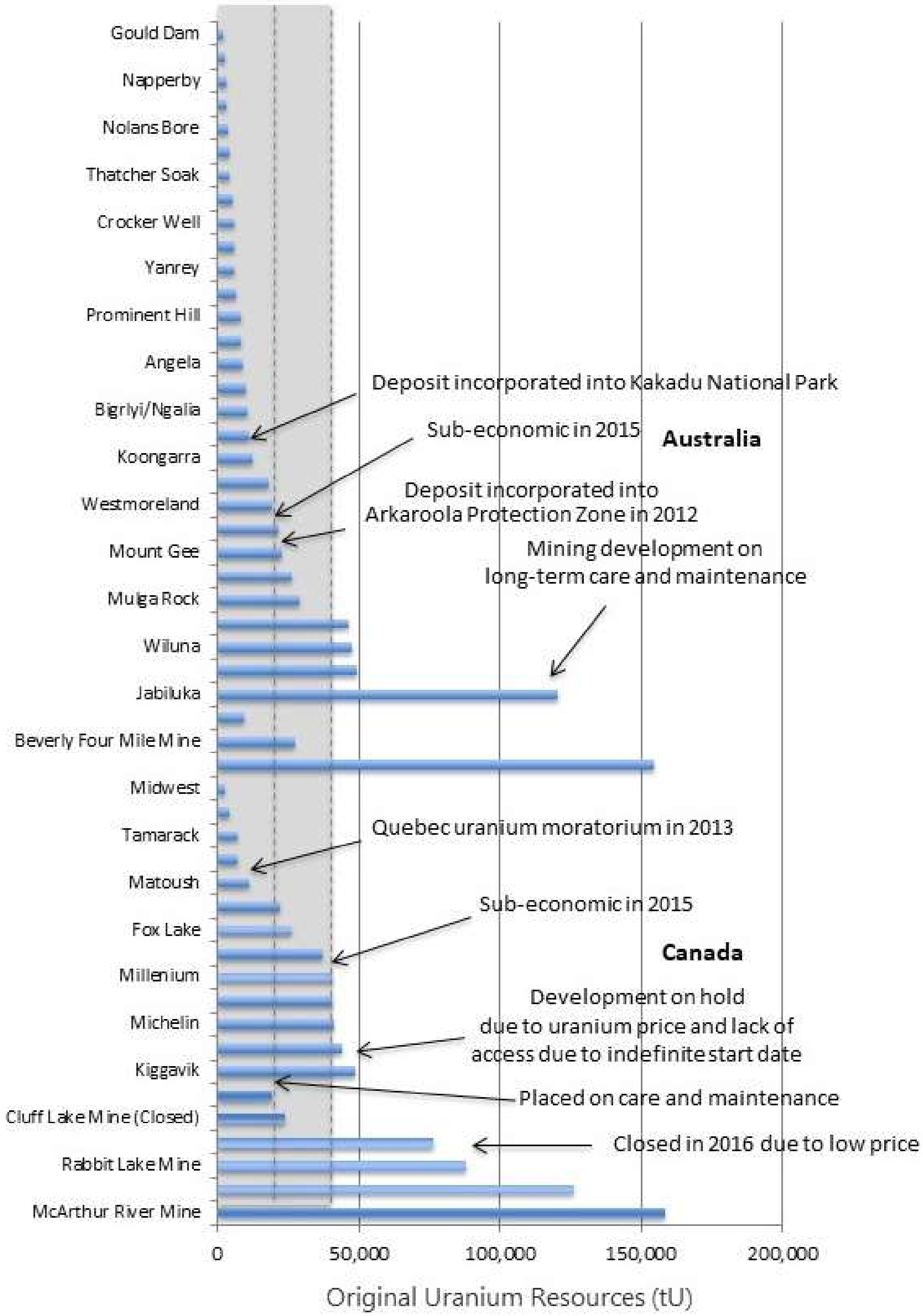

FIG. 2.12. Status and size distribution of uranium deposits in Australia and Canada. Australian deposit size data source Ref [2.16]. Figure reproduced from IAEA Ref. [2.2]).

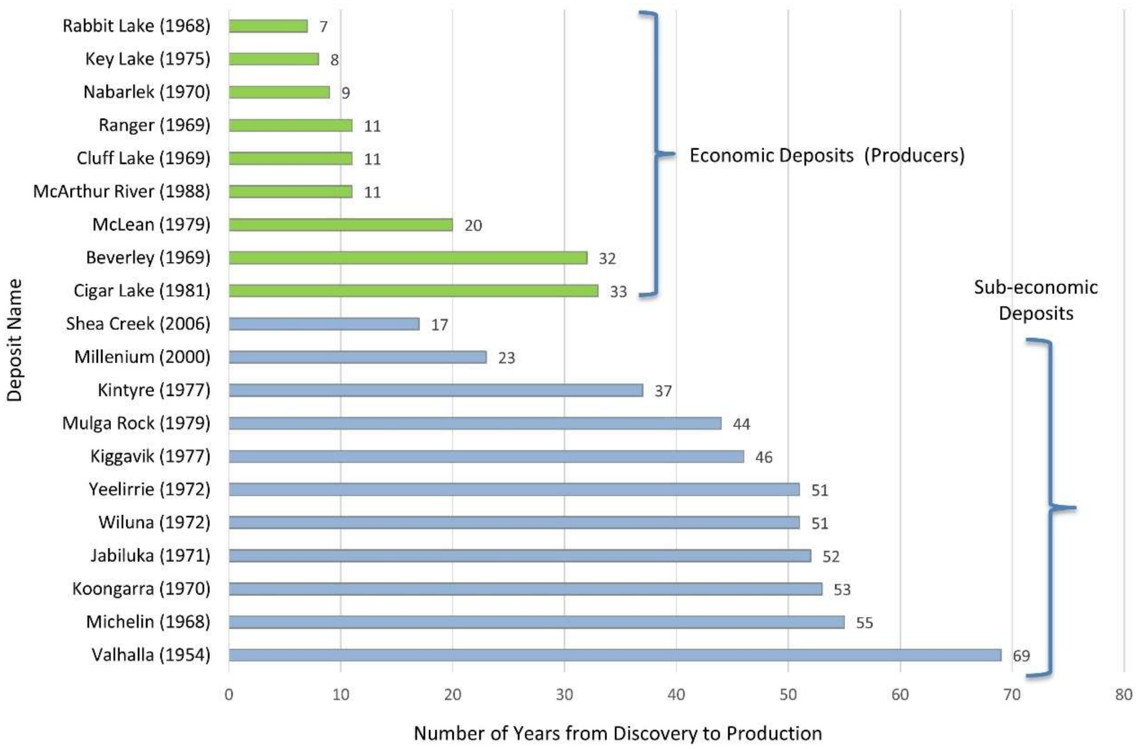

FIG. 2.13. Number of years from discovery to production for selected Australian and Canadian uranium deposits. Australian deposit, data source Ref. [2.16].

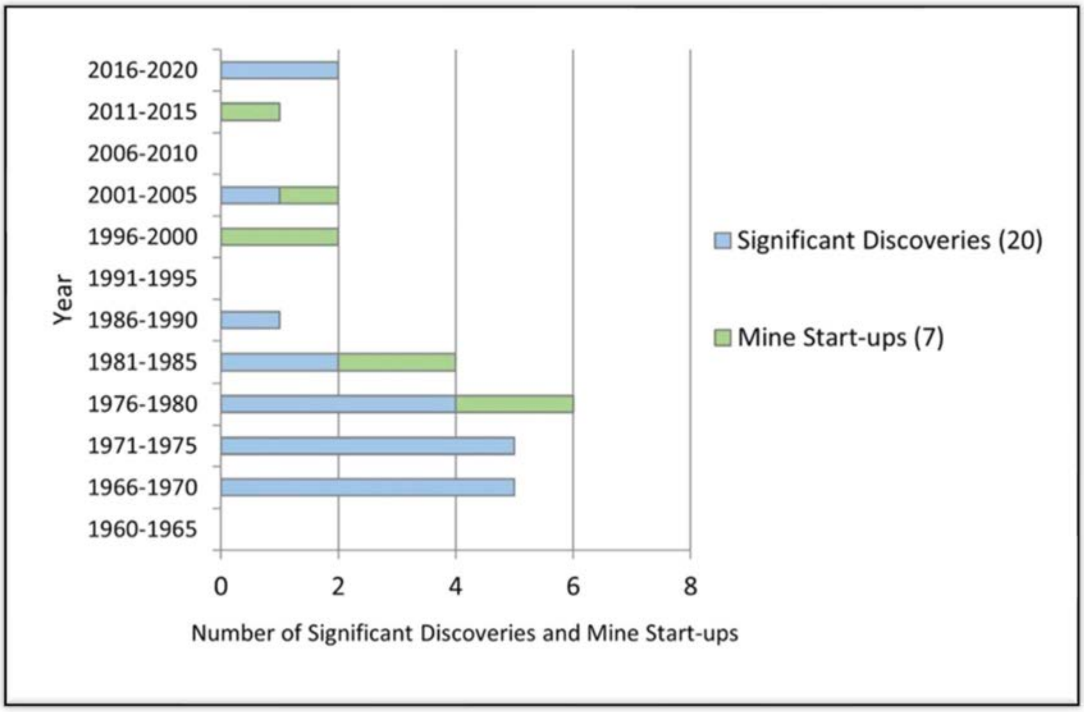

FIG. 2.14. Conversion of significant discoveries to mines for Australian and Canadian uranium deposits.

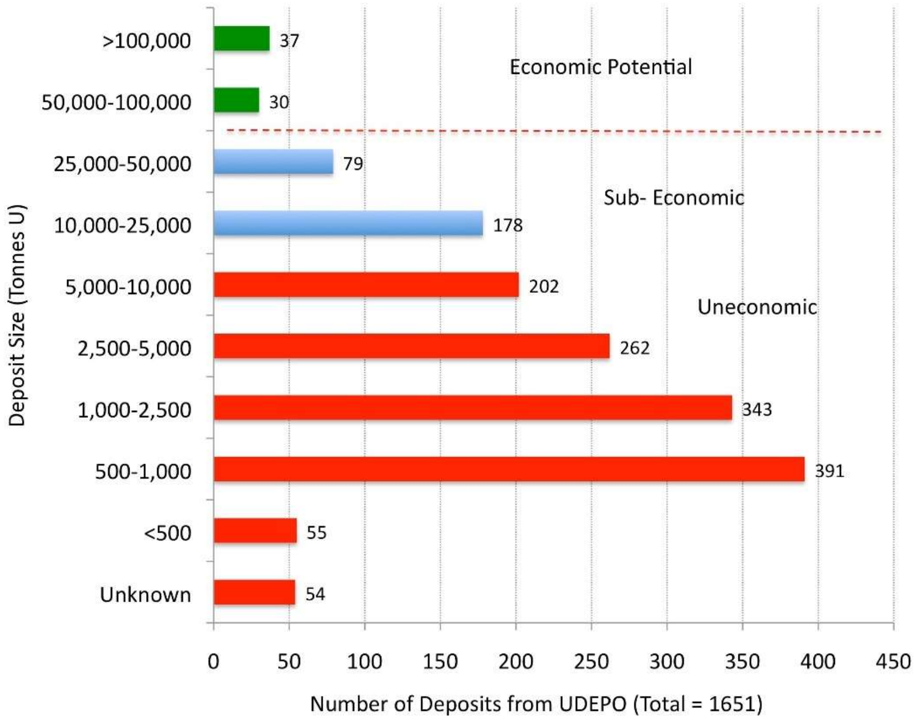

FIG. 2.15. Estimated number of uranium deposits in the world with economic potential based on size. Data source Ref. [2.8].

TABLE 2.3. COMPARISON OF UNITED STATES OF AMERICA (USA) MANUFACTURING SUCCESS RATES WITH ATHABASCA BASIN DISCOVERY RATES. USA MANUFACTURING DATA SOURCE REF. [2.17]. ATHABASCA BASIN URANIUM DEPOSIT DISCOVERY RATES DATA SOURCE REF. [2.18]

USA Manufacturing 1 in 3 000 Success Rate		Athabasca Basin 1 in 10 000 Success Rate	
Raw Ideas	3 000	Conceptual Drill Targets and	10 000
Ideas Submitted	300	Reconnaissance Drill Targets	1000
Small Projects	125	Showings	100
Significant Development	9	Advanced Projects	10
Major Development	4	Prefeasibility	3
Launches	1.7	Feasibility	1.5
Commercial Success	1	Economic Deposits	1

2.4 ASSESSING PROSPECTIVITY, EXPLORABILITY AND OTHER RISK FACTORS

From a technical perspective, the selection of exploration targets is based upon an assessment of prospectivity and explorability. Other strategic factors that can impact investment decisions include country (sovereign), mining, social and environmental risks. At an operational level, risks relate to talent availability, the capacity to innovate and the ability to conduct exploration in a safe and sustainable manner. Some of these risk factors are defined below, along with examples (Fig. 2.16).

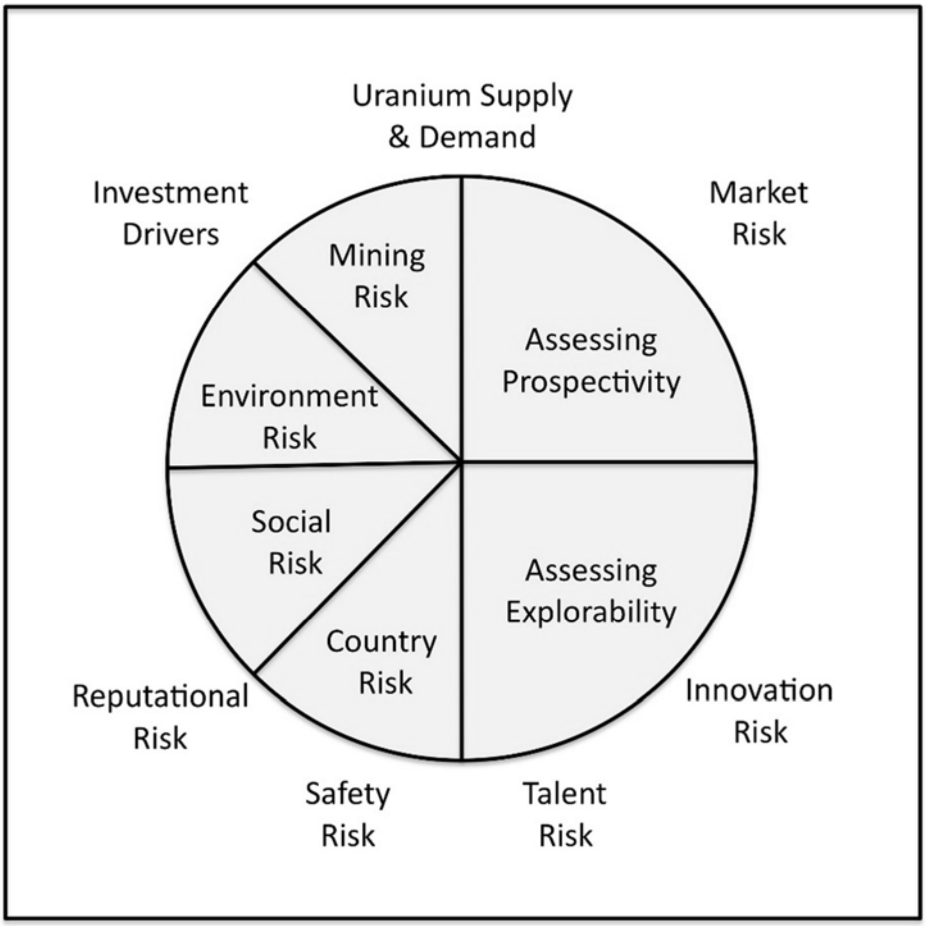

FIG. 2.16. Uranium exploration risk factors (reproduced from IAEA Ref. [2.2]).

2.4.1 Prospectivity

The likelihood that economic mineral deposits will be present in the project area is referred to as prospectivity. The economic mineral potential of the project area is considered when assessing prospectivity. Related factors to consider when assessing prospectivity include suitable deposit models, anticipated grades and tonnages, the anticipated value of discovery, exploration history and discoveries, the depletion of economic mineral resources, the exploration stage and anticipated exploration costs to discovery. Descriptive or genetic deposit models form the basis for the qualitative or quantitative assessment of mineral potential, through the ranking of geoscientific elements that point to favourable ore-forming processes. Uranium deposit models are described in Chapter3.

Examples of risks include high-risk exploration of frontier terrains based on limited technical knowledge, utilizing an incorrect deposit model and exploration in mature environments experiencing economic resource depletion.

2.4.2 Explorability

If exploration can be conducted economically and effectively using existing exploration methods and technologies, or technologies under development, then the project can be referred to as being explorable. The methods and technologies include the ‘hardware’ and ‘software’ of exploration.

This includes the array of standard geological, geochemical, geophysical, and drilling tools, and innovative thinking respectively. Access to exploration land holdings is also required.

Examples of risks include exploration in areas where access is challenging and where standard geochemical and geophysical approaches may not work, such as the exploration for deep blind deposits and exploration in logistically inaccessible terrains.

2.4.3 Mining risk

Mining risk refers to business and technical factors at the mining stage that can adversely impact production and profitability such as uncertainty related to grades and tonnages, geopolitics, social and environmental impacts, and metal price (Fig. 2.11) [2.13].

Examples of risk include poorly defined or unanticipated ore reserve geometry, inadequate stakeholder engagement, drop in metal price, unanticipated ground stability or water inflows, environmental contamination, and metallurgical processing challenges.

2.4.4 Country risk

Strategic political, economic, and financial risks can lead to increased costs of business or prohibition of working in the jurisdiction. Political instability and violence can impact operations. A changing policy may impede or prohibit uranium exploration and mining, including the security of land tenure. Examples of risk include sovereign risk of government expropriation, conflict, terrorism, corruption, inflation, exchange rate stability, and economic and social impacts related to working in jurisdictions impacted by endemic diseases, such as HIV/AIDS, COVID-19 [2.19, 2.20].

2.4.5 Environmental risk

Environmental issues can impact the capacity to conduct business in the jurisdiction, including the potential for punitive and reputational damages and exclusion. Risks include those associated with working within environmentally sensitive lands, including proximity to parks and nature reserves, government and non-governmental organization interventions, and interventions by traditional landowners. Examples of risks include the declaration and unanticipated expansion of nature reserves and parks and increased environmental regulatory oversight and regulation.

2.4.6 Social risk

Exploration and mining companies have an obligation to conduct their activities in a social and environmentally responsible manner. Failure to do so can impact project viability. Companies can

> "manage the business processes to produce an overall positive impact on society [through a] continuing commitment by businesses to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society at large." [2.21].

Examples of risks include opposition to mine developments and additional regulatory and relationship burdens.

2.4.7 Reputational risk

The risk is that exploration and mining activities will reflect poorly on the organization. Examples of risk include supporting corruption through ineffective business practices, working in environmentally or ecologically sensitive areas without appropriate assessments and policies, ignoring environmental regulations, and poor stakeholder relationship management.

2.4.8 Assessing prospectivity

A framework for assessing the likelihood that economic mineral deposits will occur in the exploration areas (prospectivity) is presented in Fig. 2.17. Assessment activities include the evaluation of strategic risks, understanding mineral occurrences and economic potential, and the identification of relevant uranium deposit models. The goal is the development of conceptual exploration targets and securing an exploration land position and exploration permits.

Economic potential can be understood through the study of geological data including historical exploration activity reports, and geological, geophysical, and geochemical datasets. Site visits to examine historical mineralized occurrences with the objective of understanding metallogenic characteristics and deposit model types are an important activity.

Prospectivity can be assessed using qualitative (spatial modelling) and quantitative methods to understand the potential for the occurrence of economic deposits on regional and more localized scales. Understanding the grade and anticipated tonnage characteristics of existing and anticipated deposits is an important factor in evaluating the investment worth of exploration. Mineral potential assessments can also focus on understanding the ore genesis mineral systems processes from the perspective of the source, transport, trap, and preservation of ore-forming fluids. Exploration companies typically approach country geological survey organizations to access free, or low-cost, pre-competitive information in support of these assessments [2.22].

2.4.9 Assessing explorability

The likelihood that exploration can be undertaken economically and effectively is illustrated in Fig. 2.18. These assessments include the evaluation and selection of exploration methods, gaining an understanding of project logistics, land access, the availability of exploration service providers, and the availability of baseline geological information. Historical exploration reports provide insight into approaches leading to project success or failure. The estimation of depth below the land surface to target informs the viability of different exploration methods. Data compilation, the nomination of exploration targets, and the development of preliminary programmes and budgets are critical activities in evaluating investment worth.

2.4.10 Exploration methods

Exploration programmes focus on identifying geological, geophysical, and geochemical signatures that are indicative of economic mineral occurrences. Descriptive and genetic uranium deposit models are used to describe these signatures [2.7, 2.8]. Bedrock drilling is a key method in testing anomalies identified from exploration surveys that might reflect mineralization. Different methods are appropriate at different scales of exploration from reconnaissance to advanced stages.

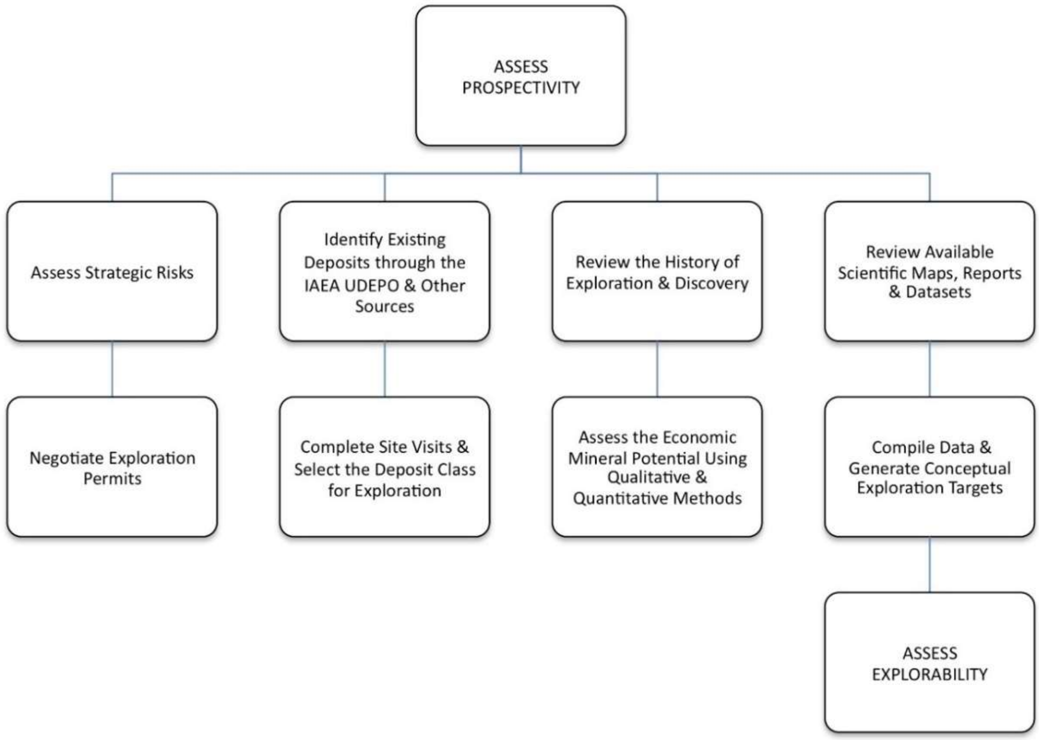

FIG. 2.17. A Basic Framework for Assessing Prospectivity (reproduced from IAEA Ref. [2.2]).

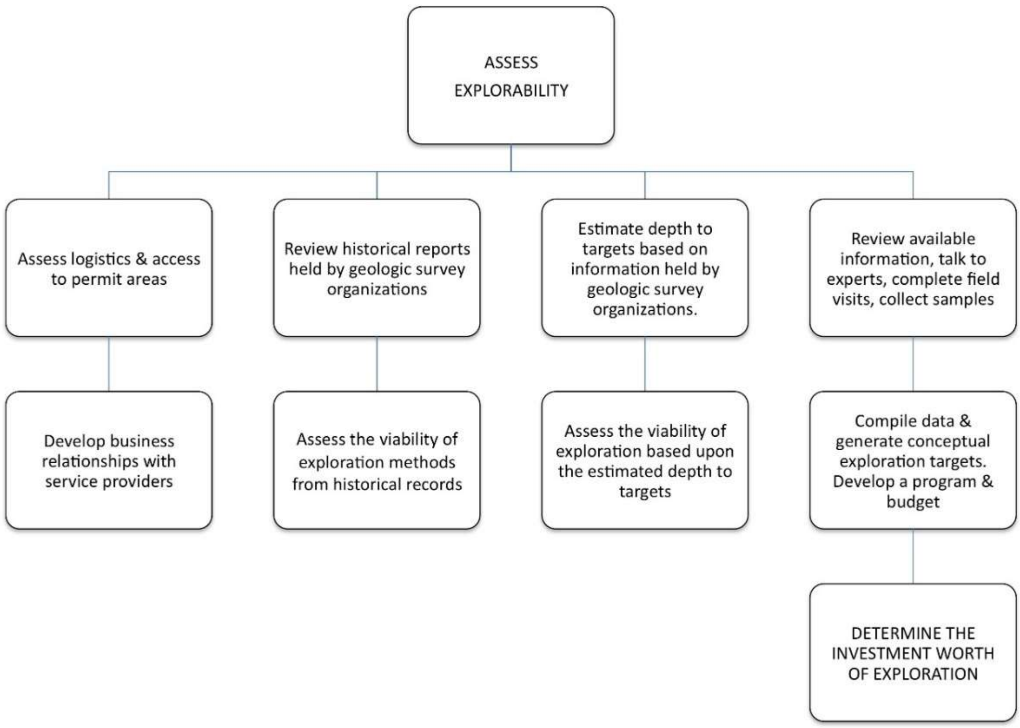

FIG. 2.18. A basic framework for assessing explorability (reproduced from IAEA Ref. [2.2]).

As an example, a list of exploration methods for unconformity-related uranium deposits, and estimated costs is presented in Fig. 2.19. The methods can be categorized according to their focus on geology, geochemistry, geophysics, and drilling. Geophysics can be further divided into radiometric, spectroscopy, topography, electrical and electromagnetic, magnetic, gravity, and seismic methods. Satellite-based remote sensing is used at reconnaissance scales of exploration. The selection of exploration methods can be dictated by physical geography and geology. Surface geochemical sampling methods are often favoured in tropical environments, for example. The investment worth of utilizing specific exploration methods is assessed given their utility and cost. Further information on exploration methods can be found in Chapter 4 and other IAEA publications including, *Advances in Airborne and Ground Geophysical Methods of Uranium Exploration* [2.23].

Exploration companies often engage specialist consulting companies, independent consultants, and commercial laboratories, to complete geological surveys over project areas. The development of innovative exploration methods is also supported through research and development activities, involving universities and other organizations. The goal is to improve the rate of discovery of economic mineral deposits. Methods have evolved to test for responses at increasing depth below surface. Innovations related to biogeochemical and isotopic methods in mineral exploration are also notable [2.24].

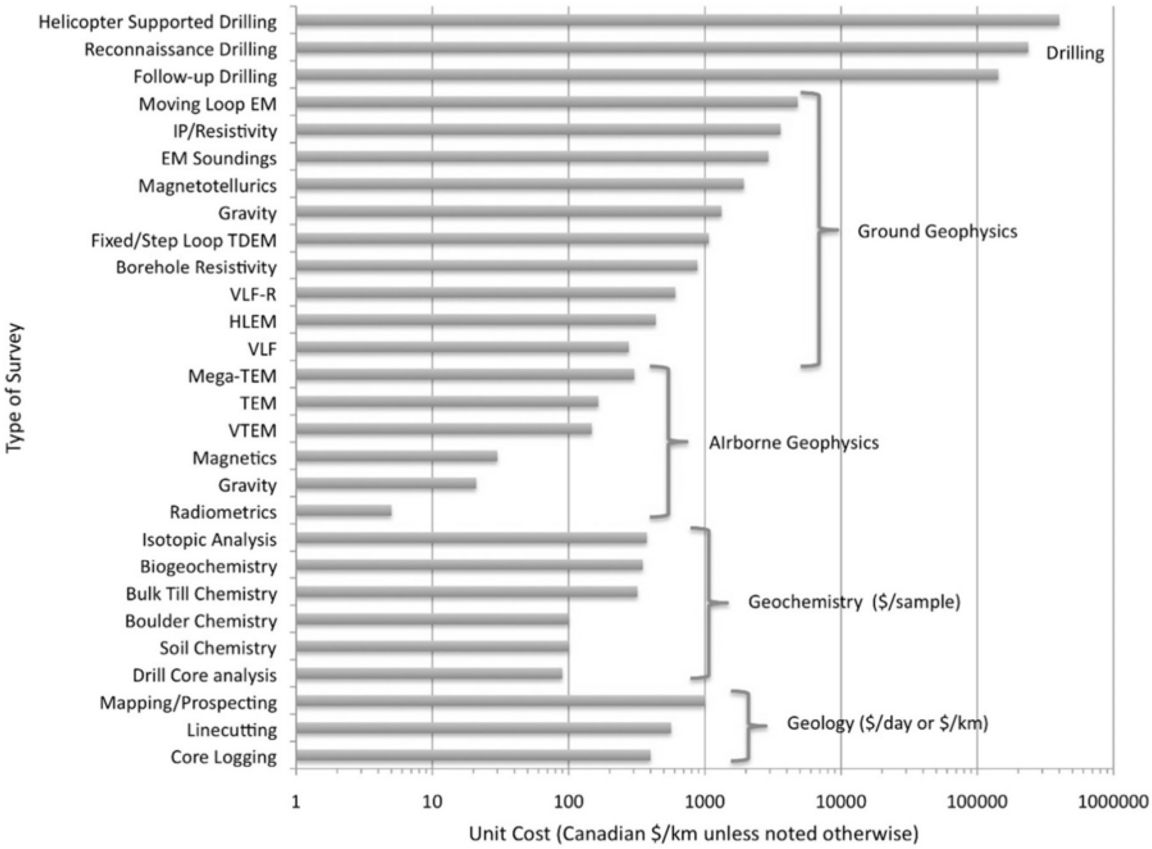

FIG. 2.19. Approximate unit cost of exploration by type of survey (reproduced from IAEA Ref. [2.3]).

2.5 OVERVIEW OF THE MANAGEMENT OF MINERAL EXPLORATION

A general overview of the management of mineral exploration includes situating the exploration process within the overall mineral resource development enterprise, understanding the role of exploration planning, the different phases of exploration, and the definition of mineral resources as a precursor to mine development.

2.5.1 Exploration and mining process

Uranium exploration is conducted at the front end of the nuclear fuel cycle. The business context of working in different jurisdictions is assessed to determine the investment worth of exploration and the potential for mining development. Consideration is given to the efficacy of uranium policies, and the business environment. The technical focus of exploration management is the selection of the deposit type for exploration considering economic potential, sustaining exploration over a portfolio of projects from early to late stages over long time frames, and the definition of economic mineral resources through mining feasibility studies. A positive feasibility study can lead to mine development and uranium production. Environmental sustainability and social responsibility are important throughout the exploration and mining process (Fig. 2.20).

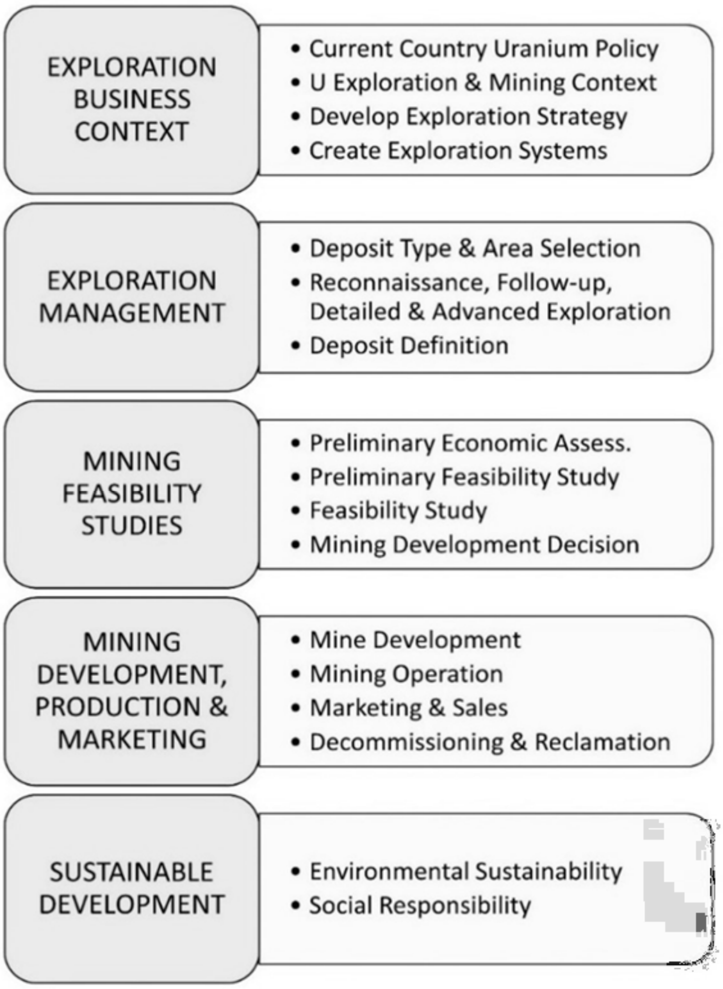

FIG. 2.20. Exploration and mining process elements.

2.5.2 Exploration project planning

Before implementing exploration programmes, the exploration strategy is developed. Conceptual exploration targets are developed based upon exploration models considering prospectivity and explorability with predictions about the expected return on investment in the form of a mineable economic deposit. Exploration management system is developed to support exploration activities. This includes the development of the well-funded exploration organization, strategy, tactical (managerial), and operational elements. Offices are created and managerial, administrative, and technical staff are hired or contracted, and policies and technical systems are established (Fig. 2.21).

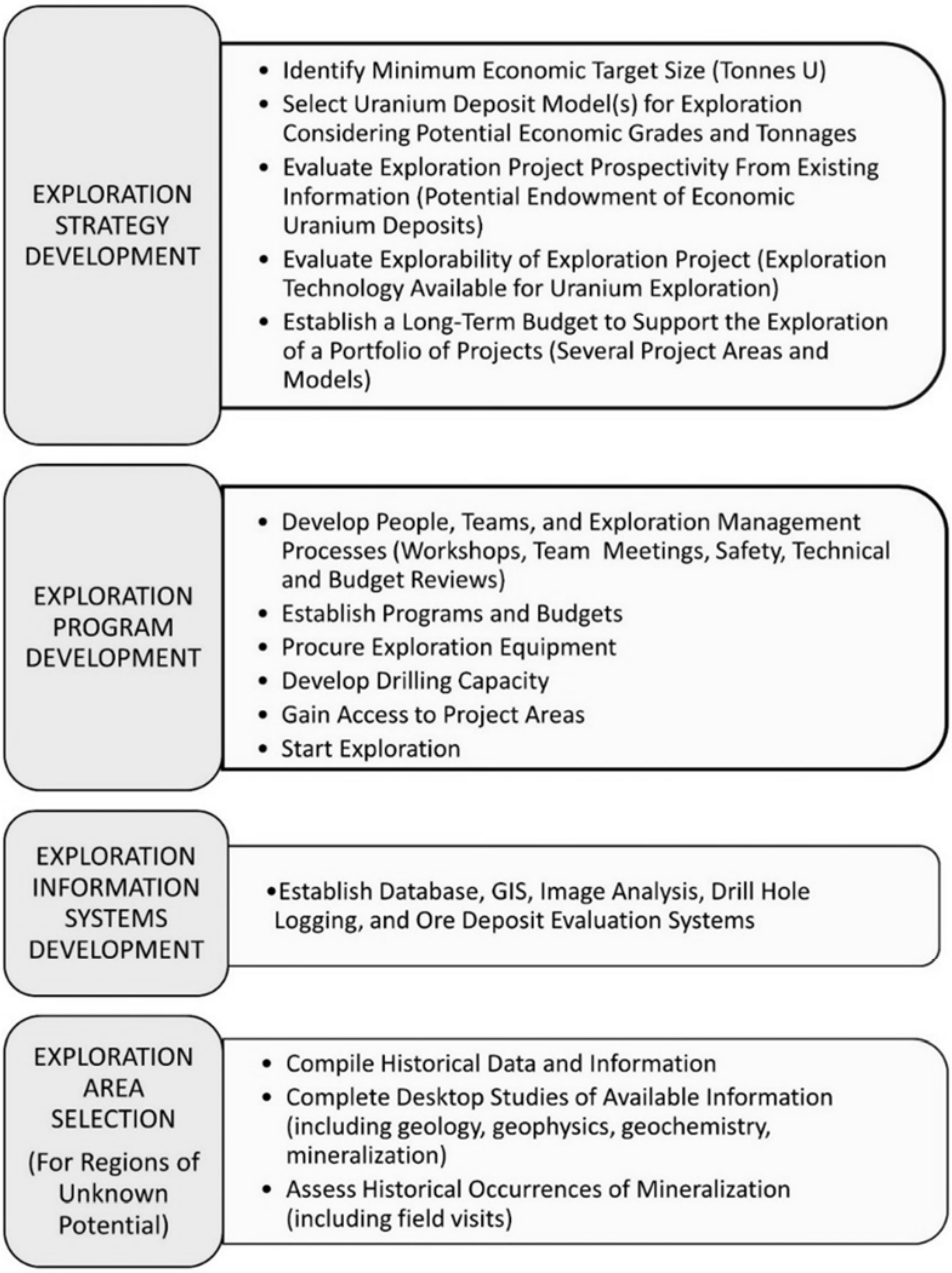

FIG.2.21. Exploration project planning.

2.5.3 Exploration phases and mineral deposit definition

Exploration programmes move from the reconnaissance phase consisting of lower density sampling over areas of unknown or speculative potential. The goal is to understand the regional mineralizing potential and the early identification of geological, geophysical, and geochemical anomalies. The follow-up phase of exploration involves intermediate density sampling to further identify areas of interest. Widely spaced drill holes are completed to understand the geological setting and to test anomalies and alteration systems. Next, the detailed phase of exploration involves high-density sampling to identify significant mineralized uranium grades and thicknesses, the geological setting, and the extent of mineralization. The advanced phase of exploration is focused on uranium prospects with indications of significant mineralization with the definition of ore bodies through additional drilling (Figs. 2.22 and 2.23).

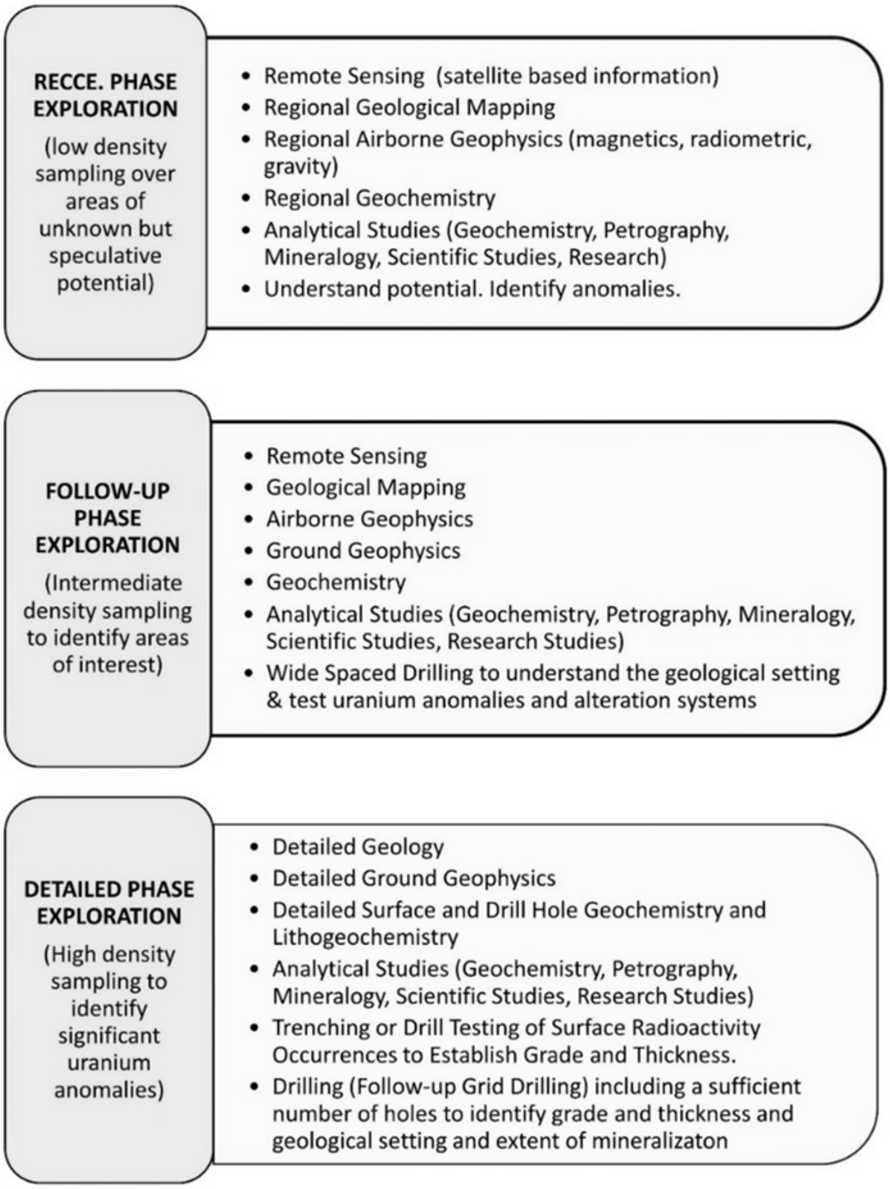

FIG. 2.22. Reconnaissance phase to detailed phase exploration elements.

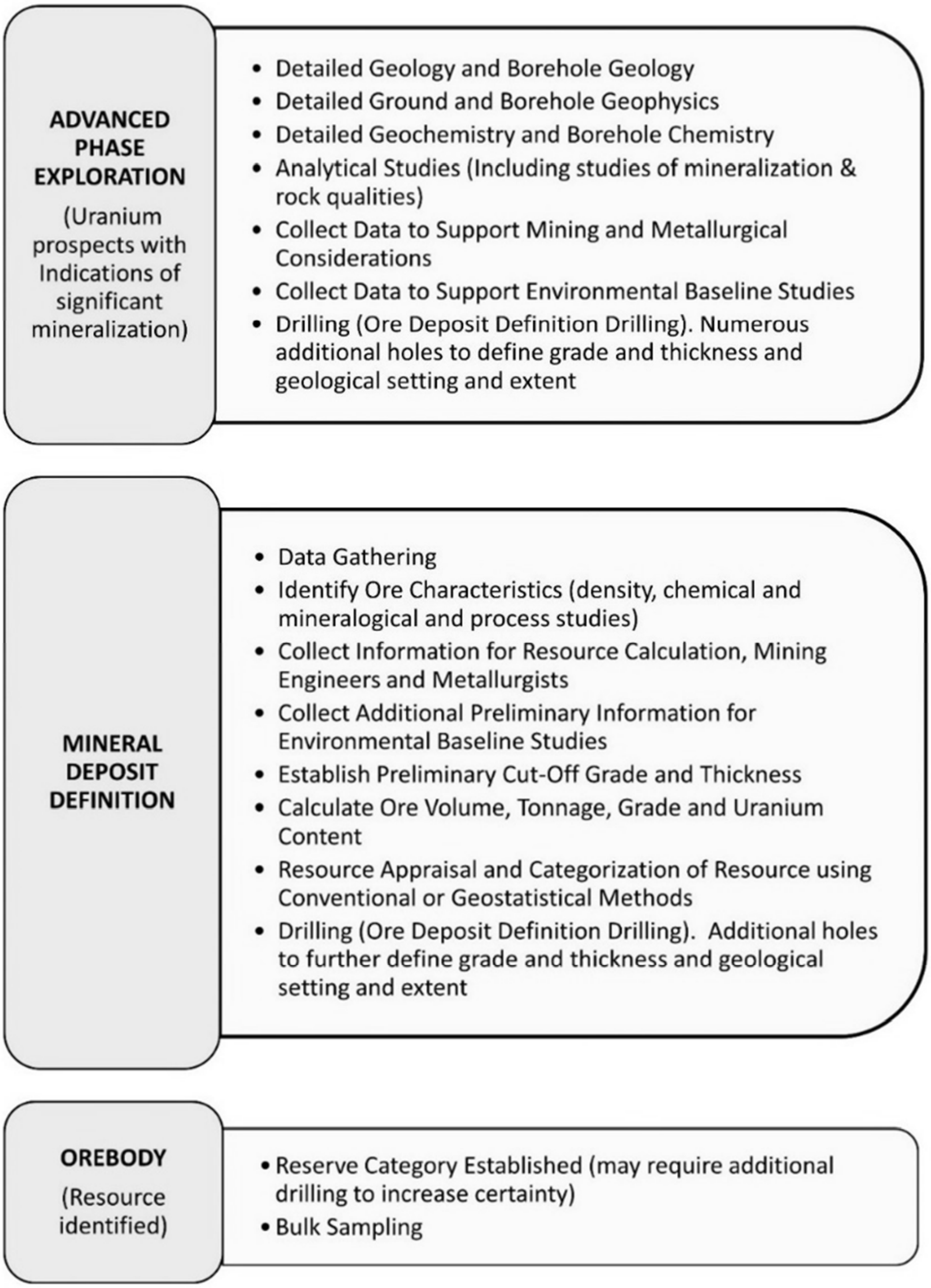

FIG. 2.23. Advanced exploration to ore body definition leading to mine development.

2.5.4 Mining feasibility studies

The evaluation of economic potential is an essential part of the mineral exploration process. With the discovery of significant uranium concentrations, three types of economic assessments are typically considered. Preliminary Economic Assessments (PEA), also known as 'scoping studies', involve an early conceptual evaluation of the economic viability of the mineral deposit with the identification of inferred resources. Preliminary Feasibility Studies include economic and engineering studies sufficient to demonstrate economic viability based on indicated and measured resources. Feasibility Studies are detailed evaluations of how the mine will be constructed and are used as a basis for decisions to move to construction and production based on probable and proven reserves (Fig. 2.24). Elements of feasibility studies are presented in Table 2.4 to demonstrate the complexity of activities, advancement of engineering studies, and increasing accuracy of cost estimates supporting economic analysis.

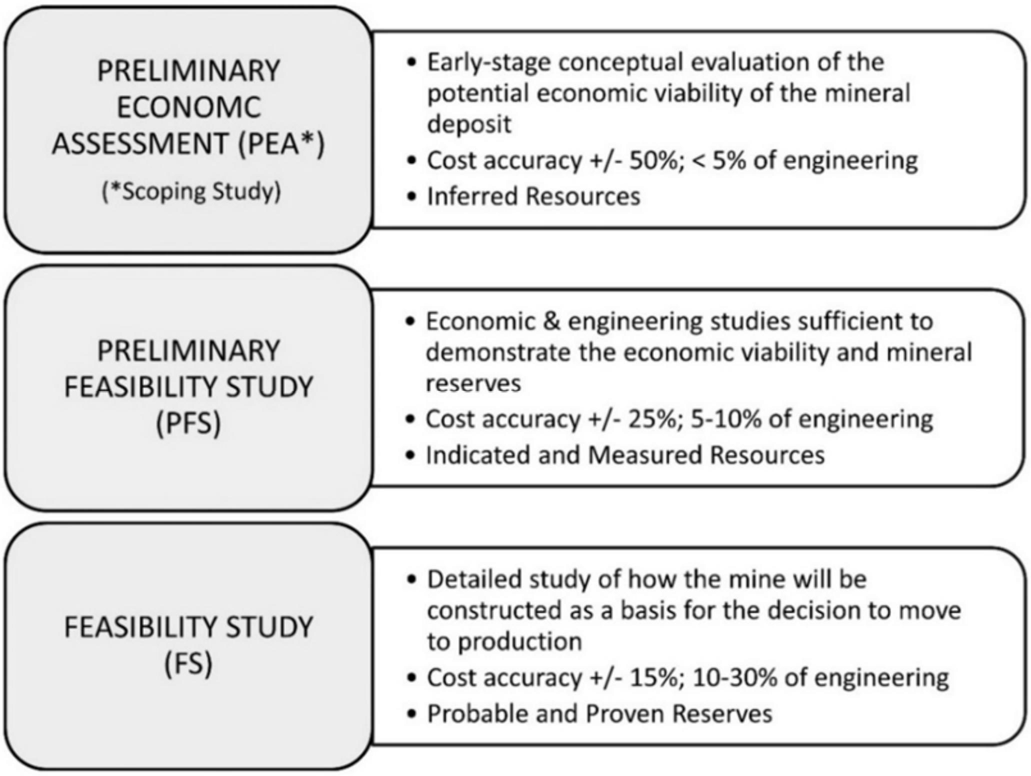

FIG. 2.24. Evaluation of economic viability of the uranium deposit.

TABLE 2.4. ELEMENTS OF FEASIBILITY STUDIES PROCEEDING MINE DEVELOPMENT

Item	Preliminary Economic Assessment (PEA)*	Pre-Feasibility Study	Feasibility Study
Orebody Reserve	Assumed	Indicated	Proven/Probable
Orebody Bulk Sampling	None	Possible	Essential
Site infrastructure	Assumed	Defined	Finalized
Mine	Assumed	Conceptual	Finalized
Process Plant	Assumed	Preliminary	Detailed
Bench lab test	Suggested	Initial	Detailed
Pilot plant test	None	None	Probably
Piping & instrumentation	Early	Preliminary	Final

TABLE 2.4. (cont.) ELEMENTS OF FEASIBILITY STUDIES PROCEEDING MINE DEVELOPMENT

Item	Preliminary Economic Assessment *	Pre-Feasibility Study	Feasibility Study
Electrical	None	None	Detailed
Concrete & steel	None	None	Detailed
Tailings & Environment	Assumed	Assumed	Defined
Decommissioning plans	Assumed	Assumed	Defined
Environmental baseline study	None	None	Finalized
Environmental impact study	Assumed	Assumed	Completed
Environmental impact statement	None	None	Completed
Permits	None	None	Submitted
Capital costs	Factored	Preliminary	Very Detailed
Operating costs	Assumed	Preliminary list	Detailed list
Project schedule	Assumed	General	Final
Economic analysis	Very Preliminary	Preliminary	Detailed

*Also known as a conceptual feasibility study or scoping study.

2.6 THE ROLE OF AGENCIES, GOVERNMENTS, CONSULTANTS AND ACADEMIA

The system of uranium exploration consists of experts, methods, and programme managers involved in supporting the process of uranium exploration. A number of entities play an important role in this process. These include the IAEA, geological survey organizations, consultants, and academic researchers (Fig. 2.25).

The IAEA promotes the peaceful and sustainable use of nuclear energy, education and training opportunities in the field of uranium exploration and mining, among others [.

Geological survey organizations support uranium exploration by providing technical expertise and pre-competitive technical data to exploration companies to support mineral potential assessments and investment decisions. Examples of effective geological survey organizations can be found in South Australia (Australia), Saskatchewan (Canada), and Finland.

Consultants offer managerial and technical advice and expertise to exploration companies. Some consultants collaborate with pure and applied academic researchers commonly focused on developing innovative methods for uranium exploration.

Specialist contractors provide exploration services to exploration companies including the collection and interpretation of remote sensing, geological, geochemical, geophysical, drilling survey data, and resource modelling.

Exploration programme managers assess prospectivity and explorability, investment worth, design exploration programmes and budgets, implement and manage programmes, and promote collaboration between the participants in the uranium exploration project in support of more efficient and effective exploration programmes.

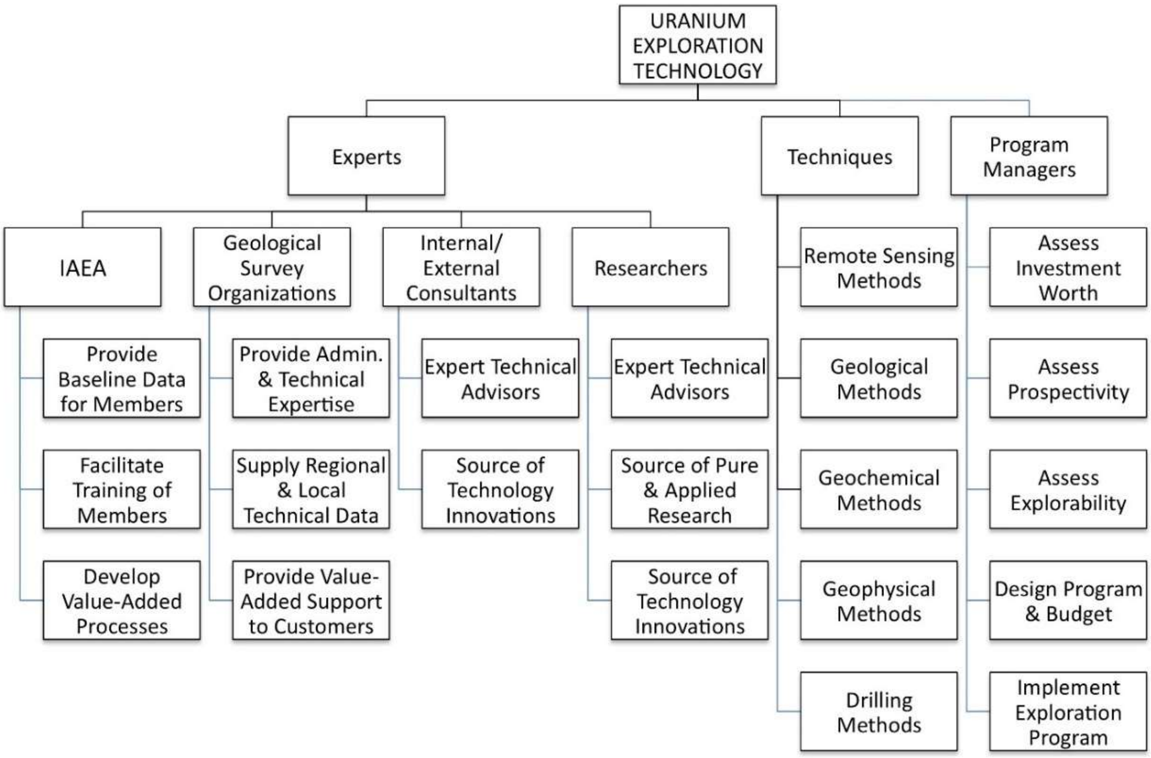

FIG. 2.25. The uranium exploration management system (reproduced from IAEA Ref. [2.2]).

REFERENCES TO CHAPTER 2

[2.1] INTERNATIONAL ATOMIC ENERGY AGENCY, The Nuclear Fuel Cycle, Information Booklet, IAEA, Vienna (2011).

[2.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Unconformity-related Uranium Deposits, IAEA-TECDOC-1857, IAEA, Vienna (2018).

[2.3] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2022: Resources, Production and Demand, OECD, Paris (2023).

[2.4] WORLD NUCLEAR ASSOCIATION, The Nuclear Fuel Report, Global Scenarios for Demand and Supply Availability 2023–2040, WNA, London (2023).

[2.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development, IAEA Nuclear Energy Series No. NF-T-1.1, IAEA, Vienna (2009).

[2.6] INTERNATIONAL ATOMIC ENERGY AGENCY, “Parameters to be considered when assessing a uranium ore resource”, IAEA-TECDOC-1174, IAEA, Vienna (2000) Ch. 4.

[2.7] DAHLKAMP, F.J., Uranium Deposit Models, Springer-Verlag, Berlin (1993).

[2.8] INTERNATIONAL ATOMIC ENERGY AGENCY, World distribution of uranium deposits (UDEPO) with Uranium Deposit Classification, IAEA-TECDOC-1629, IAEA, Vienna (2009).

[2.9] CARTER, N., A Market in Transition, IAEA International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle, IAEA, Vienna (2014).

[2.10] BOYTSOV, A., Worldwide ISL Uranium Mining Outlook, IAEA URAM 2014, IAEA, Vienna (2014).

[2.11] FRASER INSTITUTE, Annual Survey of Mining Companies 2021, Fraser Institute, Toronto (2021).

[2.12] TRANSPARENCY INTERNATIONAL, Corruptions Perceptions Index 2021, Transparency International (2021).

[2.13] SMITH, A.Y., TAUCHID, M., "Uranium exploration planning and practice", Uranium Exploration Planning and Practice, IAEA-TECDOC-583, IAEA, Vienna (1991) 15–29.

[2.14] CANADIAN INSTITUTE OF MINING METALLURGY AND PETROLEUM, Survey of Principal Mining Risks, CIMM, Toronto (2000).

[2.15] INTERNATIONAL ATOMIC ENERGY AGENCY, World Distribution of Uranium Deposits, IAEA-TECDOC-1842, IAEA, Vienna (2023).

[2.16] MCKAY, A.D., MIEZITIS, Y., Australia's Uranium Resources, Geology and Development of Deposits, Mineral Resource Report 1, AGSO - Geoscience Australia (2001).

[2.17] STEVENS, G.A., BURLEY, J., 3000 raw ideas = 1 commercial success, Research Technology Management **40** 3 (1997), 16–27, https://doi.org/10.1080/08956308.1997.11671126

[2.18] MARLATT, J., KYSER, T.K., Paradigmatic shifts in the uranium exploration process: knowledge brokers and the Athabasca basin learning curve, Society for Economic Geologists Newsletter, **84** (2011) 1–23, https://doi.org/10.5382/SEGnews.2011-84.fea

[2.19] THE PRS GROUP INC., International Country Risk Guide, XXI, 9, The PRS Group Inc. (2001).

[2.20] CENTER FOR STRATEGIC AND INTERNATIONAL STUDIES, High Country Risk Definition, CSIS (2012).

[2.21] WATTS, P., HOLME, R., Corporate Social Responsibility: Meeting Changing Expectations, World Business Council for Sustainable Development (2002).

[2.22] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantitative and Spatial Evaluations of Undiscovered Uranium Resources, IAEA-TECDOC-1861, IAEA, Vienna (2018).

[2.23] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Airborne and Ground Geophysical Methods of Uranium Exploration, IAEA Nuclear Energy Series No. NF-T-1.5, IAEA, Vienna (2013).

[2.24] KYSER, T. K., “Exploration for uranium”, Uranium for Nuclear Power, (HORE-LACEY, I., Ed.), Woodhead, Swanston (2016) 488.

[2.25] IAEA UPC Network, https://nucleus.iaea.org/sites/connect/UPCpublic/SitePages/Home.aspx

Chapter 3. URANIUM DEPOSIT TYPES

According to the publication *Uranium Resources Production and Demand*, a uranium deposit is defined as a mass of naturally occurring mineral [3.1]. Some of the information provided in this chapter was previously published by the IAEA in, *World Distribution of Uranium Deposits (UDEPO)* [3.2], *Descriptive Uranium Deposit and Mineral System Models* [3.3] and *Geological Classification of Uranium Deposits and Description of Selected Examples* [3.4].

Uranium deposit models support and often drive exploration decisions through all phases of the exploration process (refer to Chapter 5 for further details on the exploration process). For example, deposit models are often the starting point for desktop reviews and choosing the appropriate targets for further exploration and assessing the probability of a discovered deposit of a particular model type to be economic. However, one should always keep in mind that deposit models are general guides and are generic in nature, most uranium deposits have unique features that will not be reflected by the deposit model.

3.1 IAEA URANIUM DEPOSIT CLASSIFICATION SCHEME

Within the 15 deposit types defined, 36 subtypes and 14 classes have been retained (Fig. 3.1, Table 3.1). In contrast to the ordering in previous IAEA classifications, the economic parameter has not been taken into account. Instead, they are listed in a geologically meaningful order from deep, primary magmatic deposits to sedimentary and surficial deposits (Fig. 3.1). Most subtypes and classes are those defined by Dahlkamp [3.5] with minor modifications and additions. For each type, subtype and class, typical deposit examples are listed (Table 3.1).

The geological classification is also presented in [3.3] with a description of selected representative deposits of each subtype and class and mineral system models for each deposit type.

3.2 DESCRIPTION OF IAEA DEPOSIT TYPES AND SUBTYPES

3.2.1 Type 1: Intrusive-related

Deposits included in this category are hosted by intrusive rocks of many different petrological compositions including granite, pegmatite, monzonite, peralkaline syenite and carbonatite (Fig. 3.2).

Deposits of this type are broadly divided into two subtypes. Subtype 1.1, anatectic (pegmatite-alaskite) ores whose genesis is linked to partial melting processes in high-temperature, low-pressure metamorphic environments [3.4]. Examples include Rössing and Rössing South, Namibia, and deposits in the Bancroft area, Canada. The second subtype 1.2, are plutonic ores that represent products of primary magmatic differentiation processes. The plutonic subtype is further subdivided into three classes, namely 1.2.1, quartz monzonite; 1.2.2, peralkaline complex and 1.2.3, carbonatite deposits [3.4]. Some examples of this subtype include Bingham Canyon and Twin Buttes (USA), the Kvanefjeld deposit (Greenland) and the Palabora carbonatite complex (South Africa). They normally fall into the category of unconventional uranium resources, characterised by very low uranium concentrations (i.e., average: 0.07% U) that may be extractable as by-products only.

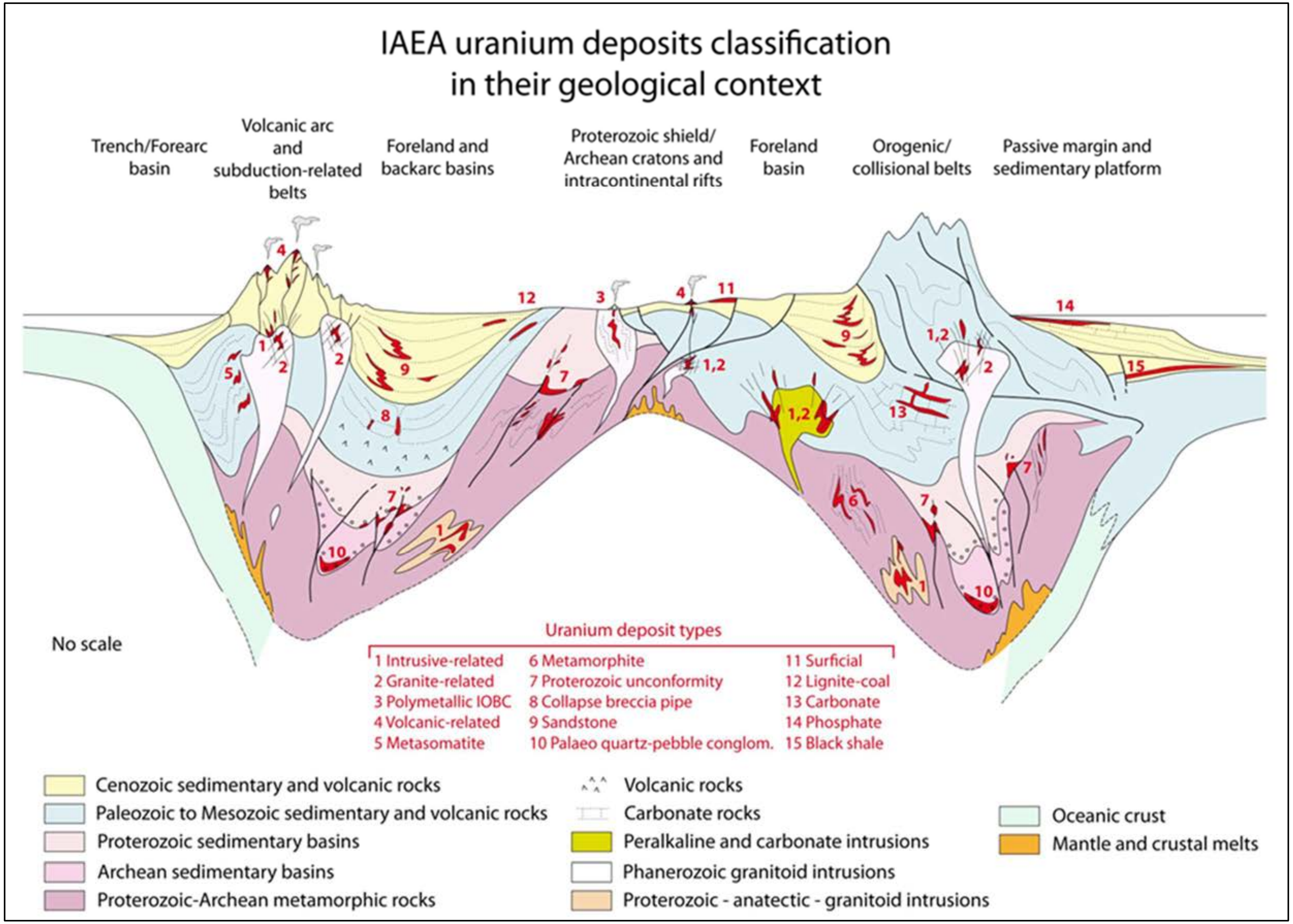

FIG. 3.1. IAEA uranium deposits classification in their geological context.

TABLE 3.1. IAEA URANIUM DEPOSIT CLASSIFICATION SCHEME [REPRODUCED FROM 3.3]

Deposit type	Deposit subtype	Deposit class	Examples
Intrusive	Anatectic (pegmatite-alaskite)		Rössing, Namibia; Bancroft district, Canada
	Plutonic	Quartz monzonite	Bingham Canyon, USA; Chuquicamata, Chile
		Peralkaline complex	Kvanefjeld, Greenland; Poços de Caldas, Brazil
		Carbonatite	Phalabora, South Africa; Catalão, Brazil
Granite-related	Endogranitic		La Crouzille district, France; Xiazhuang China
	Perigranitic		Přibram district, Czech Republic; Niederschlema, Germany
Polymetallic iron oxide breccia complex			Olympic Dam, Carrapateena, Australia
Volcanic-releated	Stratabound		Dornod (No. 7 ore zone), Mongolia; Maureen, Australia
	Structure-bound		Streltsov-Antei, Russian Federation; Kurišková, Slovakia
	Volcano-sedimentary		Anderson Mine, USA; Sierra Pintada district, Argentina
Metasomatite	Sodium (Na)-metasomatite	Granite derived	Kirovograd district, Ukraine; Lagoa Real, Brazil
		Metasediment-metavolcanic derived	Krivoy Rog district, Ukraine
	Potassium (K)-metasomatite		Elkon district, Russian Federation
	Skam		Mary Kathleen, Australia; Tranomaro, Madagascar
	Stratabound		Forstau, Austria; Nuottijarvi, Finland
Metamorphite	Structure-bound	Monometallic veins	Schwartzwalder, USA; Acefay-Verna, Canada
		Polymetallic veins	Shinkolobwe, Democratic Republic of Congo
		Marble-hosted phosphate	Itataia, Brazil; Zaozernoye, Kazhakstan

TABLE 3.1. (cont.) IAEA URANIUM DEPOSIT CLASSIFICATION SCHEME (REPRODUCED FROM [3.3])

Deposit type	Deposit subtype	Deposit class	Examples
Proterozoic unconformity	Unconformity-contact		Cigar Lake, Key Lake, McArthur River, Canada
	Basement-hosted		Jabiluka, Ranger, Australia; Eagle Point, Canada
	Stratiform fracture-controlled		Lambapur, Chitrial, India
Collapse breccia pipe			Arizona Strip, USA
Sandstone	Basal channel		Dalmatovskoye, Russian Federation; Beverly, Australia
	Tabular	Continental fluvial, uranium associated with intrinsic reductant	Arlit district, Niger
		Continental fluvial, uranium associated with extrinsic bitumen	Ambrosia Lake district (Grants region), USA
		Continental fluvial vanadium-uranium	Salt Wash member, USA
	Roll-font	Continental basin, uranium associated with intrinsic reductant	Wyoming basins, USA
		Continental to marginal marine, uranium associated with intrinsic redcutant	Chu-Sarysu basin, Kazakhstan
		Marginal marine, uranium associated with extrinsic reductant	South Texas, USA
	Tectonic-lithologic		Lodève Basin, France; Franceville Basin, Gabon,
	Mafic dykes/sills in sandstone		Westmoreland district, Australia; Matoush, Canada
Paleo quartz pebble conglomerate	Uranium dominant		Elliot Lake district, Canada
	Gold-dominant		Witwatersrand Basin, South Africa
Superficial	Peat bog		Kamushanovskoye, Kyrgyzstan; Flodelle Creek, USA
	Fluvial valley		Yeelirrie, Australia; Langer Heinrich, Namibia
	Lacustrine-playa		Lake Maitland, Lake Way, Australia
	Pedogenic and fracture fill		Beslet, Bulgaria
	Placer		Kyzyl Ompul, Kyrgyztan; Red River Valley, USA

TABLE 3.1. (cont.) IAEA URANIUM DEPOSIT CLASSIFICATION SCHEME (REPRODUCED FROM [3.3])

Deposit type	Deposit subtype	Deposit class	Examples
Lignite-coal	Stratriform		Koldzhat, Kazakhstan; Williston Basin, USA
	Fracture-controlled		Freital, Germany; Turakavak, Kyrgyzstan
Carbonate	Stratabound		Tumalappalle, India
	Cataclastic		Mailuu-Suu, Kyrgyzstan; Todilto district, USA
	Palaeokarst		Sanbaqi, China; Tyuyamuyun, Kyrgyzstan
Phosphate	Organic phosporite		Mangyshlak Peninsula, Kazakhstan; Ergeninsky region, Russian Federation
	Minerochemical phosphorite		Phosphoria Formation, USA
	Continental phosphate		Bakouma district, Central African Republic
Black shale	Stratiform		Randstad, Sweden; Chattanooga Shale Fromation, USA
	Stockwork		Ronneburg district, Germany; Dzhantuar, Uzbekistan

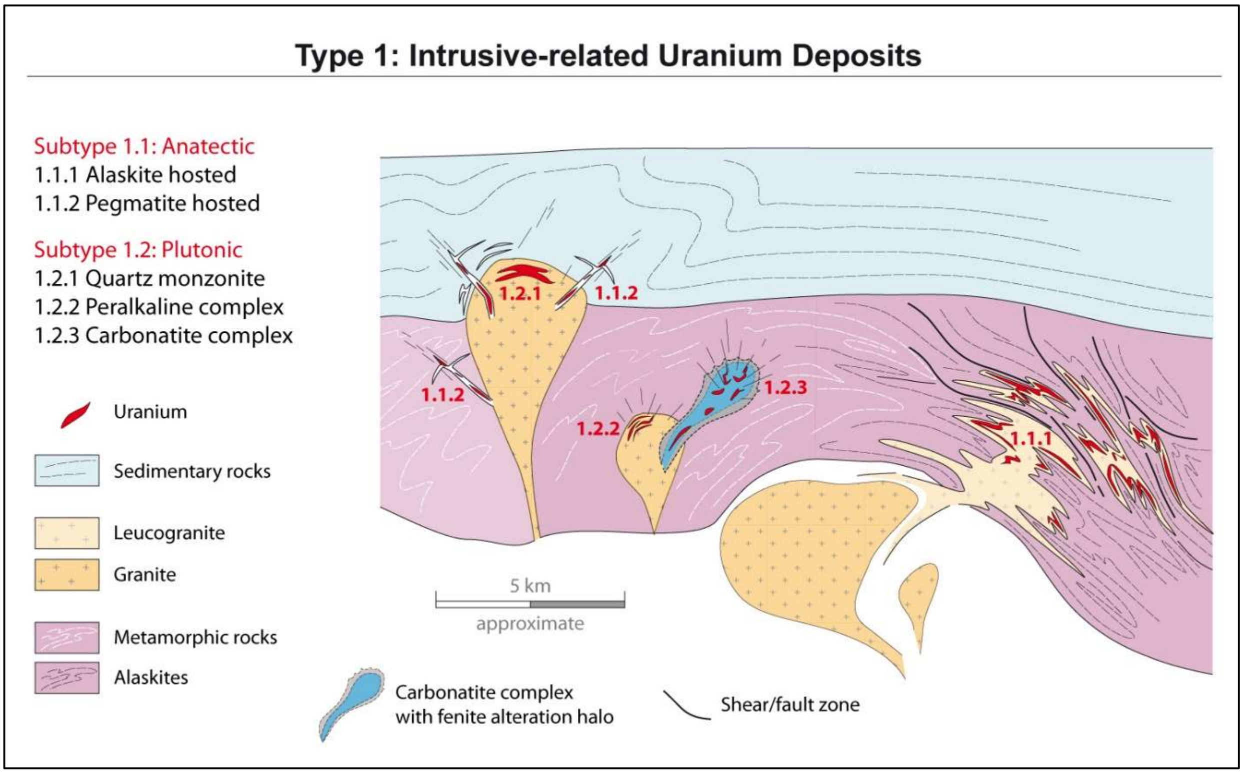

FIG. 3.2. Type 1: Intrusive-related uranium deposits.

3.2.2 Type 2: Granite-related

Granite-related deposits occur in collisional orogens but well away from the original convergent plate margins and are often spatially associated with tin-tungsten and intrusion-related gold provinces [3.4]. The uranium ores take the form of vein-, stockwork- or episyenite-hosted deposits enclosed by, at the contact with, or in the periphery of granitic intrusions, in particular highly differentiated leucogranites [3.4].

Two subtypes are distinguished based on their spatial setting with respect to the granitic pluton and country rocks, endogranitic deposits and perigranitic deposits [3.3, 3.4]. Endogranitic deposits (subtype 2.1) are mainly confined to granite and are typically monometallic (U) [3.4]. Perigranitic deposits (subtype 2.2), on the other hand, may be monometallic (uranium) or polymetallic (U ± Ag, As, Bi, Co, Ni) and are characteristically confined to the country rocks at the contact with and/or surrounding granitic intrusions [3.4]. Figure 3.3 illustrates the subtypes of granite-related uranium deposits.

In Europe's Hercynian Belt and in other parts of the world, these deposits are generally associated with large, peraluminous two mica granite complexes (leucogranites). Examples of subtype 2.1 include the La Crouzille district, France and the Xiazhuang district, China and for subtype 2.2 Příbram district, Czech Republic and Niederschlema, Germany. Total resources range from small to large and average 1280 tU but with a few deposits exceeding 10 000 tU and grades are on average 0.20% U.

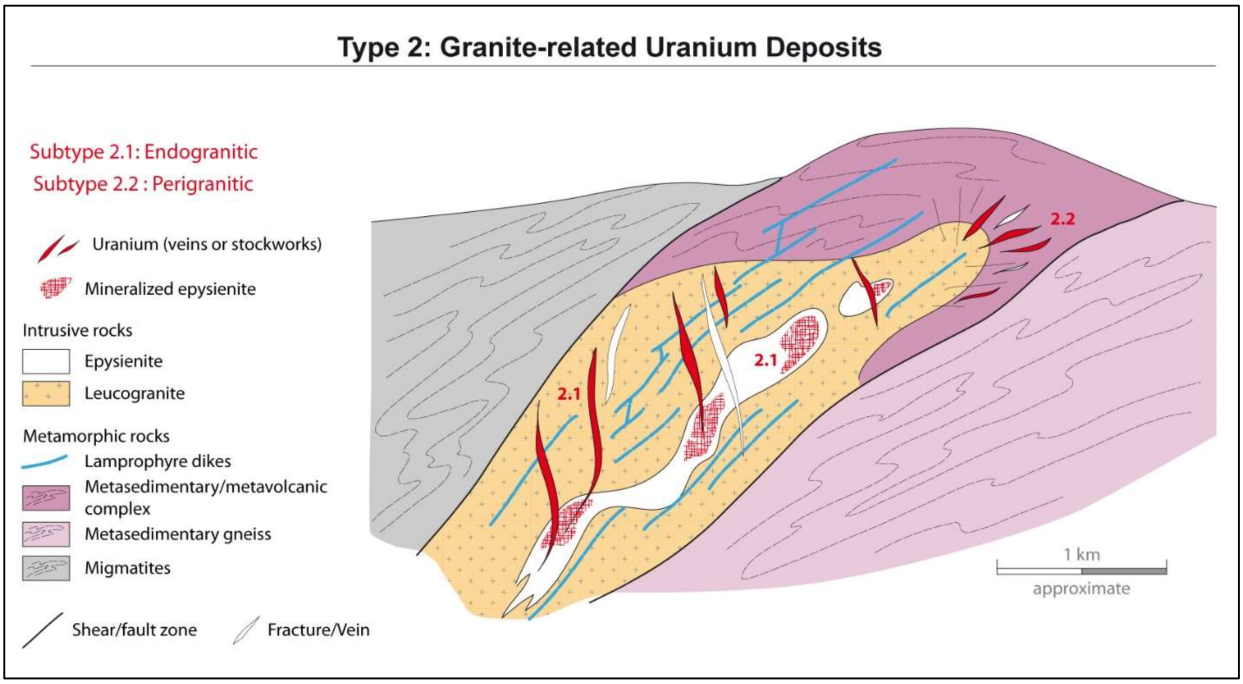

FIG. 3.3. Type 2: Granite-related uranium deposits.

3.2.3 Type 3: Polymetallic iron oxide breccia complex

Polymetallic iron oxide breccia complex deposits are represented by the giant Mesoproterozoic Olympic Dam iron oxide copper-gold-uranium deposit [3.4]. The polymetallic ores at Olympic Dam are contained entirely within a polyphase haematite-rich granite breccia, the outer boundary of which is gradational with the host granite (Fig. 3.4). The bulk of the uranium occurs in the copper ore domains, associated with potassic alteration assemblages and copper-iron sulphides [3.4]. Olympic Dam is the only known polymetallic iron oxide breccia complex deposit that contains significant uranium [3.4]. The deposit hosts the world's largest uranium resource with more than 2 000 000 tU at relatively low grades (230 parts per million (ppm) U). Deposits of this type typically occur in haematite-rich granitic breccias (examples include Olympic Dam, Gawler Craton) or in metasedimentary–metavolcanic breccias (Salobo and Sossego, Carajas District, Brazil) which contain low grade disseminated uranium in association with copper, gold, silver and rare earth elements [3.4].

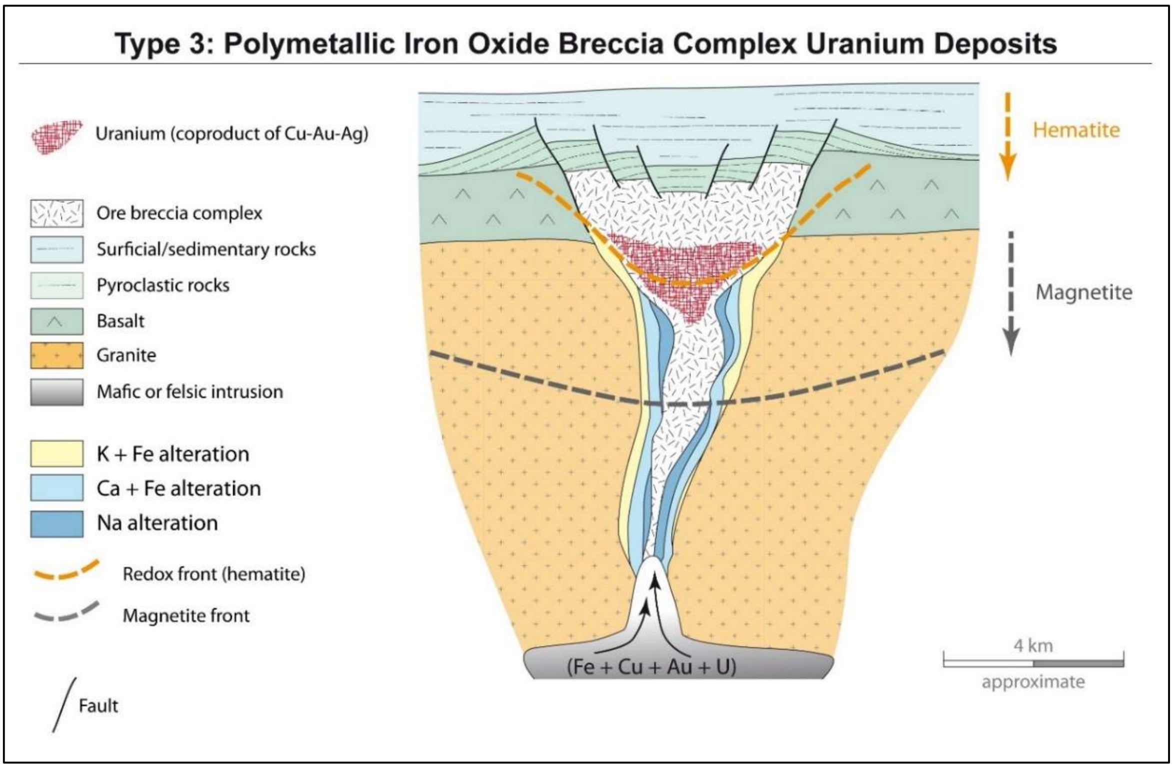

FIG. 3.4. Type 3.4: Polymetallic iron oxide breccia complex uranium deposits.

3.2.4 Type 4: Volcanic-related

Volcanic-related uranium deposits are hosted within or near volcanic calderas that are either filled with mafic to felsic lavas or, more commonly, pyroclastic rocks and intercalated clastic sediments [3.3]. Uranium mineralization is preferentially controlled by structures such as veins and stockworks (i.e., structure-bound deposits), but also appear as disseminations and impregnations in permeable flows and volcanoclastic sediments (i.e., stratabound deposits). Mineralization occurs at several stratigraphic levels within the volcanic and sedimentary units and may extend well into the underlying basement. Uranium minerals (pitchblende, coffinite, U^{6+} minerals and less commonly brannerite) are associated with molybdenum-bearing sulphides and pyrite [3.3]. Other anomalous elements associated with this type of deposit includes Ag, As, Bi, Li, Pb, Sb, Sn and W.

Three subtypes can be distinguished: stratabound, structure-bound, and volcano-sedimentary deposits (Fig. 3.5). Stratabound deposits (subtype 4.1) consist of uranium disseminations and impregnations in permeable and/or chemically reactive lava flows, flow breccias, tuffs and intercalated pyroclastic and clastic sedimentary units; structure bound deposits (subtype 4.2) are the most common and comprise structurally-controlled veins and stockworks hosted by volcanic, subvolcanic and pyroclastic rocks; and volcano-sedimentary deposits (subtype 4.3) are low-grade, peneconcordant uranium ores in carbonaceous, fluvio-lacustrine sediments deposited in an exocaldera environment [3.4]. The most significant deposits are located within the Streltsovska caldera in the Russian Federation. Other examples are known in China (Xiangshan district), Mexico (Peña Blanca district), Mongolia (Dornod and Gurvanbulag districts), Peru (Macusani district) and the USA (McDermitt caldera). Uncommon volcano-sedimentary deposits consist of peneconcordant, low grade carbonaceous lacustrine sediments with a tuffaceous component (Anderson Mine, USA). Typically, these deposits occur as low grade (average: 0.12% U) deposits of less than 1500 tU and but there are several that are greater than 10 000 tU. The largest known district in the world is the Priargunsky Mining Centre in the Russian Federation which consists of production from a few volcanic deposits with combined recoverable uranium resources of about 73 000 tU [3.1].

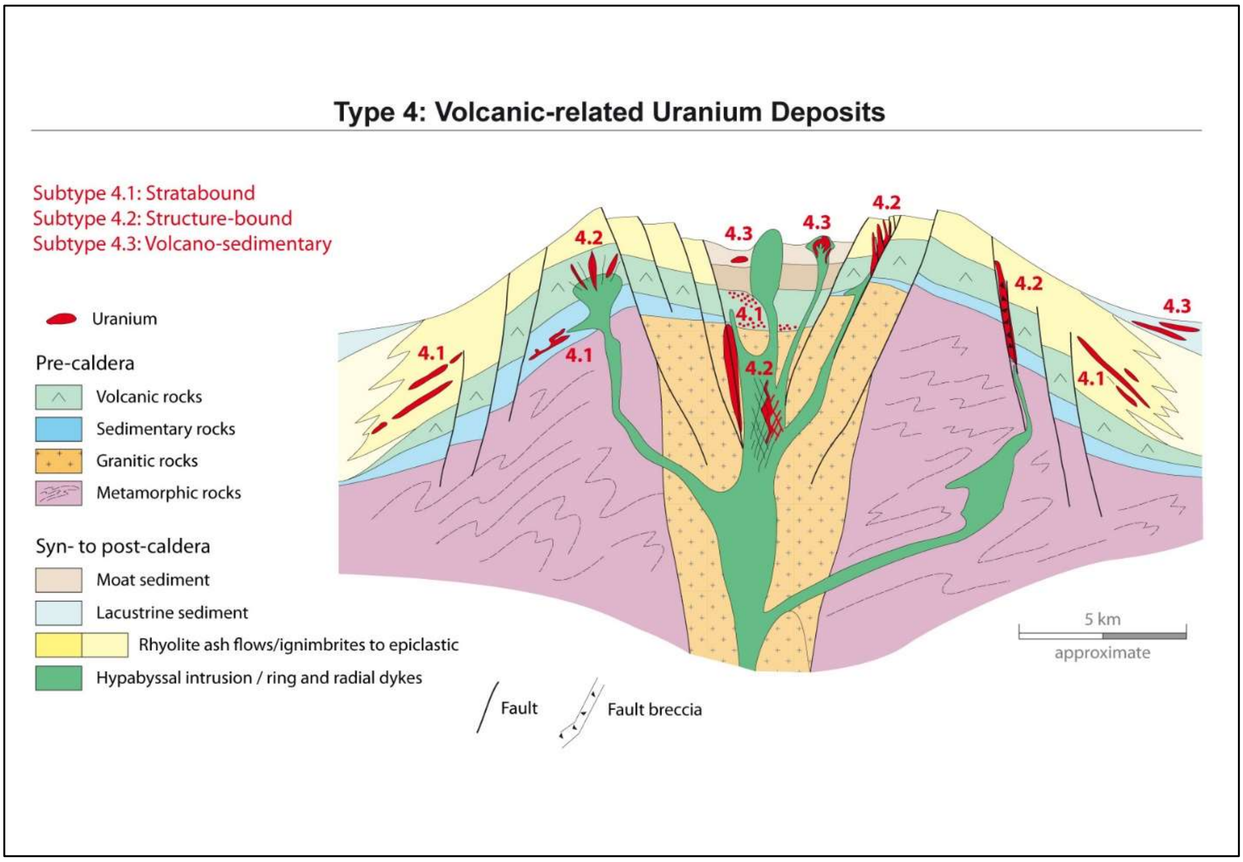

FIG. 3.5. Type 4: Volcanic-related uranium deposits.

3.2.5 Type 5: Metasomatite

Deposits of this type are usually confined to Precambrian Shields (a notable exception is the Coles Hill deposit in the USA) in orogenic belts affected by intense Na-metasomatism or K-metasomatism which produced illitized or albitized rocks along deeply rooted fault systems [3.4]. In the Ukraine, these deposits are hosted within granite, migmatite, gneiss and ferruginous quartzite, which were subsequently altered into albitite, aegirinite, alkali amphibolite, as well as carbonate and ferruginous rocks [3.4]. Three subtypes can be distinguished based on their protoliths and type of metasomatism: subtype 5.1 sodium (Na)-metasomatite, subtype 5.2 potassium (K)-metasomatite, and subtype 5.3 skarn [3.4] (Fig. 3.6). The principal uranium phases are uraninite, brannerite and other Ti–U-bearing minerals, pitchblende, coffinite and hexavalent uranium minerals. Examples include the Valhalla (Australia), Espinharas and Lagoa Real (Brazil), Michelin (Canada), Lianshanguan (China), Kurupung (Guyana), deposits of the Elkon district (Russian Federation), Michurinskoye, Vatutinskoye, Severinskoye, Zheltorechenskoye, Novokonstantinovskoye deposits (Ukraine), Coles Hill (USA), and several small deposits in the Arjeplog region of northern Sweden.

The uranium resources for this type of deposit have an average grade of 0.12%U and are small to medium sized deposits from 1000 to 25 000 tU, but there some larger deposits, i.e. larger than 50 000 tU, including some of the examples listed above.

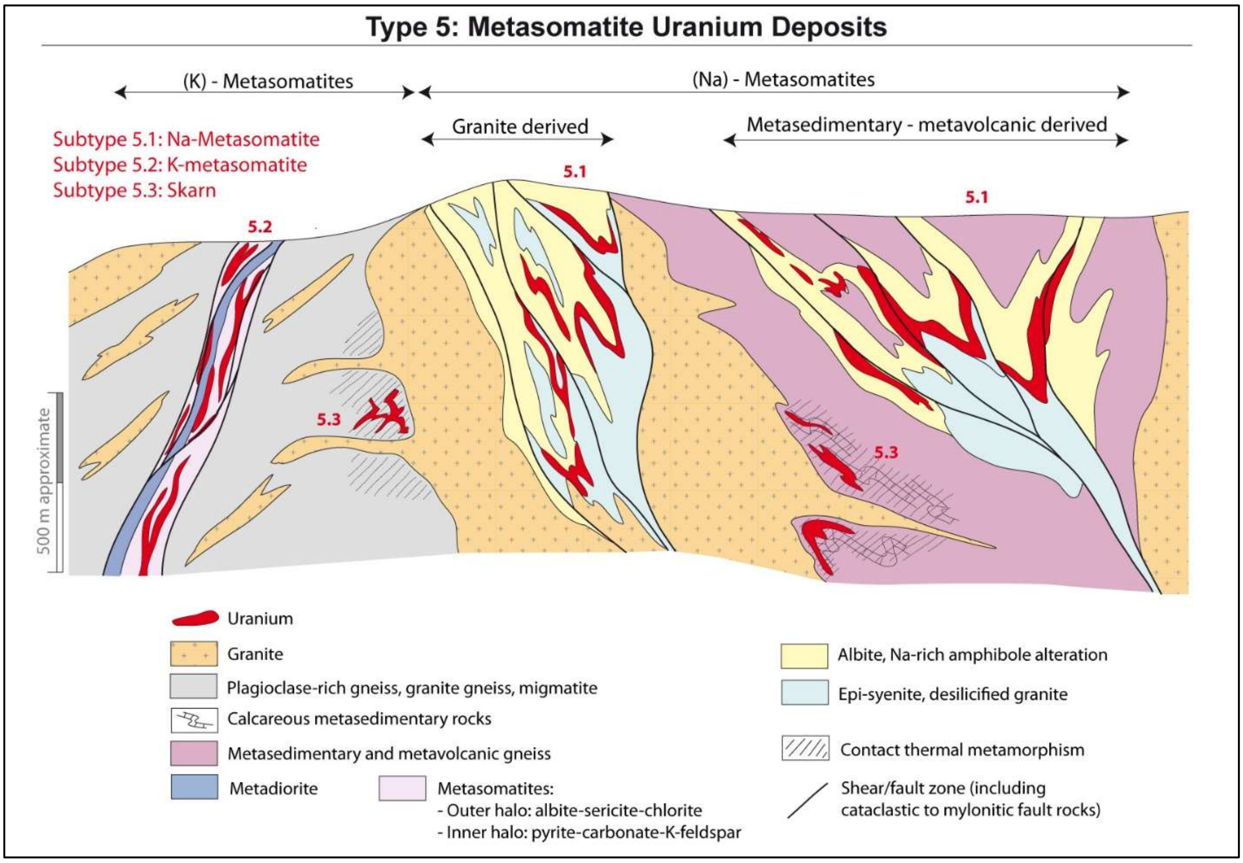

FIG. 3.6. Type 5: Metasomatite uranium deposits.

3.2.6 Type 6: Metamorphite

These deposits are hosted by metamorphosed supracrustal rocks associated with collisional orogens of Precambrian to Cenozoic age [3.4]. Two subtypes are recognized: stratabound (subtype 6.1) and comprise irregularly distributed uranium impregnations and disseminations that are conformable to bedding and structure-bound deposits (subtype 6.2) are structurally controlled vein- and mylonite-hosted uranium ores precipitated from externally derived metamorphic fluids [3.4]. The formation of stratabound type ores, on the other hand, is thought to be linked to chemical and physical changes of a uranium enriched sedimentary protolith during regional metamorphism which results in the redistribution and recrystallisation of primary synsedimentary uranium phases [3.4]. Some examples of stratabound deposits, which are uncommon include Forstau, Austria; Nuottijarvi and Lampinsaari, Finland. Structure-bound deposits which are well represented include Ace–Fay–Verna and Port Radium, Canada; Shinkolobwe, Democratic Republic of the Congo; Jaduguda, India; Kamyshevoye, Kazakhstan; Schwartzwalder, USA. Within the subtypes there are three classes: monometallic veins; polymetallic veins and marble-hosted phosphate (Fig. 3.7) These deposits are highly variable in terms of size, uranium resources and grade.

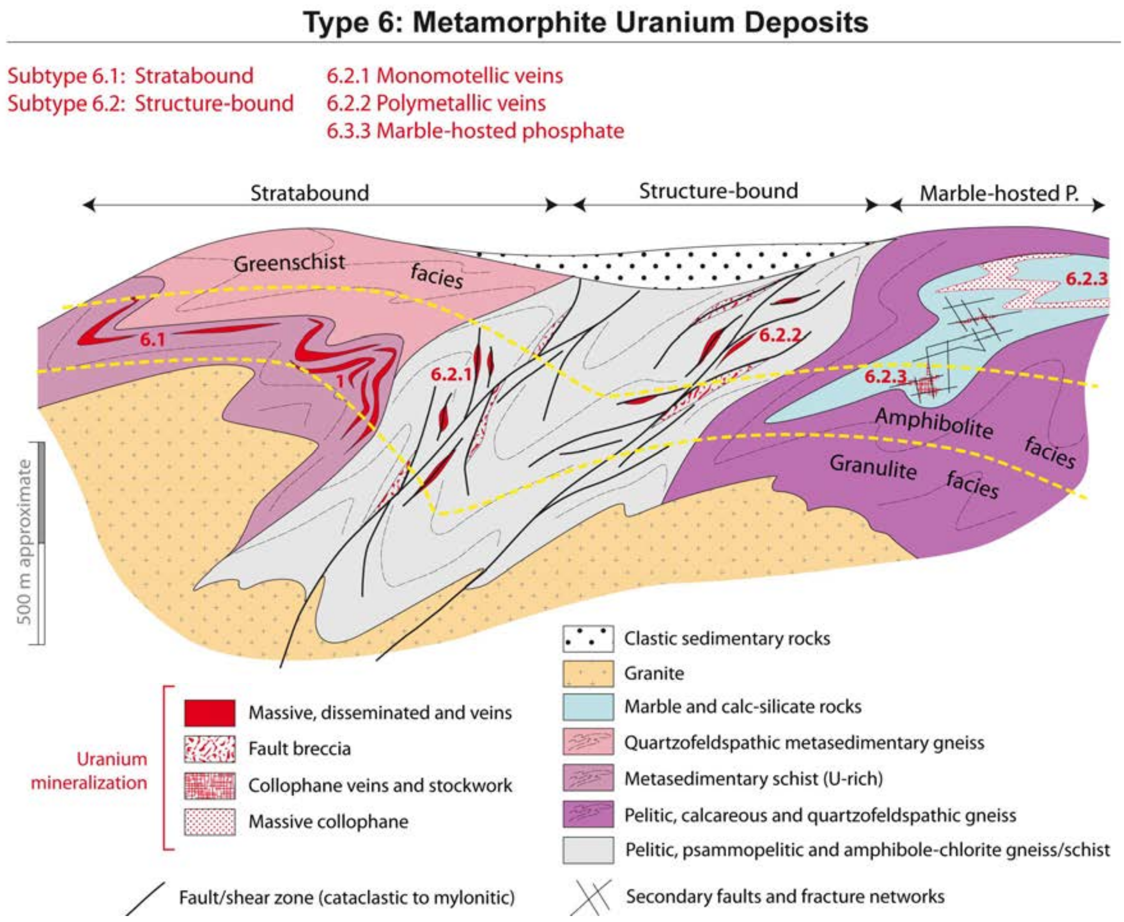

FIG. 3.7. Type 6: Metamorphite uranium deposits.

3.2.7 Type 7: Proterozoic unconformity

Unconformity deposits are associated with, and occur immediately below, above or spanning, an unconformable contact that separates Archean–Palaeoproterozoic crystalline basement from overlying, red bed clastic sediments of Proterozoic age [3.4]. The basement rocks immediately beneath the unconformity near these deposits are usually strongly haematized and exhibit clay alteration, possibly as a result of palaeoweathering and/or diagenetic or hydrothermal alteration [3.7]. Deposits consist of pods, veins and semi-massive replacements comprising mainly pitchblende. Strong quartz dissolution is generally associated with these deposits. They occur in two major districts: the Athabasca Basin (Canada) and the Pine Creek Orogen (Australia). The Proterozoic unconformity deposits include three subtypes (Fig. 3.8) of variable importance: (subtype 7.1) unconformity-contact deposits, which all occur in the Athabasca Basin (Canada), (subtype 7.2) basement-hosted deposits (examples: Millennium and Eagle Point in the Athabasca Basin, Kintyre, Jabiluka and Ranger, Australia; and Kiggavik and Andrew Lake in the Thelon Basin (Canada) and (subtype 7.3) stratiform structure-controlled deposits (examples: Chitrial and

Lambapur, Cuddapah Basin, India). The grades of these deposits can exceed 20% U and based on the currently known deposits have an average grade of 1.5% U and size of 15 500 tU.

The IAEA has published a comprehensive technical document, *Unconformity-related Uranium Deposits* [3.7] which contains additional descriptions and practical information on how to explore for these types of deposits.

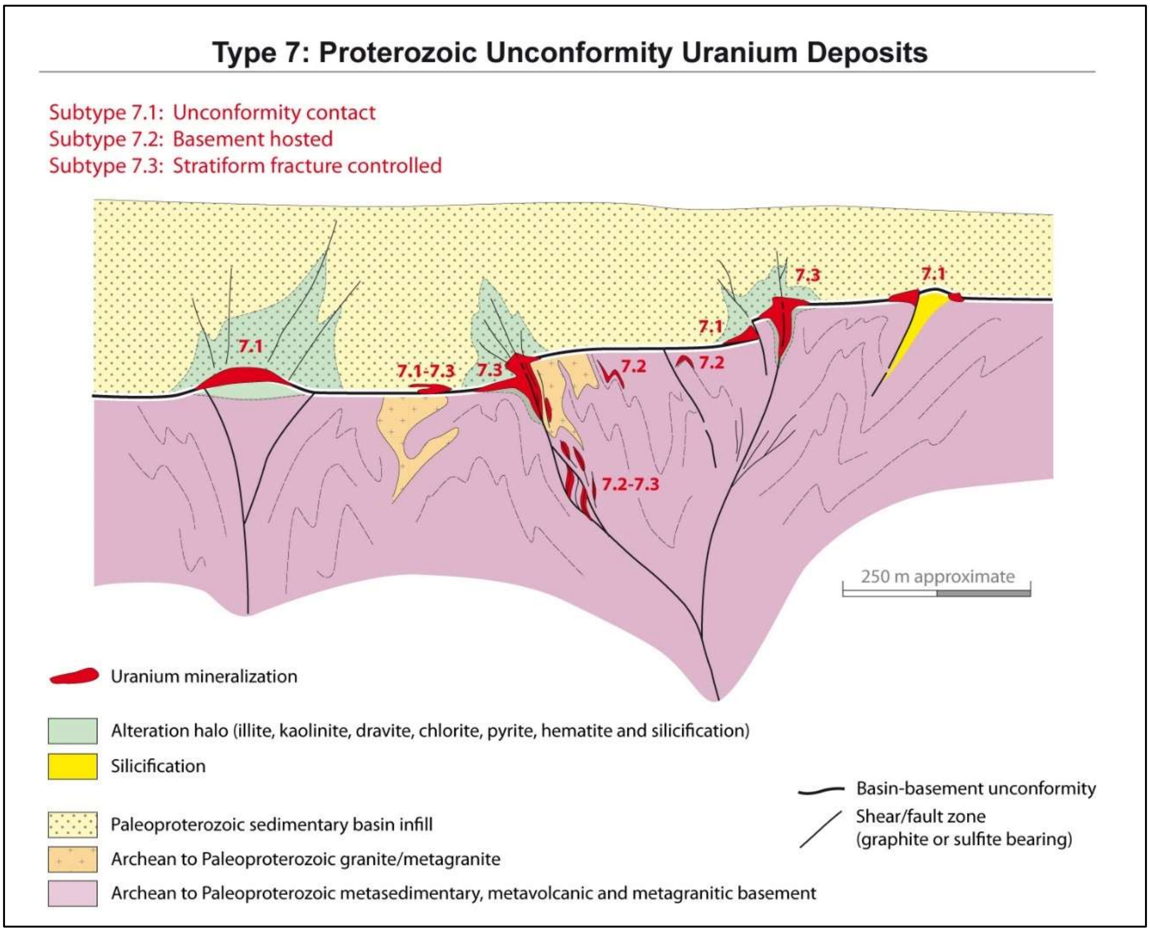

FIG. 3.8. Type 7: Proterozoic unconformity uranium deposits.

3.2.8 Type 8: Collapse breccia pipe

Deposits in this group occur in sedimentary basins within cylindrical, vertical pipe shaped dissolution cavities (karst) developed in underlying carbonate strata which have subsequently been filled with collapsed fragments from overlying lithological units. The uranium is concentrated as primary uranium minerals in the tetravalent state, mainly as pitchblende within a permeable breccia matrix and in the arcuate ring-fracture zone surrounding the pipe [3.4] (Fig. 3.9). The pitchblende is generally associated with numerous sulphide and oxide minerals containing Ag, As, Co, Cu, Fe, Pb, Mo, Ni, Se, V and Zn [3.4]. Uranium mineralization is understood to be linked to upward directed artesian flow of basinal brines through the permeable breccia column and mixing of these brines with uranium-bearing, oxidizing waters that flowed laterally through oxidized sandstone aquifers [3.4]. Typical examples are the deposits of the Arizona Strip, north of the Grand Canyon, and those immediately south of the Grand Canyon in the USA [3.4].

Uranium resources are small to medium (300–2500 tU) with moderate to relatively high grades of about 0.20–0.80% U.

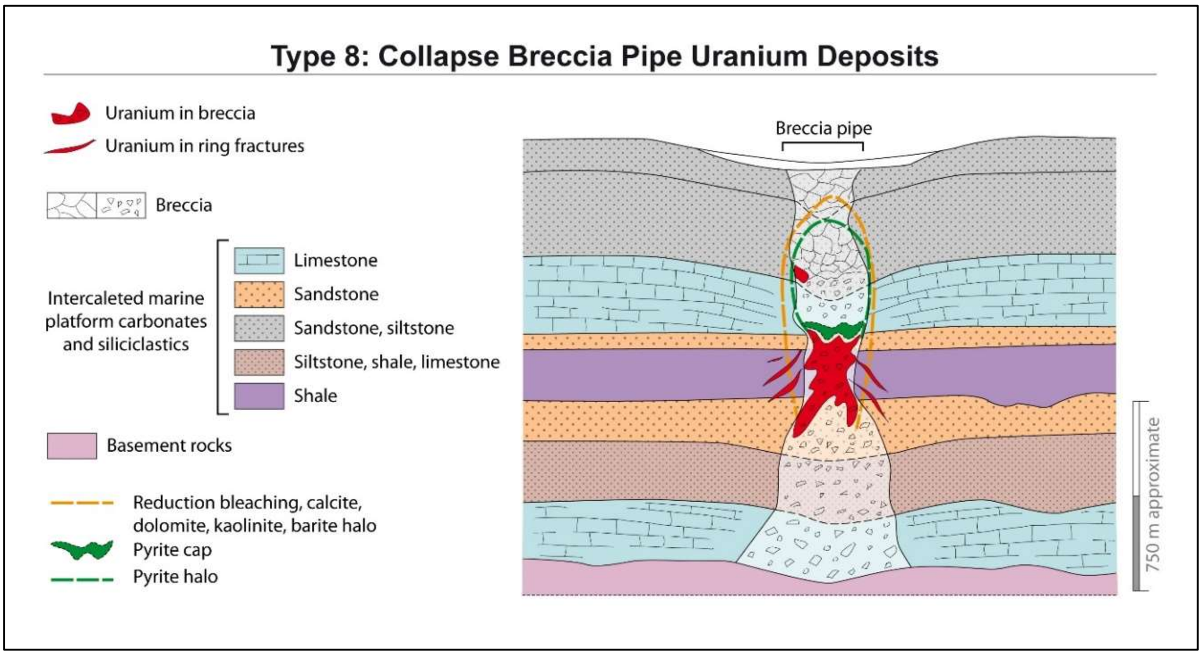

FIG. 3.9. Type 8: Collapse breccia pipe uranium deposits.

3.2.9 Type 9: Sandstone

Sandstone hosted uranium deposits are hosted by medium- to coarse-grained sandstones deposited in continental fluvial or marginal marine sedimentary environments [3.4]. Volcanic ash occurring within the sandstone may represent the principal source of the uranium (Lodève, France; Akouta and Arlit, Niger; Wyoming, USA). Uranium is precipitated by reduction processes caused by the presence of a variety of reducing agents within the sandstone which may include carbonaceous material (mainly detrital plant debris), sulphides (pyrite), ferro-magnesian minerals (chlorite), bacterial activity, migrated fluids from underlying hydrocarbon reservoirs and others [3.3, 3.4]. Sandstone hosted uranium deposits can be divided into five main subtypes, with transitional types also occurring. Sandstone deposits are divided into five subtypes (Fig. 3.10) with many gradual transitions between them: (subtype 9.1) Basal channel, (subtype 9.2) tabular, (subtype 9.3) roll-front, (subtype 9.4) tectonic-lithologic, and (subtype 9.5) mafic dyke/sills in Proterozoic sandstones [3.3, 3.4]. Deposit sizes vary from small to large and on average are 3500 tU with an average grade of 0.15% U.

Major deposits of this type occur in Kazakhstan and Uzbekistan and since 2009 production from these types of deposits account for the highest percentage of world total uranium production [3.1, 3.8]. The IAEA is currently working on a technical document entitled, *Sandstone Uranium Deposits* which will contain information about exploration and mining for these types of deposits.

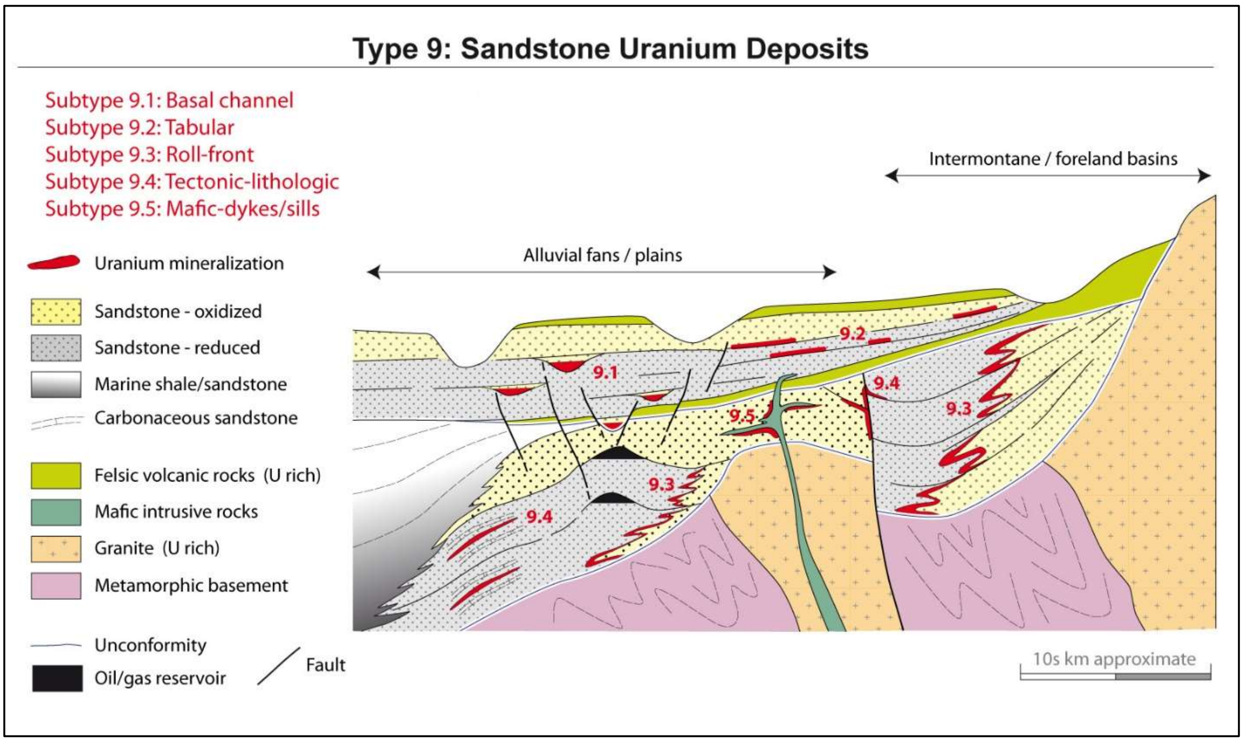

FIG. 3.10. Type 9: Sandstone uranium deposits.

3.2.10 Type 10: Paleao quartz pebble conglomerate

The hosts of this detrital uranium deposit type are Palaeo quartz-pebble conglomerates of Archaean to early Palaeoproterozoic age that were deposited at the base of and within fluviatile braided river and shallow marine transgressive sedimentary complexes that formed in intracratonic or foreland basins [3.3, 3.4]. The genesis of palaeo quartz-pebble conglomerate deposits is one of the most controversial topics in economic geology, with the current debate focused on modified placer versus hydrothermal origins [3.4]. Two subtypes are distinguished (Fig. 3.11): (subtype 10.1) uranium dominant, for example the Elliot Lake district, Canada and (subtype 10.2) gold dominant deposits, an example of which is the Witwatersrand Basin, South Africa. Deposits are low grade to very low grade and sizes range widely, from 100 tU to even greater than 100 000 tU in the largest known deposits. The average deposit size is 18 600 tU and the average grade is 0.03% U.

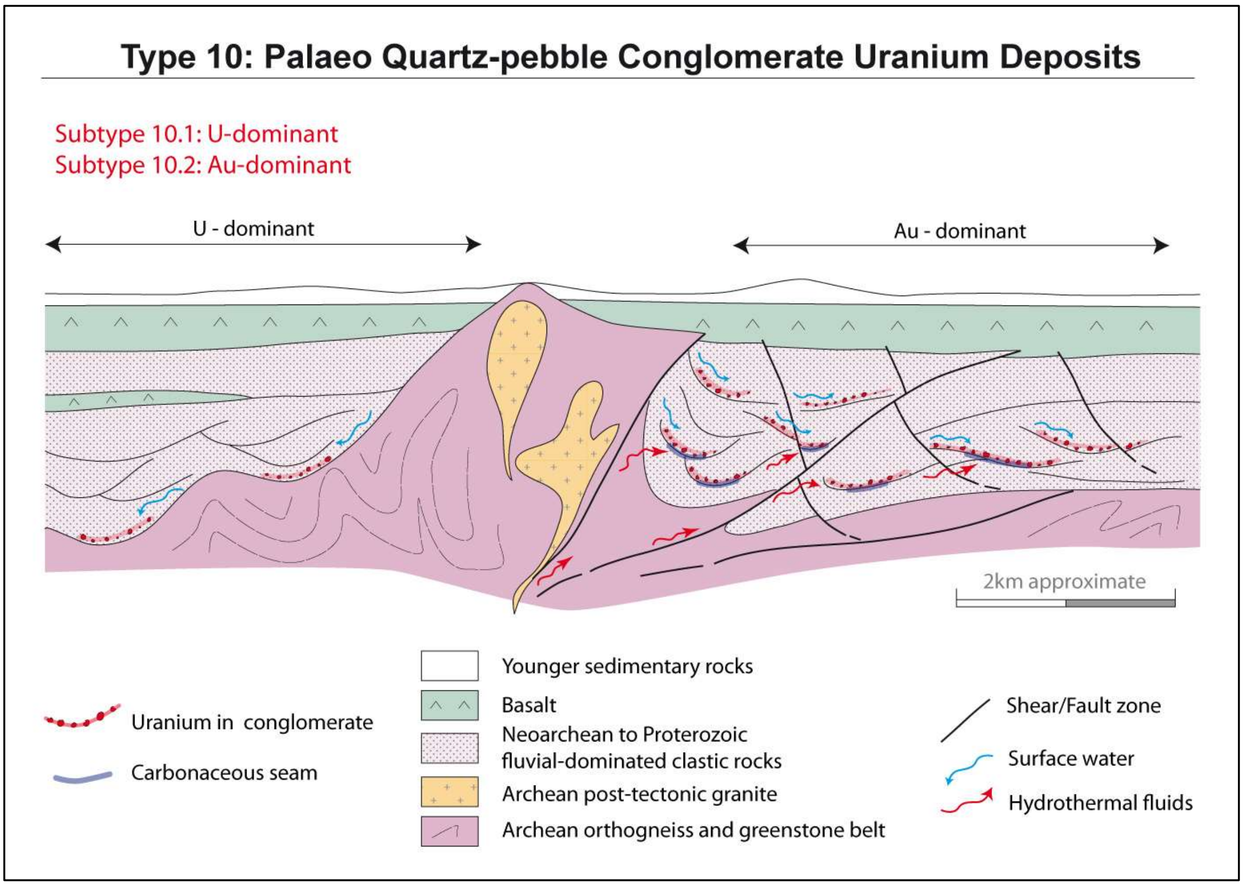

FIG. 3.11. Type 10: Paleao quartz pebble conglomerate uranium deposits.

3.2.11 Type 11: Surficial deposits

Surficial deposits include relatively young, i.e., Tertiary to recent, near-surface uranium concentrations in unconsolidated or poorly consolidated sediments or soils [3.4]. Five subtypes are recognized: (subtype 11.1) Peat bog, (subtype 11.2) fluvial valley, (subtype 11.3) lacustrine-playa, (subtype 11.4), pedogenic and fracture fill, and (subtype 11.5) placer (Fig. 3.12). Carnotite is the principal uranium mineral. There are several examples of these deposits including: subtype 11.1, Kamushanovskoye, Kyrgyzstan; Flodelle Creek, USA; subtype 11.2, Yeelirrie, Australia; Langer Heinrich, Namibia; subtype 11.3, Lake Maitland, Lake Way, Australia; subtype 11.4, Beslet, Bulgaria; subtype 11.5, Kyzyl Ompul, Kyrgyzstan and Red River Valley, USA [3.4]. Deposit sizes vary widely but the average is 1400 tU but there are few larger deposits, i.e., greater than 10 000 tU. Grades are low and average 0.04% U.

3.2.12 Type 12: Lignite-coal

Elevated uranium contents occur in lignite and coal mixed with mineral detritus (silt, clay), and in seams which lie immediately adjacent to carbonaceous mud and silt/sandstone beds. The source of uranium for these deposits was most likely uraniferous crystalline basement rocks, granitoids or pyroclastic sediments that sometimes overly or are intercalated with lignite-coal seams [3.4]. Two subtypes are recognized: subtype 12.1, stratiform and subtype 12.2, fracture-controlled (Fig. 3.13). Examples include deposits in the south-western Williston Basin (USA); Koldjat and Nizhne Iliyskoe (Kazakhstan); Freital (Germany) and Ambassador (Australia). Given the typically very low average grades (i.e., 0.07% U) and complex metallurgy, very few lignite-coal deposits have been mined for uranium and, thus, classify as unconventional uranium resources [3.4]. The size of the deposits varies but some are quite large, i.e., up to 100 000 tU.

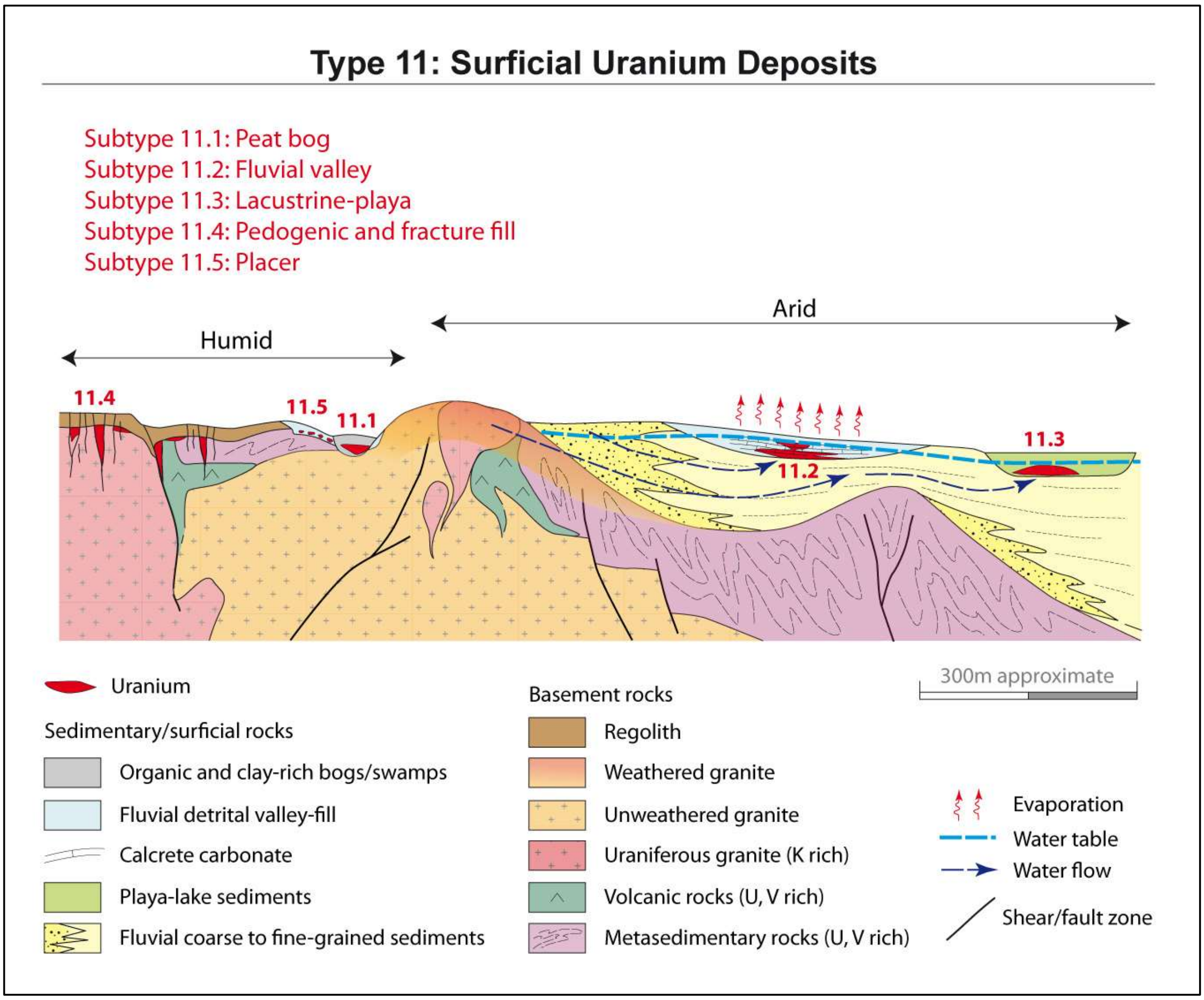

FIG. 3.12. Type 11: Surficial deposits uranium deposits.

3.2.13 Type 13: Carbonate

Carbonate deposits comprise diverse syn- and epigenetic uranium ores that have formed in a variety of geological settings. The uniting feature of these deposits is their occurrence in calcareous host rocks, which are atypical given they tend to have low permeability and lack chemical reductants [3.4].

Three subtypes (Fig. 3.14) have been described: subtype 13.1, stratabound, example, Tumalappalle, India; subtype 13.2, cataclastic, examples include Mailuu-Suu, Kyrgyzstan; Todilto district, USA; and subtype 13.3, palaeokarst, examples Sanbaqi, China; Tyuya-Muyun, Kyrgyzstan. The deposits are of variable size and grade and the average uranium grade is 0.17% U and average tonnage for these deposits is 4800 tU.

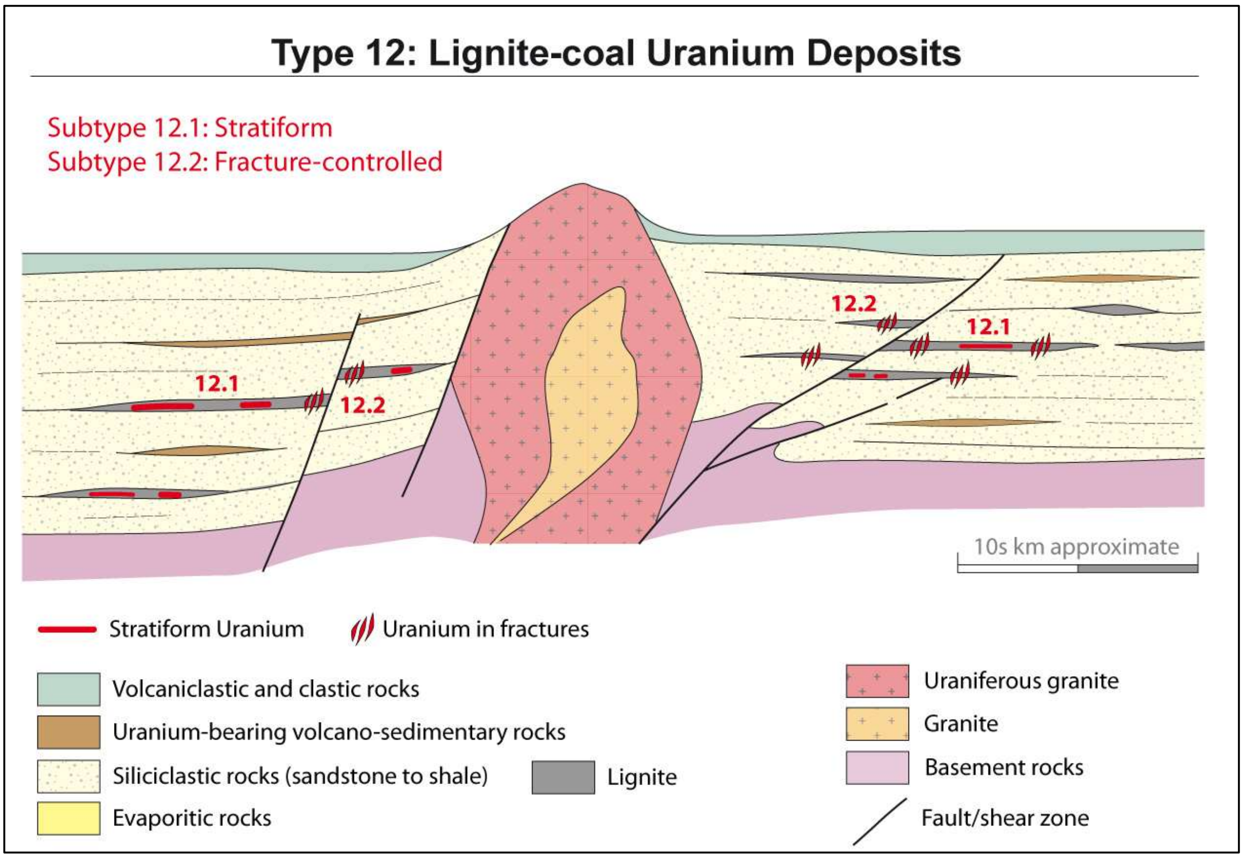

FIG. 3.13. Type 12: Lignite-coal uranium deposits.

3.2.14 Type 14: Phosphate

Phosphate deposits, the main global source of phosphorus, can host significant uranium resources up to several million tonnes, albeit at very low concentrations. The uranium mineralization occurs as synsedimentary, stratiform, disseminations of ore associated with fine-grained apatite [3.4]. Most deposits are classified as unconventional resources. An exception is the Itataia deposit in Brazil which is estimated to contain just over 67 000 tU at a grade of 0.08% U.

Three subtypes (Fig. 3.15) have been described: subtype 14.1, organic phosphorite; subtype 14.2, minerochemical phosphorite, and subtype 14.3, continental phosphate.

3.2.15 Type 15: Black shale

Black shale deposits are very low to low grade uranium deposits and contain some of the world's largest uranium accumulations. Grades are on average 0.05% U and average deposit size is about 400 000 tU. They are classified as unconventional uranium resources from which uranium may be produced as a by- or co-product [3.1, 3.4]. Two subtypes (Fig. 3.16) are recognized, stratiform (subtype 15.1) and stockwork (subtype 15.2). Stratiform type comprise marine, organic–rich shale and coaliferous, pyritic shale, containing synsedimentary, uniformly disseminated uranium adsorbed onto organic material and clay minerals typical examples include Ranstad, Sweden and the Chattanooga Shale Formation, USA [3.4]. Stockwork type consists of structurally controlled, stratabound uranium ores in microfracture stockworks developed within or adjacent to black shale horizons, examples include the Ronneburg district, Germany and Dzhantuar, Uzbekistan [3.4].

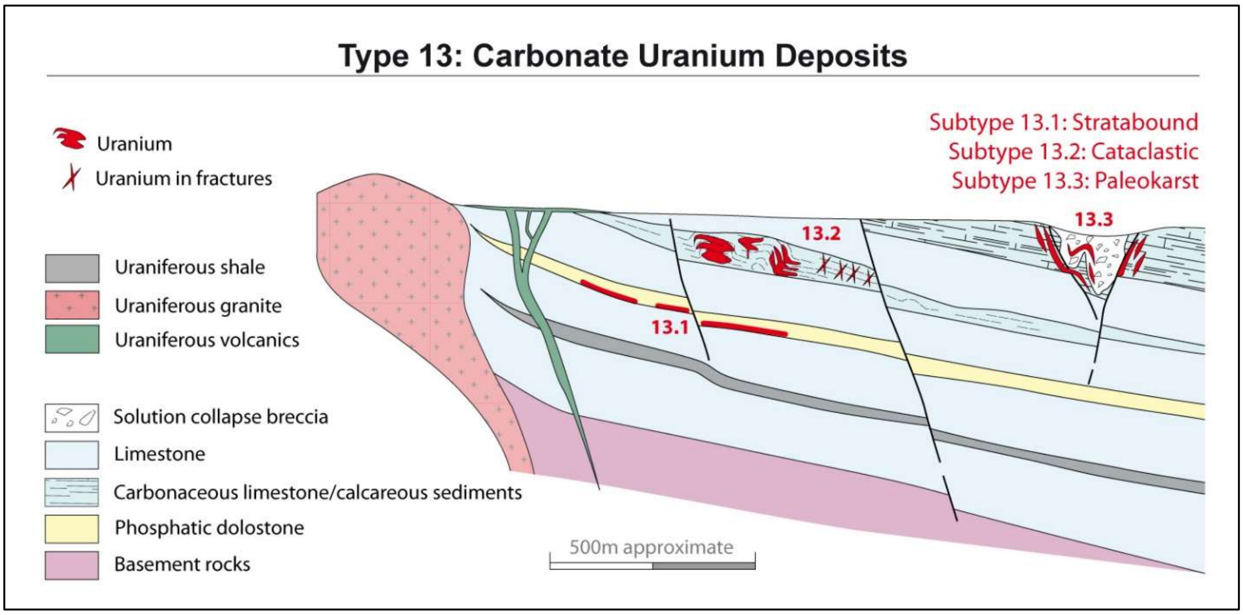

FIG. 3.14. Type 13: Carbonate uranium deposits.

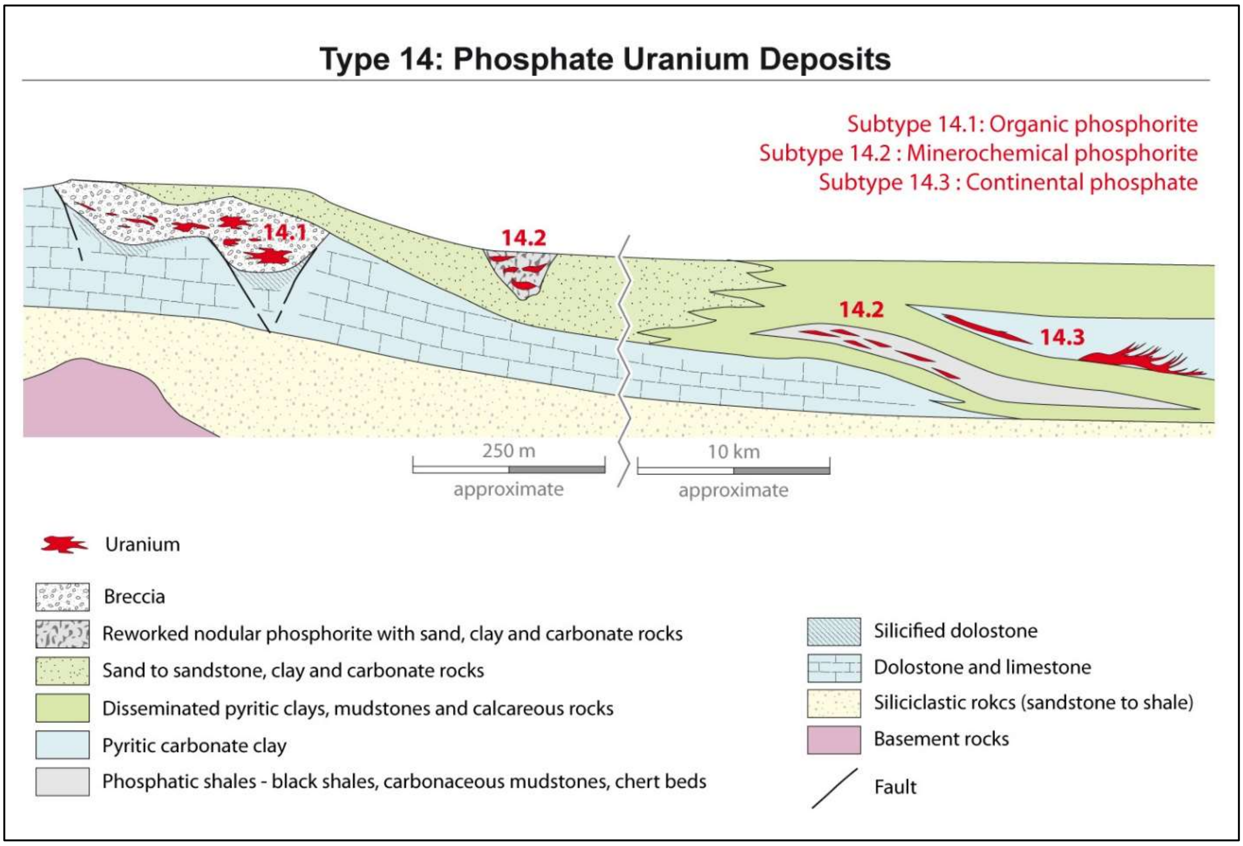

FIG. 3.15. Type 14: Phosphate uranium deposits.

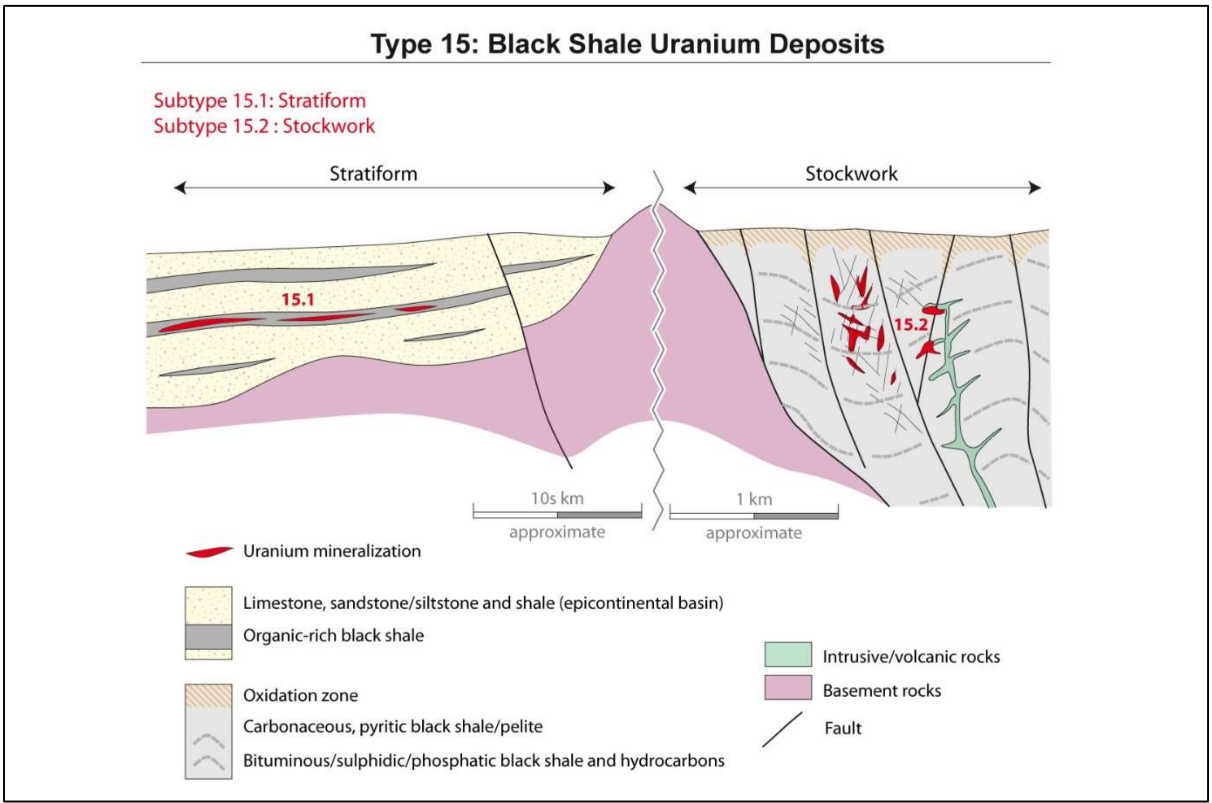

FIG. 3.16. Type 15: Black Shale uranium deposits.

REFERENCES TO CHAPTER 3

[3.1] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2022: Resources, Production and Demand, OECD, Paris (2023).

[3.2] INTERNATIONAL ATOMIC ENERGY AGENCY, World Distribution of Uranium Deposits (UDEPO), IAEA-TECDOC-1843, IAEA, Vienna (2018).

[3.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Descriptive Uranium Deposit and Mineral System Models, Non-serial Publications, IAEA, Vienna (2020).

[3.4] INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Classification of Uranium Deposits and Description of Selected Examples, IAEA-TECDOC-1842, IAEA, Vienna (2018),http://dx.doi.org/10.13140/RG.2.2.36449.56162

[3.5] DAHLKAMP, F.J., Uranium Deposits of the World: Asia, Springer-Verlag, Berlin and Heidelberg (2009) 493 pp,https://doi.org/10.1007/978-3-540-78558-3_6

[3.6] INTERNATIONAL ATOMIC ENERGY AGENCY, World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification, IAEA-TECDOC-1629, IAEA, Vienna (2009).

[3.7] INTERNATIONAL ATOMIC ENERGY AGENCY, Unconformity-related Uranium Deposits, IAEA-TECDOC-1857, IAEA, Vienna (2018).

[3.8] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2009: Resources, Production and Demand, OECD, Paris (2010),https://doi.org/10.1787/uranium-2009-en

Chapter 4. EXPLORATION METHODS

4.1 INTRODUCTION

Mineral exploration is an iterative and systematic process which progresses through the phases of exploration: planning and area selection, reconnaissance exploration (regional), follow-up exploration, detailed (camp scale) exploration, and advanced exploration including deposit definition. As exploration progresses the search area decreases, and more detailed information is sought. New knowledge is gained through the different methods and additional research. The techniques and methods that are utilized fall into the key categories of geology, geochemistry, geophysics and remote sensing; with drilling required to test below the surface especially during the advanced phases of exploration. The methods are generally used in combination to increase the legitimacy of the targets. Selection of exploration methods, survey configurations, their timing and duration of deployment are part of the overall exploration project strategy which is subject to financial budgets and human resources availability along with other operational considerations. It is incumbent on the exploration team to ensure the chosen methods are fit for purpose including being affordable and efficient for testing the targeting hypothesis with the intention of economic discovery.

Compared to other minerals, uranium exploration is unique since ground radiometric surveys are easily and inexpensively carried out and additionally, airborne radiometric surveys can be flown over large areas and may lead to the direct detection of significant uranium mineralization without detailed prior geological knowledge or even the intention of locating uranium. Airborne radiometric surveys are commonly acquired in conjunction with airborne magnetic surveys during the search for many commodities and so are widely available at a variety of resolutions ranging from country to prospect scales.

Relating ore forming processes and expected physical and chemical contrasts are fundamental to the planning and implementing of exploration activity which is depicted in Fig. 4.1. For each style of uranium deposit the mineral processes can be divided into the following categories [4.1, 4.2]: source, enrichment of U in the source region, and availability of U in the source region are critical to the formation of uranium deposits. Different deposit types are related to different source terrains. For example, volcanic glass is an easily mobilized source for sandstone hosted deposits; alkaline intrusions may be the source for some magmatic type deposits.

There are four main critical components in the ore forming process [4.1, 4.2]:

- Transport: Processes required to transfer the ore components from source to trap;
- Trap: Processes creating a physical or chemical trap(s) that can focus melt or fluid flow and accommodate significant accumulations of metal;
- Deposition: Processes required to extract mineralizing components from melts or fluids passing through the trap and depositing them;
- Preservation: Geological factors that prevent mineralization from being subsequently redistributed.

There may be processes that cannot be determined by any tangible physical/chemical variation and may not be detectable. However, in most cases observable property changes exist which can be identified by the different methods due to mineralization styles, host rocks, structural features and alteration characteristics. In some instances, 'proxy' characteristics are related indirectly for instance as a different paragenetic event pre or post ore formation that provides clues the key ore forming process were or are present. An example of this is pathfinder geochemistry elements indicating significant alteration and fluid movement due to a structure which hosts mineralization, even though the ore forming event is separate to those that produced the pathfinder elements. In most situations, it is the contrast in physical properties to the host rocks which is crucial to differentiate those that are ore forming from normal lithological variations.

To guide exploration activities, it can be beneficial to verify targeted physical and chemical property contrasts of the host rock, altered rock and mineralized rock. To understand the bulk properties and to test different instruments or configurations, it is advised to conduct trial orientation surveys over known mineralization. This approach may be invaluable at ensuring the best techniques are used in the correct manner. Furthermore, known local mineralization may provide insights that slightly vary from the classical models used elsewhere. Another approach to understand physical property changes and applicable methods is to use computer-based forward modelling to simulate different geological scenarios and processes along with their observable characteristics. A key benefit of this approach is the ability to assess three dimensional and time variant aspects. Petrophysical characterization of rock samples in a laboratory, using hand-held instruments or down-hole probes may also provide valuable insights. Typical characteristics that can be measured include radioactive decay products of uranium, thorium and potassium, density, susceptibility, remanent magnetization, electrical conductivity and resistivity (galvanic and inductive), induced polarization, seismic velocity, porosity and reflectance spectroscopy.

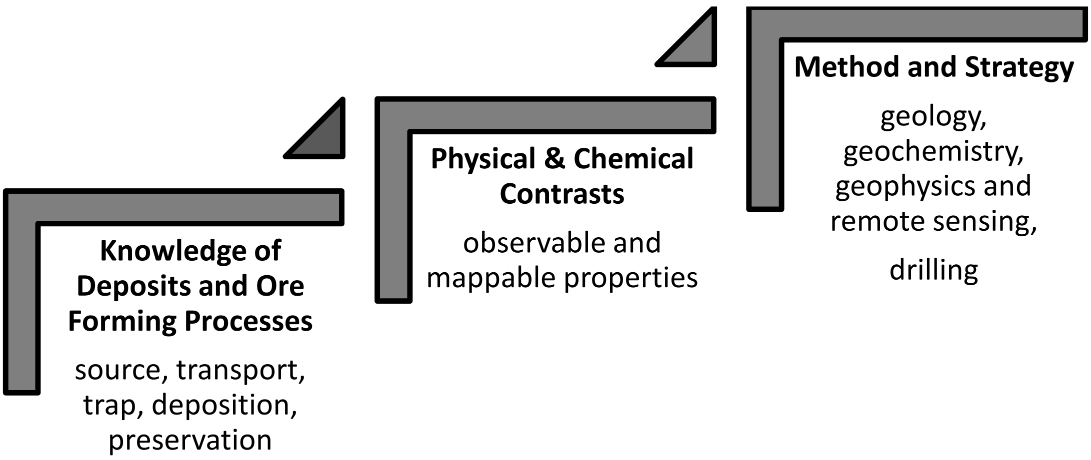

FIG. 4.1. Observable physical and chemical property contrasts related to ore forming processes.

4.2 METHODS

Exploration methods should be aligned with the overarching exploration strategy, the regional metallogenic setting, the deposit model under consideration, and the relevant phase of exploration. Once the mineral deposit model and the associated chemical and physical properties variations have been identified, an exploration strategy is formulated to deploy various techniques to target and evaluate mineralization. As with any commodity, successful uranium exploration generally relies on integrating the results of all the surveys which have been undertaken using a variety of methods. A key aim is understanding the overall controlling factors of the mineral system and to advance the genetic understanding. Cuney and Kyser [4.3] provide a comprehensive treatise on the relationship of these critical elements and their role in developing an exploration strategy and selecting exploration methods.

4.3 GEOLOGICAL OBSERVATIONS AND MAPPING

Recognition of changes in the porosity, structure, mineralogy and chemistry of stratigraphic units is critical, as uranium deposit formation typically involves some structural and/or stratigraphic control to promote fluid migration and concentration of uranium-bearing fluids [4.1, 4.2, 4.3]. Geological observations, inferences and mapping provide the essential framework for all phases of exploration. This geological information may be applied to constructing a geological model as well as understanding the physical and chemical processes involved in forming uranium mineralization and subsequent post mineralization processes. Information gained may include the relationship between rock types, host rock sequences, distinguishing between barren and mineralized structures, metamorphic grade, and the paragenesis of mineralization and alteration mineralogy. Surface mapping is also used to characterize recent cover sequences, erosional terrains, soil character and vegetation. This information may enhance the interpretation of geochemical data and assist with planning geophysical and geochemical surveys.

Publicly available geology maps and geophysical surveys are particularly valuable resources for planning and area selection phases of uranium exploration programmes [4.4]. Geological mapping focuses on the lithologies and their structural relationships as well as evidence of alteration. Geological mapping together with geochemical and geophysical surveys may help identify fractionated igneous rocks which are candidates for uranium mineralization or providing a uranium-rich source for nearby mineralization [4.5]. Stratigraphy and structures are important for understanding possible uranium transport or hosting mechanisms.

The mapping scale is important when evaluating structures. Although structures are critical in the formation of many types of uranium deposits, the vast majority of structures are not mineralized and, in many instances, it is the localized second or third-order structures which are important due to the timing of mineralization. Regional scale structures or lineaments are generally transcrustal and active over long time periods. Structural mapping and their prospectivity should be integrated with geophysical methods that identify possible structures at surface and depth that host favorable alteration and mineralization.

Sequence stratigraphy, the study of the relationship of rocks within a chronostratigraphic framework and mapping the related erosional or depositional bounding surfaces allows understanding of the large-scale forces acting on the depositional environments. Isotopic data integrated with sequence stratigraphic analysis contributes to understanding changes in climatic and sea level changes, and their roles in the evolution of stratigraphic successions which may help identify and evaluate favorable environments for mineralization [4.6].

An example of the mineral system concept applied to the exploration of sediment-hosted uranium deposits includes that proposed by McCuaig et al. [4.7] which illustrates this multi-scale and disciplinary approach such as the characterization of processes, including mapping of geological features and processes and integration of data and interpretative products.

4.4 MINERALOGICAL OBSERVATIONS

To properly assess a uranium occurrence the mineralization should be characterized in terms of occurrence size, crystal form, chemical composition, morphology, texture, association with other minerals and other physical attributes. This is particularly important for more advanced prospects being evaluated for their economic potential.

In some cases, uranium deposits contain uranium minerals that are 'refractory'. These complex mixed uranium oxides such as davidite, pyrochlore, betafite and brannerite are considered to be refractory because the uranium contained within them is difficult to extract. Brannerite (a uranium titanate) is the most abundant of the refractory uranium minerals [4.8, 4.9]. The economic implications of the amount and cost of chemical reagents and energy consumption required to process refractory minerals should be considered at early stages of exploration and especially during economic viability assessment.

Whole and partial rock and mineral geochemistry reveal the chemical composition of the rocks. This information in combination with subsurface geology is used to establish the distribution patterns of elements that are spatially related to mineralization, alteration or geological structures. An example includes the use of lithogeochemical-mineralogical haloes around unconformity-type uranium deposits in northern Saskatchewan to expand the extent of drill targets [4.10, 4.11].

When specific alteration minerals are known to have developed in association with the uranium occurrence, mineralogy can be a powerful exploration tool. For example, Mg-rich minerals (sudoite, dravite), altered monazite and zircon, and aluminum phosphate sulfate minerals are associated with unconformity-related uranium deposits; evidence for oxidation and reduction fronts in sandstone type systems; and albitization associated with deposits related to sodium metasomatism. Many alteration minerals can be identified by conventional petrographic microscopy, scanning electronic microscopy, secondary ion mass spectrometry, thermal ionization mass spectrometry, infrared spectrometers, X ray fluorescence and X ray diffraction techniques [4.12].

4.5 PARAGENETIC AND PETROGRAPHIC STUDIES

Paragenetic and petrographic studies are conducted to address the factors and timing which control uranium mineralization. Detailed petrographic analysis in reflected and transmitted light using conventional petrographic microscopy and scanning electron microscopy and electron microprobe studies may be used to characterize host rock, mineralized rocks and alteration mineralogy, and to establish the paragenetic history of mineralization.

Fluid inclusion studies have become a fundamental part of petrographic studies as they provide a direct source of information about the composition, pressure-temperature conditions, chronology, and even the metal content of the mineralizing fluids [4.13, 4.14, 4.15].

4.6 GEOCHEMISTRY

Geochemical methods are an essential component of uranium exploration and may be conducted at all phases and scales of exploration.

FIG. 4.2. depicts the typical terrain variations which may occur and the use of geochemistry to identify primary and secondary dispersion. In addition to the identification of the uranium minerals, recognition of reduced and oxidized lithologies, associated alteration minerals, and associated chemical enrichments including sulphides, carbonates, sulphates and corresponding elements such as Mo, Se, V, Te, Re, Se, Sc may be important as they are often associated with uranium mineralization and may be dispersed from the depositional location. The specific geochemical survey method applied depends on the nature of the target including the deposit

model, the terrain, the type of sample media available, relative costs and potential rewards in comparison to alternative methods. In addition to sampling outcrop from bedrock and drill hole sampling, geochemical surveys in transported, cover terrains may utilize samples from glacial till, streams, soils and lakes. A good example of very broad scale exploration reconnaissance geochemical surveys is the sampling of glacial till and lake sediments in Canada in the Athabasca Basin, Saskatchewan and Nunavut [4.16, 4.17]. The important features and contrasts of various uranium deposit types and their relationship to geochemistry and geochemical survey methods are addressed by Kyser [4.18] and the IAEA [4.19].

Technological advances in field-portable analytical instruments, such as portable visible and near-infrared spectrophotometers, gamma-ray spectrometer, portable X ray fluorescence, portable X ray diffraction, portable LIBS, and µRaman spectrometer, have increased their on-site applications in mineral exploration studies. These instruments provide direct, rapid, on-site, real-time, non-destructive, cost-effective identification, and determination of target elements, indicator minerals and pathfinder elements in rock, ore, soil, sediment, and water samples, in the field with minimal or no sample preparation and can provide timely decision-making support during fieldwork [4.20]. Laboratory analyses of materials continue to be relevant and are especially useful in the advanced stages of exploration. Table 4.1 summarizes some of the most relevant analytical techniques [4.21].

TABLE 4.1. ANALYTICAL TECHNIQUES

Technique	Description
Portable X Ray Diffraction	Closed-beam field portable X ray diffraction to provide full phase identification of mineral components; sometimes coupled with a qualitative X ray fluorescence spectrometer
X ray diffraction, micro-X ray diffraction, micro-and regular X ray fluorescence elemental mapping, computed tomography and fluorescence computed tomography, extended X ray absorption fine structure and micro-extended X ray spectroscopy, scanning transmission X ray microscopy	Synchrotron light used as a source of intense and energy-tuneable X rays for a variety of techniques
Short Wave Infrared Spectroscopy	Infrared reflectance spectroscopy for mineral identification
Raman Spectroscopy	Raman spectroscopy uses the vibrational modes of molecules; sometimes coupled with short wave infrared
Inductively Coupled Plasma Atomic Emission Spectrometry	Plasma used to excite ions in solutions or solids and excited atoms and ions emit electromagnetic radiation at wavelengths characteristic of a particular element.
Electro Thermal Vaporization Inductively Coupled Plasma Optical Emission Spectrometry	Solids or solutions are evaporated into a plasma and excited atoms and ions emit electromagnetic radiation at wavelengths characteristic of a particular element.
Deep Exploration Technologies Cooperative Research Centre Coiled Tubing Drill Rig with Sensors in-line	Trailer-mounted assay system that provides near real-time X ray fluorescence geochemistry and X ray diffraction mineralogy on drill cuttings.

TABLE 4.1. (cont.) ANALYTICAL TECHNIQUES

Technique	Description
Laser Ablation Inductive Coupled Plasma Mass Spectrometry	Laser is used to ablate material that is carried into a plasma torch and the excited ions are introduced to a mass spectrometer detector for both elemental and isotopic analysis.
Quality Assurance & Quality Control	Correct and transparent protocols are used in analyses to ensure they are of the appropriate quality.
Portable X ray Florescence	Handheld Xray fluorescence for in situ chemical compositions.
Off-Axis Integrated Cavity Output Spectroscopy	The concentration or amount of an isotopic species in a gas phase is determined by absorption spectrometry with a laser.
Laser Induced Breakdown Spectroscopy	Laser is used to sample material and the chemical composition determined using emission spectra.
Inductive Coupled Plasma Mass Spectrometry	Excited ions in plasma torch are introduced to a mass spectrometer detector for both elemental and isotopic analysis.
Continuous Flow Isotope Ratio Mass Spectrometry	Elements of interest (H, C, N, O, S) are prepared as gases and separated in-line with a stable isotope ratio mass spectrometer.

4.6.1 Uranium

The uranium concentrations that can be considered anomalous vary according to deposit type and geological environment. Geochemical detection of relatively elevated uranium contents (i.e., more than twice background) may increase the detectable “footprint” area surrounding an economic uranium accumulation [4.22]. For instance, sandstones typically have very low levels of uranium so that even 1 ppm may be considered anomalous whereas in comparison, U-rich intrusive rocks can have background concentrations of 10 to 30 ppm U. Intrusive rocks and dykes with elevated uranium are not only potential host rocks but are also important to identify as potential source rocks for sandstone and surficial (e.g., calcrete) uranium deposits [4.5, 4.23].

4.6.2 Trace element dispersion

Many uranium deposit types are characterized by enrichment of one or more trace elements in addition to uranium. Where multiple elemental anomalies are coincident, there may be enhanced potential for discovery. Two distinct geochemical processes are reflected in trace element geochemical data and may be applied to expand the detectable expression of a deposit: (1) primary dispersion provides information on alteration and primary element dispersion associated with mineralization; and (2) secondary dispersion provides indications of element migration from alteration zones and mineralized zones post formation. During primary dispersion, mineralizing fluids permeate into the host rocks, chemically altering primary minerals and elevating the concentrations of ‘pathfinder’ elements. This relative enrichment may be evident in the lithogeochemistry well away from the uranium mineralization with the degree of dispersion and lateral and vertical extent of this enrichment being dependent on a myriad of factors such as the composition, porosity and permeability of the lithologies, type of structures and their activation history and the effects of other geological processes that may have been present during and after mineralization.

Most uranium deposits contain elements in a reduced chemical state. This makes the deposits suitable environments for microbes that can mobilize elements through secondary dispersion processes. Microbe-mobilized elements can involve aqueous or gaseous metal complexes, with the metals from the mineralized rocks, and the ligands from microbial waste or decay products. These complexes can migrate to surface, particularly along fractures and faults, where they can become adsorbed on clay and Fe-Mn oxide surfaces in soils and enter the biosphere. These may be detected by biogeochemical methods.

4.6.3 Stable and radiogenic isotope geochemistry

Pathfinder element enrichments and hydrothermal alteration zoning related to specific ore-forming fluids may be indicated by the isotopic compositions of stable and radiogenic isotopes. The isotopic concentrations and ratios of elements such as H, Li, B, C, O, S, Pb, and U and other elements in mineralized zones and alteration mineral halos can sometimes be used to trace the genesis of the uranium mineralization including the fluid history and physiochemical conditions of uranium deposition [4.24].

In deposit types where reduction of uranium by bacteria is an effective mechanism for deposit formation (e.g., sandstone uranium deposits), then microbially induced geochemical signals such as carbon and sulphur isotopes or enhanced mobile metals could indicate favourable areas for exploration [4.24].

Lead isotopes can be effective pathfinders for uranium mineralization with isotope ratios of $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{206}Pb$ providing information on mineralization timing, element remobilization and migration. Lead isotopes proximal to mineralization display radiogenic signatures, often with 'excess Pb' suggestive of derivation from greater uranium concentrations than are known or currently present. Weak acid leach and partial digest analytical techniques [4.25] are increasingly being used in Pb isotope pathfinder geochemical surveys [4.25, 4.26].

4.6.4 Biogeochemistry and hydrogeochemistry

A report by the IAEA summarizes exploration using biogeochemistry with some indications of elevated uranium in plant material above deposits occurring at up to 300 m depth [4.27]. Dunn [4.28] points out that a uranium biogeochemical anomaly occurs in the Athabasca Basin in an area known to host more than 20 uranium deposits. A study at the Four Mile sandstone uranium deposit in Australia found that although the deposit is buried by 130–150 m of sediments there is a biogeochemical expression of the mineral system [4.29].

Water from boreholes and wells can be used to identify oxidized and reduced sandstone horizons and proximity to mineralized redox fronts for exploration follow up. Selected pathfinder elements and isotopes may include U, ^{234}U, ^{238}U, ^{210}Pb, ^{210}Po, Ra, ^{226}Ra, ^{228}Ra, Rn, Mo, Zn, Rh. The use of hydrogeochemistry for uranium exploration relies on disequilibrium calculations of multielement geochemistry together with Pb isotope analysis [4.30].

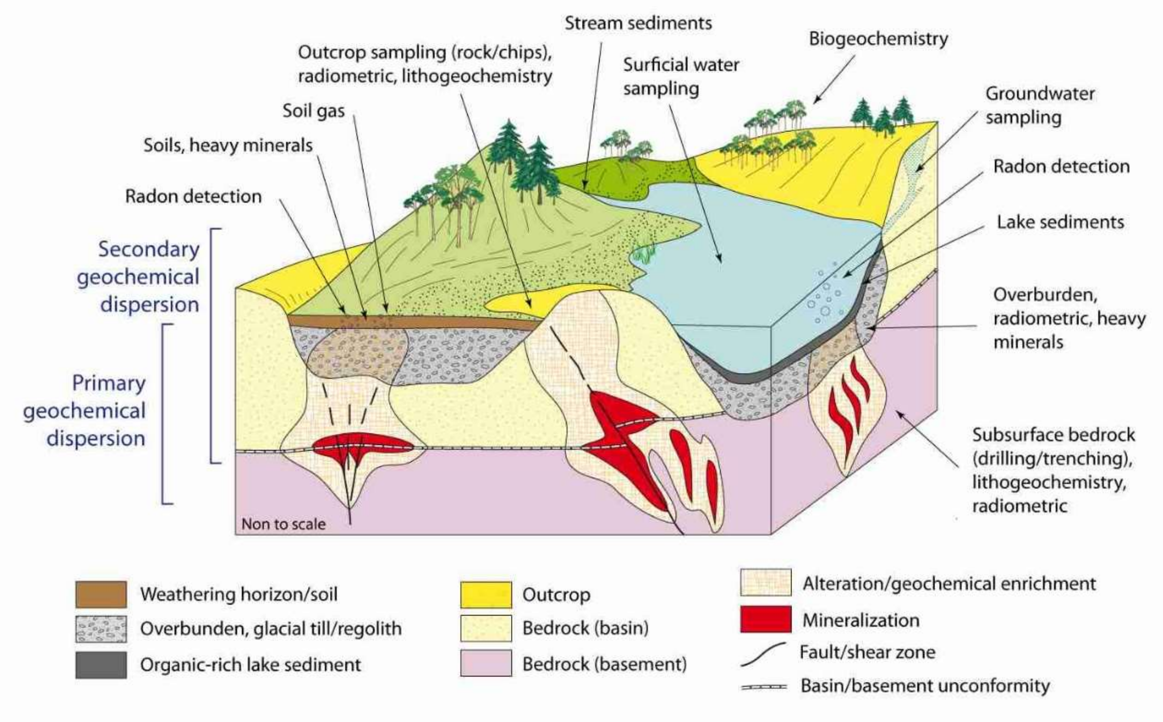

FIG. 4.2. Exploration geochemistry in various terrains focused on primary and secondary dispersion.

4.7 GEOPHYSICS AND REMOTE SENSING

The IAEA has produced a Technical Document on the utilization of airborne and ground geophysical methods for uranium exploration [4.31]. Most geophysical and remote sensing methods are relevant to uranium exploration due to the wide range of deposit styles. Table 4.2. lists the broad categories, physical properties, methods and their deployment platform. Remote sensing and airborne surveys are utilized to cover broad areas during the reconnaissance phase of exploration whereas ground surveys and drill hole methods become more relevant during more focused and advanced phases. Most methods may have multiple avenues of deployment depending on the resolution and scale. Satellite based remote sensing methods are restricted to spectroscopy and topography applications, although broad scale satellite gravimetry may also be used to understand basin architecture. Seismic is restricted to ground and drill hole applications.

4.7.1 Spectroscopic and topographic methods

Spectroscopy systems measure the visible, near-infrared, shortwave-infrared and thermal infrared regions of the electromagnetic spectrum. The simplest of these is red, green and blue imagery similar to photography. The more complex methods rely on spectrometers to measure detailed wavelengths sometimes referred to as hyperspectral. By comparison of bands with libraries, it is possible to discriminate different high and low temperature minerals for mapping rock types and alteration. Satellite and airborne systems rely on the daylight reflection whereas hand-held systems use their own internal light source. Unconformity-related uranium deposits generally have significant alteration present and are therefore a prime candidate for reflectance spectroscopy, however, these deposits are often buried and so may not be readily detected by airborne and satellite systems, unless the alteration system extends well beyond the mineralization.

TABLE 4.2. LIST OF GEOPHYSICAL AND REMOTE SENSING CATEGORIES AND METHODS FOR EXPLORATION

Category	Physical Parameter	Method	Satellite	Airborne	Ground	Downhole
Radiometric	Gamma Emanation (U, K, Th), Gas Emanation	Gamma Ray		✓	✓	✓
		Radon (Helium) Gas			✓	
Spectroscopy and Topography	Visible and Infrared Reflectance, Terrain Height	Photogrammetry	✓	✓		
		Hyperspectral	✓	✓	✓	
		Laser Induced breakdown Spectroscopy	✓	✓		
		Synthetic-Aperture Ranging	✓			
Electrical and Electromagnetic	Conductivity / Resistivity, Dielectric Permeability, Polarization, Chargeability, Susceptibility	Time Domain		✓	✓	✓
		Frequency Domain		✓	✓	✓
		Magnetotelluric		✓	✓	
		Self-Potential		✓	✓	✓
		Induced Polarization			✓	✓
		Ground Penetrating Radar			✓	✓
Magnetic	Susceptibility, Remanent Magnetization	Magnetometry		✓	✓	✓
Gravity	Density	Gravimetric	✓	✓	✓	✓
Seismic	Reflection/Refraction of Elastic Waves	Seismic			✓	✓
		Passive Seismic			✓	

The topography can be derived primarily from satellite and aerial systems as a digital terrain model. The digital terrain model is calculated from stereo analysis, laser induced breakdown spectroscopy and synthetic aperture ranging instruments. Imaging the terrain allows topographic, drainage and landform analysis which is of general use in uranium exploration primarily for geological mapping.

4.7.2 Radiometric methods

Airborne, vehicle-borne, ground, and downhole gamma-ray surveys are utilized extensively within the industry at all phases and scales of uranium exploration due to their cost-effective, quick, and reliable application. The IAEA has been involved with providing guidelines for gamma ray use including a Nuclear Energy Series document on *Radioelement Mapping* [4.32]. Single channel gamma-ray scintillometers and Geiger counters measure a broad energy range for a total count response; however, since the 1960s, multi-channel spectrometers have been used in radiometric surveys to relate specific energy levels to concentrations of potassium (% K) and equivalent (estimated) concentrations of uranium and thorium (ppm eU, ppm eTh). Equivalent concentrations are quoted using a proceeding ‘e’ to distinguish the results from laboratory assay data, since there are several built-in assumptions and the gamma ray daughter products of uranium and thorium being measured could be in disequilibrium from their original source.

Although gamma radiation can travel long distances through air, the main limitation for measuring gamma-rays is the absorption by different media including surface soil and water. In general, the gamma radiation is derived from the uppermost (50 cm) part of the soil and bedrock

[4.31]; consequently, the underlying bedrock is often masked by cover. This means that even minor responses could be vital indicators of underlying uranium mineralization. However, surficial and airborne radiometric surveys are less important in areas of significant cover or basins where mineralization is located at significant depths.

Airborne geophysical surveys flown at various scales often utilize multi-channel gamma ray spectrometers to estimate equivalent potassium, equivalent uranium, equivalent thorium and total concentrations. The radiometric acquisition is often a cost-effective addition to other geophysical methods such as airborne magnetic surveys. In addition to uranium, the discrimination of potassium and thorium estimates can help identify a broad range of rock and cover types along with alteration and is superior to total count methods. Thorium is a relatively immobile element and therefore a ratio of uranium to thorium (U/Th) or uranium squared to thorium (U^2/Th) is often used to enhance anomalous uranium response compared to background and general geological variations [4.33, 4.34]. When planning and interpreting spectrometer surveys it is important to note that the response drops off proportionately with distance and so broadly spaced airborne surveys, and particularly ground surveys, may miss important responses between survey lines. Due to the sensor height, airborne surveys are more likely to achieve complete coverage, including detection of elevated uranium between lines allowing interpolated grid assessment rather than being limited to points or lines.

Buried uranium deposits may give off radon and helium during the radioactive decay. These may be detected by ground emanatory surveys and have the benefit of potentially detecting uranium below the surface. The method is especially applicable where uranium is below a thin layer of cover such as sand or soil, however, there can be complicating sub-surface factors such as permeability and pressure which affect the response and interpretation. Devine et al. [4.35] studied radon emissions over deeply buried unconformity-related uranium deposits and concluded that dissolved radon in groundwaters could be useful when exploring for similarly buried unconformity-related deposits.

Some deposits are in disequilibrium (particularly those that are basin related), which means that the measured gamma rays given off by daughter nuclides do not accurately reflect uranium concentration. Therefore, in general laboratory analysis is preferred to accurately establish the uranium content. Disequilibrium is especially common for sandstone hosted uranium deposits and, in some of these instances, a correction factor may be applied to the downhole gamma probing data to estimate uranium concentrations based on comparisons with laboratory chemical analyses [4.36, 4.37]. Prompt fission neutron probes rely on the measurement of neutron activation fission products of ^{235}U which measures in-situ uranium concentrations which avoids disequilibrium affects [4.38].

4.7.3 Electrical and electromagnetic methods

There are a broad range of electrical and electromagnetic methods which are applicable to uranium exploration deployed as airborne and ground surveys along with probes that can be lowered down drill holes. The configuration of the surveys can vary significantly depending on the depth, target size and orientation along with the coverage being sought. A common objective is to detect carbonaceous material and sulphides which may provide important chemical traps and also indicate physical trap sites. Induced polarization can detect disseminated sulphides which can help identify structures and alteration, however, the volume of sulphides is generally insufficient to precipitate significant uranium from oxidized fluids. Several electrical and electromagnetic methods are aimed at identifying alteration (conductive clay or resistive silicification) which is particularly diagnostic for unconformity-related uranium deposits. Basin architecture and paleotopography can also be imaged by some methods to understand fluid migration, trap sites and unconformity depths.

4.7.4 Magnetic methods

Magnetic surveys are routinely used across the exploration industry for mapping lithologies, structure and alteration. This is the case for most of the uranium deposit types. For basin related deposits, magnetics may assist with understanding the stratigraphic sequences and extents including possible depositional channels. Particularly pertinent to unconformity-related uranium mineralization is the identification of structural traps and alteration which may be derived from magnetic data on a regional scale. Reactive Fe^{2+} and sulphide-bearing rocks may control uranium-bearing fluids and precipitate uranium; therefore, it can be important to map the magnetic pyrrhotite and magnetite-rich rocks [4.2].

4.7.5 Gravity methods

Primary uranium minerals such as uraninite are very dense; however, these are not deposited in sufficient concentrations for detection with gravimetry instruments. Instead, gravity is used in uranium exploration for mapping density contrasts which assists in identifying lithologies, structures and alteration along with assisting in understanding basinal features, especially the paleo-topographic architecture. Alteration halos, especially clay enrichments which are important for some deposits such as Paleoproterozoic unconformity uranium deposits may be detected as low gravity anomalies [4.39].

4.7.6 Seismic methods

Seismic is mostly used to understand deposits or explore for basin-related uranium deposits by mapping the stratigraphy and basin architecture to understand aquifer and aquitard relationships and other features important for understanding the mineralization system. Historically, seismic surveys have been expensive and thus restricted in use to broad reconnaissance lines. However, passive seismic is gaining popularity as a cheaper alternative which can be employed more broadly. Seismic has the advantage of greater penetration of the signals used in the survey, providing information at greater subsurface depths than the other ground and surface geophysical techniques.

4.8 DRILLING

As with other commodities, uranium exploration relies heavily on drilling to search for and understand sub-surface mineralization and geology in three dimensions. This is particularly important as targets are progressed from initial discovery, which require increasing technical knowledge and increased density of drilling to identify economic resources.

The main drilling methods for exploration are listed in Table 4.3 together with the considerations for choosing the method. Apart from budget and availability considerations, the choice of drilling method should consider drill rig size and transportation, ground conditions, target depth, type of samples collected, availability of water, and volume of the sample collected. A particular advantage of diamond drilling is the ability to replicate the subsurface which provides avenues for investigations including mineralogical characterization [4.19]. Oriented core measurements can be used to understand relationships and structural trends. Diamond drilling is commonly used for verifying the data obtained from other drilling methods such as those which produce only rock chips and are less informative but can be acquired more economically.

TABLE 4.3. DRILLING METHODS AND APPLICATIONS

Drilling Methods	Applications
Auger	Commonly used for reconnaissance exploration to collect samples in soft unconsolidated surfaces at shallow depths (i.e., < 2 m) but there can be some contamination from wall rock.
Percussion Rotary Air Blast	Used primarily for first-pass mineral exploration and development, where reasonable quality samples can be readily obtained.
Air-Core	Generally preferred over RAB drilling as it provides cleaner samples. Cuttings are removed inside the drill rods and are less prone to contamination than those obtained by auger or RAB drilling.
Rotary Mud	High speed penetration, relatively inexpensive. Injection of mud into the cores and permeable layers may damage wall conditions.
Reverse Circulation (RC)	RC drill rigs are considerably larger than RAB or air-core rigs and typically reach depths up to 500 m. This method is slower and more expensive than RAB or air core drilling but achieves better penetration in harder rocks. It is less expensive than diamond drilling and coring and is thus the preferred method for most preliminary mineral exploration work. Good land access is generally needed for these large drilling rigs; however, an advantage is that there is no requirement for water during drilling if using RC. The diameter of the drilling bore is generally quite large compared to the other methods which can be important for accurately representing vein mineralization.
Diamond	Diamond drilling rigs are portable, lightweight and capable of depths in excess of 500 m. The advantage of diamond drilling is the coring which provides a true representation of the sub-surface rock. This also provides a more accurate profile of the mineral composition at each depth and allows detailed geochemical, mineral, and structural investigations. Water is required for diamond drilling.
Sonic	Sonic drilling is particularly useful when hard-to-drill formations are encountered, and a high level of sample recovery is required

During drilling, hand-held scintillometers and spectrometers should be used to identify uranium mineralization on site to guide the hole depth and assist with sampling decisions. Downhole gamma probes and prompt fission neutron probes can be used to estimate uranium grades at very close intervals (i.e., 5 cm) and can be effective at providing an estimate of the uranium concentration of wall rock as opposed to the drilling, rock or chip samples, which may be limited to broader intervals representing less volumes of material.

4.9 SURVEY CONSIDERATIONS

When utilizing a specific exploration method, the targeted physical or chemical properties should have sufficient contrast to be discerned from background lithological variations. Even when there is sufficient contrast; cover, depth and target size are important factors which should be considered when planning surveys.

4.9.1 Cover (overburden)

Uranium mineralization that is exposed at the surface, in outcrop, is a straightforward exploration target where 'direct detection' of gamma-ray emissions can be identified by radiometric surveys. Hence, airborne and ground radiometric surveys have identified many uranium occurrences world-wide. However, uranium mineralization frequently occurs in the subsurface, with no surface expression, since the gamma radiation is derived from the top 50 cm [4.31].

The composition and thickness of the overburden can influence the outcome of geophysical surveys. For instance, strong conductive surface material like carbonaceous shales may restrict the penetration of electromagnetic and electrical methods, and surface magnetic rocks like maghemite can produce noise for magnetic surveys depending on how close the material is to the sensor and the volume of the material.

4.9.2 Depth and size

Increasing depth is always associated with decreasing resolution so it is a crucial consideration when planning both surface and airborne surveys. Generally, the deeper the target, the greater the physical size and physical property contrast required for detection. Basin related uranium deposits rarely have a surface expression and outcropping exposures are unlikely. In these instances, exploration may utilize proxies that can be indicative of the uranium mineralizing processes. The type of proxy or secondary feature will vary based on the style of the mineralization and the geology. An example would be the detection of graphitic units displaying a conductivity response using electromagnetics where the graphite may indicate a major structure as well as provide a chemical contrast for uranium precipitation.

When planning a survey, it is important to consider the depth at which a deposit is no longer economically viable. This typically depends on the whether the mineralization would be accessed by open pit, in-situ recovery or underground mining along with the grade, tonnage and mining aspects.

4.9.3 Configuration of methods

Geophysical methods can be deployed as airborne or ground surveys depending on the resolution and coverage being sought balanced against a finite budget. Sometimes the configuration is chosen due to availability of equipment, limitations in ground access, environment and impact to the community/stakeholders. Drones are more recently being utilized to bridge the gap between airborne and ground approaches. For some surveys like magnetics, having a sensor well above the ground reduces the noise but there is a trade-off if the sensor is too far above the ground, as this reduces the signal. Since gamma rays are affected by water it is important that radiometric surveys are not conducted during periods of rain and snow which is an aspect which should be considered as part of the survey contract (e.g., flexibility in scheduling). For grid-based surveys east-west and north-south lines are generally preferred for both simplicity and to generate coverage that is unbiased by existing geology knowledge. However, some methods use single or limited traverse lines, and these should generally be acquired perpendicular to the features of interest on a local grid to maximize the signal of the target. The same principle is relevant for drilling where the hole should be aimed perpendicular to the strike and dip of the target to test the true dimension of geological features and mineralization. For most situations, it is important for the survey or drilling to extend well beyond the features of interest to understand the context in terms of background response and characteristics.

4.10 DATA INTERPRETATION

Interpretation of exploration information is an important part of the exploration cycle, which is sometimes overlooked or not allocated sufficient funding. The information comes in a variety of forms including paper reports and maps, digital reports/records and samples of natural materials (e.g., rock, soil, water, vegetation). Digital data may be in a format for visualizing in geographical information systems (GIS), as a database or in specialized formats (especially common for geophysics). As the exploration progresses, the requirement for strict database controls and Quality Assurance and Quality Control (commonly referred to as QAQC) of the data heightens particularly when the objective is to conduct rigorous resource estimation and economic assessments. Acquiring geoscience data generally involves significant cost and time, and so it is incumbent on explorationists to make sure information is stored in suitable formats that are accessible and can be effectively used by stakeholders and government agencies. It should be preserved for future use so that it can be readily transferred or communicated. Prudent government agencies assist with storing geoscience information and enabling the data to be used by third parties (generally after a legislated confidentiality period).

Over time, deposit knowledge and technologies evolve, hence it is common for historical data to be reused and reinterpreted. In some instances, data is collected for a different commodity which may be used for uranium exploration. For instance, downhole gamma probing data is often collected during drilling programmes by coal, oil or gas exploration companies, which may be utilized to explore for sandstone uranium deposits. Similarly, these companies may also collect sequence stratigraphy information and drill core to help identify structures and sedimentary units permissive for uranium migration and reduced lithologies or stratigraphic units favourable for uranium precipitation.

Geophysical data is often complex, relying on sophisticated processing and modelling to relate collected data to physical properties and geological characteristics. For instance, it is common to normalize total field magnetic data by reduction to the pole and apply Fourier transforms to enhance high frequency features such as dykes and structures. Electrical and electromagnetic data is often inverted to depths with equivalent parameters such as resistivity, conductivity and induced polarization. In addition to geophysics, computerized modelling programmes may also be used for geology and geochemistry data and in combination with each other. As inversions and modelling capabilities have grown, the shift has been from two to three dimensions and sometimes to a fourth dimension (to incorporate time variation). The objective for all inversion and modelling is to relate observations to the actual sub-surface geology and processes including structures and alteration. At the detailed and advanced stages of exploration, a primary objective is to estimate uranium resources and reserves where the accuracy of the estimate relies upon the density of drilling and sampling to establish the continuity required to support geological modelling and resource estimation.

Effective exploration generally involves integrated interpretation and targeting analysis using a multi-disciplinary approach. Having the right specialists with relevant experience and software, may be crucial for discovery. Sometimes it is prudent to hire experts to add valuable short-term insights or investigate key research questions. The use of GIS software is almost mandatory for effective visualization and management of the many layers of geoscientific and ancillary data. Also, databases can be critical to manage observation and drilling data in a rigorous fashion which becomes paramount for resource reporting stages. Assimilating the information to guide the targeting decisions is typically referred to as prospectivity analysis.

4.11 OVERVIEW OF EXPLORATION METHODS AND STRATEGY

The choice of exploration methods and objectives is highly dependent on the chosen target amongst the various deposit types and identifying the observable physical property contrasts in the relevant deposit models all within the context of an exploration strategy. Examples of relating mappable criteria to define exploration targets is described in a recent IAEA technical document entitled, *Quantitative and Spatial Evaluations of Undiscovered Uranium Resources* [4.40]. New exploration requires planning considerations and deciding on the specifications followed by carrying out the survey and activity as depicted in Fig. 4.3. Once the method has been chosen, then the cover, depth and size along with the scale of the search should be weighed against cost and logistical constraints. A well-designed exploration programme should be formulated which fits with the exploration strategy and is executed to meet the stakeholder requirements whilst adhering to industry good practices. Prior to data acquisition, it is important to determine the optimal specifications which may include details on the configuration, acquisition orientation and the extents to be investigated. During data acquisition, QAQC will help to ensure that the activity is always fit for purpose and the data should be carefully managed and stored before being interpreted. Suitably qualified and experienced personnel should process and interpret the data as individual datasets as well as integrating with other data, that is combining geology, geochemistry and geophysics. A continual feed-forward of learning is best where the understanding of the model and targeting approach is continuously refined by testing hypotheses, for example, anomalies are progressed to targets which are then tested by drilling. Chapter 5 discusses in more detail the practical implementation and management of exploration.

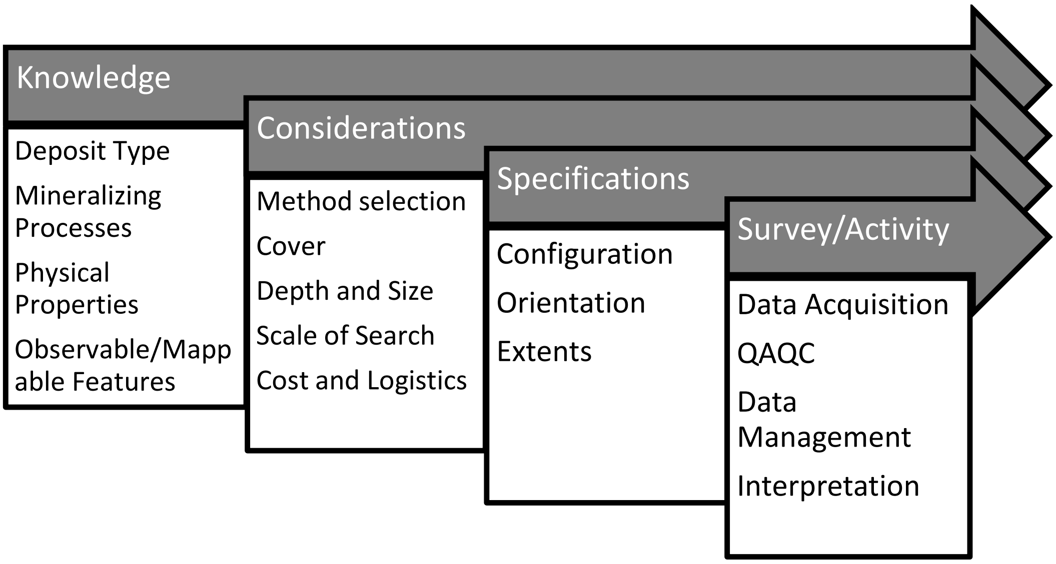

FIG. 4.3. General steps leading to survey/activity.

REFERENCES TO CHAPTER 4

[4.1] INTERNATIONAL ATOMIC ENERGY AGENCY, World Uranium Geology, Exploration, Resources and Production, Non-serial Publications, IAEA, Vienna (2020) 972 pp.

[4.2] SKIRROW, R., JAIRETH, S., HUSTON, D., BASTRAKOV, E., SCHOFIELD, A., VAN DER WIELEN, S., BARNICOAT, A., Uranium Mineral Systems: Processes, Exploration Criteria and a New Deposit Framework, Geoscience Australia Record **20** (2009) 1–57.

[4.3] CUNEY, M., KYSER, K., Geology and Geochemistry of Uranium and Thorium Deposits, Mineralogical Association of Canada (2015) 345 pp., https://doi.org/10.1007/s00126-016-0681-9

[4.4] BRUCE, M., KREUZER, O., WILDE, A., BUCKINGHAM, A., BUTERA, K., BIERLEIN, F., Unconformity-type uranium systems: a comparative review and predictive modelling of critical genetic factors, Minerals **10** (2020) 738, https://doi.org/10.3390/min10090738

[4.5] CUNEY, M., Felsic magmatism and uranium deposits, Bulletin de la Société Géologique de France **185** 2 (2014) 75–92, https://doi.org/10.2113/gssgfbull.185.2.75

[4.6] BEYER, S., HIATT , E., KYSER, K., DREVER, G., MARLATT, J., Stratigraphy, diagenesis and geological evolution of the Paleoproterozoic Roraima Basin, Guyana: links to tectonic events on the Amazon Craton and assessment for uranium mineralization potential, Precambrian Research **267** (2015) 227–249, https://doi.org/10.1016/j.precamres.2015.06.017.

[4.7] MCCUAIG, T. CARSELLI, S., O'CONNOR, T., BUSUTTIL, S., MCCORMACK, N., The Power of a Systems Approach to Mineral and Petroleum Exploration in Sedimentary Basins (2018), https://doi.org/10.5382/SP.21.03

[4.8] INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium Extraction Technology, Technical Report Series No. 359, IAEA, Vienna (1993).

[4.9] GILLIGAN, R., NIKOLOSKI, A., The extraction of uranium from brannerite: a review, Minerals Engineering **71** (2015) 34–48, https://doi.org/10.1016/j.mineng.2014.10.007

[4.10] SOPUCK, V., DE CARLA, A., WRAY, E., COOPER, B., The application of lithogeochemistry in the search for unconformity-type uranium deposits, Northern Saskatchewan, Canada, Developments in Economic Geology **17** (1984) 77–99, https://doi.org/10.1016/B978-0-444-42268-2.50011-4

[4.11] JEFFERSON, C., THOMAS, D., GANDHI, S., RAMAEKERS, P., DELANEY, G., BRISBIN, D., OLSON, R., Unconformity-associated uranium deposits of the Athabasca Basin, Saskatchewan and Alberta, Bulletin of the Geological Survey of Canada **588** (2007) 23–67.

[4.12] ZHANG, G., WASYLIUK, K., PAN, Y., The characterization and quantitative analysis of clay minerals in the Athabasca Basin, Saskatchewan: application of shortwave infrared reflectance spectroscopy, The Canadian Mineralogist **39** 5 (2001)1347–1363, https://doi.org/10.2113/gscanmin.39.5.1347

[4.13] RICHARD, A., ROZSYPAL, C., MERCADIER, J., BANKS, D., CUNEY, M., BOIRON, M., CATHELINEAU, M., Giant uranium deposits formed from exceptionally uranium-rich acidic brines, Nature Geoscience **5** 2 (2012) 142–146, https://doi.org/10.1038/ngeo1338

[4.14] MARTZ, P., CATHELINEAU, M., MERCADIER, J., BOIRON, M. C., JAGUIN, J., TARANTOLA, A., LEDRU, P., C-O-H-N fluids circulations and graphite precipitation in reactivated Hudsonian shear zones during basement uplift of the Wollaston-Mudjatik transition zone: example of the Cigar Lake U deposit, Lithos **294** (2017) 222–245, https://doi.org/10.1016/j.lithos.2017.10.001

[4.15] RABIEI, M., CHI, G., POTTER, E. G., PETTS, D. C., WANG, F., FENG, R., Spatial variations in fluid composition along structures hosting unconformity-related uranium deposits in the Athabasca Basin, Canada: implications for ore-controlling factors, Mineralium Deposita **58** (2023) 1075–1099, https://doi.org/10.1007/s00126-023-01171-1

[4.16] CAMERON, E. M., Geochemical exploration for uranium in northern lakes, Journal of Geochemical Exploration **13** 2–3 (1980) 221–250, https://doi.org/10.1016/0375-6742(80)90008-4

[4.17] ROBINSON, S., JEFFERSON, C., PAULEN, R., LAYTON-MATTHEWS, D., JOY, B., QUIRT, D., Till and bedrock heavy mineral signatures of the Kiggavik uranium deposits, Nunavut, Open File 7771, Geological Survey of Canada (2016) 70 pp, https://doi.org/10.4095/297563

[4.18] KYSER, K., Exploration for uranium, Uranium for Nuclear Power (2016), 53–76, https://doi.org/10.1016/B978-0-08-100307-7.00003-X

[4.19] INTERNATIONAL ATOMIC ENERGY AGENCY, Unconformity-related Uranium Deposits, IAEA-TECDOC-1857, IAEA, Vienna (2018) 299 pp.

[4.20] BALARAM, V., SAWANTS, S., Indicator minerals, pathfinder elements, and portable analytical instruments in mineral exploration studies, Minerals **12** 4 (2022) 394, https://doi.org/10.3390/min12040394

[4.21] KYSER K., BARR J., CHRISTIAN IHLENFELD C., Applied Geochemistry in Mineral Exploration and Mining, Elements **11** 4 (2015) 241–246,

[4.22] COHEN, D. R., KELLEY, D. L., ANAND, R., COKER, W. B., Major advances in Exploration Geochemistry 1998–2007, Geochemistry: Exploration, Environment, Analysis **10** 1 (2010) 3–16, https://doi.org/10.1144/1467-7873/09-215

[4.23] PLANT, J., SIMPSON, P., SMITH, B., WINDLEY, B.F., "Uranium ore deposits - Products of the radioactive earth", Uranium: Mineralogy, Geochemistry and the Environment, Vol.38 (BURNS, P.C., FINCH, R., Eds.), Mineralogical Society of America (1999) Ch. 6.

[4.24] KYSER, K. and CUNEY, M., Recent and not-so-recent developments in uranium deposits and implications for exploration. Mineralogical Association Canada, Short Course Series. (2008).

[4.25] HOLK G., KYSER, T.K., HIATT, E., MARLATT, J., Mobile Pb-isotopes in Proterozoic sedimentary basins as guides for exploration of uranium deposits, Journal of Geochemical Exploration **80** 2–3 (2003) 297–320, https://doi.org/10.1016/S0375-6742(03)00196-1

[4.26] QUIRT, D., BENEDICTO, A., Lead isotopes in exploration for basement-hosted structurally controlled unconformity-related uranium deposits: Kiggavik project (Nunavut, Canada), Minerals **10** 512 (2020), https://doi.org/10.3390/min10060512

[4.27] INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium Biogeochemistry: A Bibliography and Report on the State of the Art, IAEA-TECDOC-327, IAEA, Vienna (1985) 83 pp.

[4.28] DUNN, C., New perspectives on biogeochemical exploration (Proc. Exploration 07': 5th Decennial International Conf. on Mineral Exploration, 2007), Association of Applied Geochemists, Toronto (2007).

[4.29] HILL, S.M., HORE, S.B., NORMINGTON V.J., Uranium in animals, vegetables and minerals: landscape geochemical and biogeochemical expressions of the Four Mile West sedimentary uranium deposit, South Australia, Austral. J. Earth Sci **67** (2020) 1161–1194, https://doi.org/10.1080/08120099.2020.1812717

[4.30] DICKSON, B., GIBLIN. A., Effective exploration for uranium in South Australian palaeochannels, Applied Earth Science **116** (2006) 50–54.

[4.31] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Airborne and Ground Geophysical Methods for Uranium Exploration, Nuclear Energy Series NF-T-1.5, IAEA, Vienna (2013) 58 pp.

[4.32] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioelement Mapping, IAEA Nuclear Energy Series No. NF-T-1.3, IAEA, Vienna (2010) 110 pp.

[4.33] US GEOLOGICAL SURVEY, Aerodiometric Map Image Thumbnails (1999), https://pubs.usgs.gov/of/1999/ofr-99-0016/view_maps.html

[4.34] POUDJOM DJOMANI, Y., MINTY B.R.S., Radiometric Grid of Australia (Radmap) v4 ratio uranium squared over thorium, Geoscience Australia (2019), http://dx.doi.org/10.26186/5dd4926ec026e

[4.35] DEVINE, M., HATTORI, K., KOTZER, T., CORNETT, J., The Dispersion of Radon Above Deeply Buried Uranium Ore: Millennium Deposit, Athabasca Basin, SK, CMIC-NSERC Exploration Footprints Research Network (2014).

[4.36] CANADIAN INSTITUTE OF MINING, METALLURGY AND PETROLEUM (CIM), CIM Estimation Best Practice Committee (2003), https://mrmr.cim.org/media/1040/best-practices-in-uranium-estimation-guidelines.pdf

[4.37] NIYA G. GROZEVA, J. R., BEAUCAIRE, C., DESCOSTES, M., Reactive transport modelling of U and Ra mobility in roll-front uranium deposits: Parameters influencing $^{226}Ra/^{238}U$ disequilibria, Journal of Geochemical Exploration **236** (2022) 106961, https://doi.org/10.1016/j.gexplo.2022.106961

[4.38] AMES, C., QUINN, D., ROSS, A., PENNEY, R., Disequilibrium in uranium deposits and direct measurement of uranium in wireline logging using prompt fission neutron technology, AusIMM Bulletin **3** (2012) 27–28.

[4.39] ROY, R., BENEDICTO, A., GRARE, A., BÉHAEGEL, M., RICHARD, Y., HARRISON, G., Three-dimensional gravity modelling applied to the exploration of uranium unconformity-related basement-hosted deposits: the contact prospect case study, Kiggavik, northeast Thelonregion (Nunavut, Canada), Can. J. Earth Sci. **54** (2017) 869–882.

[4.40] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantitative and Spatial Evaluations of Undiscovered Uranium Resources, IAEA-TECDOC-1861, IAEA, Vienna (2018).

Chapter 5. GUIDELINES FOR SYSTEMATIC URANIUM EXPLORATION USING THE STAGE-GATE APPROACH

5.1 OVERVIEW OF THE STAGE GATE APPROACH

The objective of uranium exploration is the discovery of a uranium deposit that can be developed and exploited in an economically viable, sustainable, and socially acceptable manner. It is advised that exploration follows a systematic and phased approach using key criteria and decisions analogues to climb a set of defined steps or progressively opening a series of gates, hence the term 'stage-gate approach'.

There are five main uranium exploration phases which are depicted as a pyramid in Fig. 5.1 and outlined in Table 5.1. The pyramid layers reflect the changes in exploration area and scale. The first phase, planning and area selection is conducted at a broad regional or even country scale depicted at the base of the pyramid. Whereas the fifth and final phase consists of advanced exploration focused on deposit studies and is depicted towards the top of the pyramid. After the final phase of exploration, an investment decision is required to develop a mine based on the outcomes of a Feasibility Study to confirm the economic viability. In very simple terms progressing through the phases involves increasingly detailed work and is like navigating to the right neighbourhood, street, house and then to a room. Planning, exploration strategy and operational aspects are uniformly pertinent to all exploration phases but are initiated during the first phase of exploration.

The progression of exploration phases involves increasingly more detailed evaluations using a variety of geological, geophysical, remote sensing, geochemical methods. The application of these methods is based on observable features of specific uranium types that might be present. Generally, a large number of anomalies are generated by the first phases of exploration activities, which leads to targets with the objective of identifying promising prospects in the middle phases which are progressively tested by drilling and/or trenching in order to discover a deposit.

During each exploration phase, a decision to proceed to the next phase is required, which is shown on the right-hand side of the pyramid between the exploration phase layers (Fig. 5.1). This can be envisioned as a series of gates which open and close depending on the results that has been achieved. Once key criteria are reached, a decision is made to proceed through the gate to the next exploration phase, or undertake further work, or to relinquish the exploration area. The first gate opens if favourable areas are identified for exploration. The next gates open if viable anomalies and high-grade intercepts are located through reconnaissance and follow-up exploration, respectively. Technical and economic studies become more important in the detailed and advanced exploration/deposit studies phases, and the outcome of a Preliminary Economic Assessment (Scoping Study) typically determines whether the gate opens or closes at the end of the detailed exploration phase. In practice, the phase approach should be used to guide exploration strategy, and different exploration areas and individual targets may be simultaneously at different phases of exploration within an exploration programme.

Anomalies and targets may be readily generated, however, there is a low probability of these progressing to a discovery and subsequently mined. The exploration process may take 15–20 years or longer and so should be approached as a long-term endeavour. For example, it has been estimated that only one in every 1000 conceptual drill hole targets in the Athabasca Basin in Canada is successful despite the region's high uranium endowment and relative maturity [5.1]. Exploration organizations should constantly seek ways to determine the investment worth of exploration by managing risk versus reward and exploration investment versus long-term mining profit. To combat this, it is common for exploration to be conducted over large areas and desirable to have both early and late-stage exploration opportunities in the exploration portfolio. Strategies may also be based on applying new understandings of ore-forming processes and leveraging innovative technology. These niche strategies may be seen as an advantage over competing exploration organizations to fast-track the road to discovery.

Exploration management may be viewed as a cycle as depicted in Fig. 5.2 [5.2]. As the exploration knowledge progresses, new knowledge and insights inform modifications to the approach or selecting new areas. Successful discovery may provide the funding and motivation for further exploration investment. Central to successful exploration management are operational drivers including permitting, jurisdiction policies, community favour, uranium supply and demand, personnel, data and field protocols along with systems, and logistics support and planning.

It is important to note that exploration phases may not automatically or sequentially follow each other. Exploration planning and area selection can be followed by any kind of exploration phase (reconnaissance, follow-up, detailed, or even advanced exploration) depending on the maturity of exploration areas and exploration strategy of the exploration organization. Management-related aspects are highly relevant and should be considered in detail during exploration planning for all phases. A review of the existing data and historical information in a country can result in the identification of new prospective areas with uranium potential, and lead to reconnaissance-type exploration (phase 2). In contrast, exploration planning can be directly followed by advanced exploration (phase 5) if a sufficient knowledge base is already established in an area through previous detailed work, such as drilling, or even resource definition. For example, a national or state geological survey organization might have previously conducted reconnaissance-style exploration, comprehensive regional field investigations and ground checks of airborne radiometric anomalies in a selected area in the past. In this case, there is no need to repeat the previous surveys in the same exploration areas if promising uranium anomalies have been already generated and delineated by other organizations during historical reconnaissance-type exploration. Therefore, in this case an exploration organization may move from the planning phase to follow-up exploration (phase 3), skipping reconnaissance-style exploration (phase 2). However, preliminary geological field visits and terrain assessments are always advised during the exploration planning phase before starting the actual field work.

5.2 PHASE 1 – EXPLORATION PLANNING AND AREA SELECTION

Discovery success and development of economic uranium deposits are largely dependent on a suitable and effective operational and technical framework implemented by well-defined exploration strategies, selection of the most relevant uranium deposit models and appropriate exploration techniques. The probability of economic discovery can be increased through consistent long-term funding, adequate human and technical resources, specialist uranium geology expertise, careful project planning and area selection, and effective project management. These all commence during the first phase of a uranium exploration project culminating in the identification of an area for exploration to be undertaken. The exploration planning and selection stage is sometimes known as the preparatory stage and project generation stage. This includes research and review of existing data to identify prospective areas, often referred to as desktop studies.

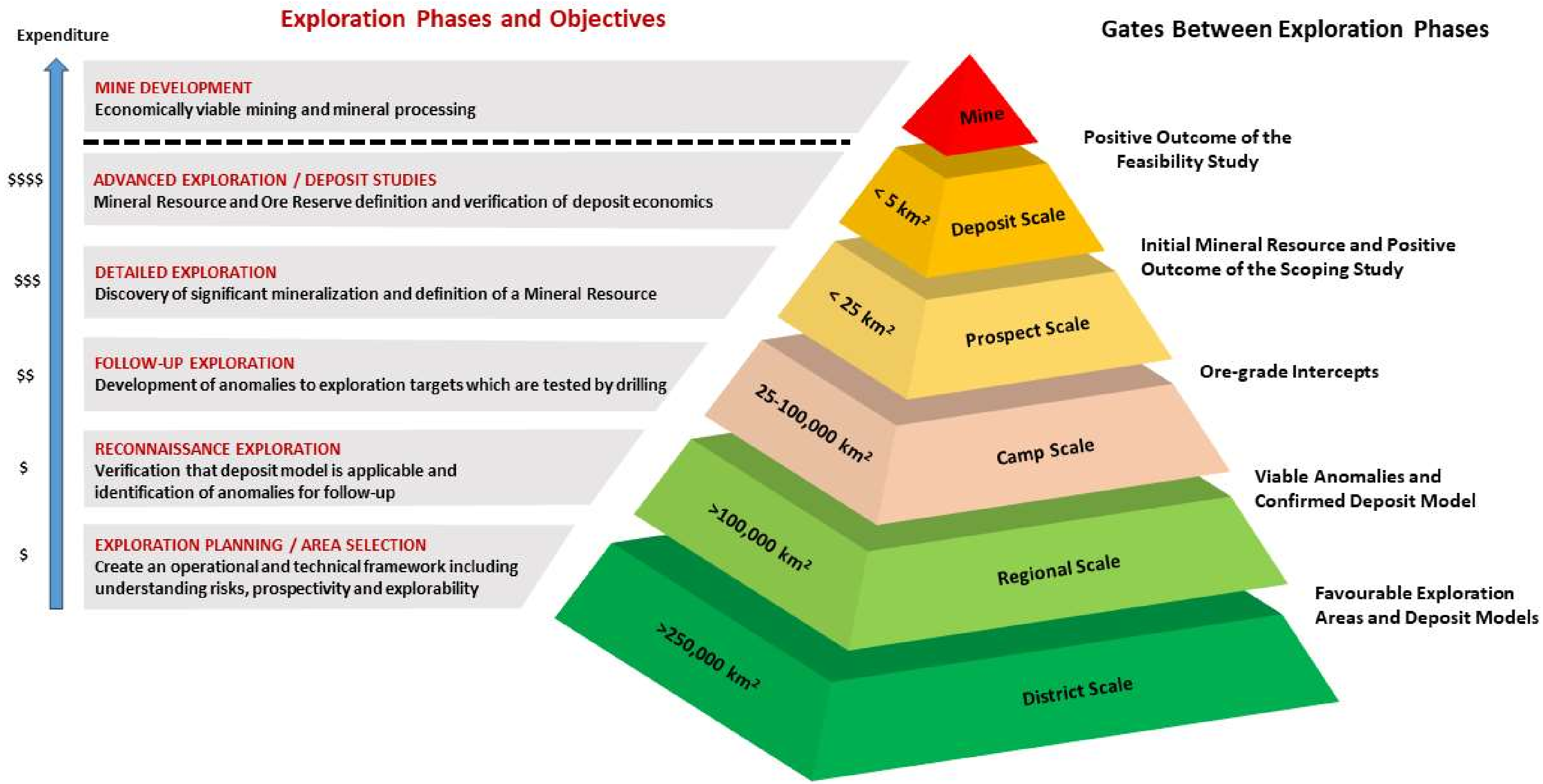

FIG. 5.1. Simplified illustration of the stage-gate approach showing the main exploration phases, their objectives, and gates between exploration phases.

TABLE 5.1. MAIN OBJECTIVES AND TYPICAL ACTIVITIES OF EACH EXPLORATION PHASE, AND STAGE GATES BETWEEN THE EXPLORATION PHASES

Exploration Phase	Main Objectives	Typical Activities
Exploration Planning and Area Selection	To understand exploration risks, prospectivity and explorability, to select prospective exploration areas, to complete field assessments, and to generate uranium exploration projects.	Desktop assessments of prospectivity and explorability, selection of deposit model, area selection, selection of exploration methods, budgeting, scheduling and quality planning.
Stage Gate: prospective areas and deposit models selected		
Reconnaissance Exploration	To confirm that the deposit model is applicable and to identify anomalies and prospects for follow-up uranium exploration.	Regional-scale airborne geophysical surveying, remote sensing, geological mapping, ground follow-up of aeroradiometric anomalies, ground radiometric surveying, geochemical bedrock sampling and soil sampling.
Stage Gate: viable anomalies identified and the applicable deposit model confirmed		
Follow-up Exploration	To identify positive indicators of mineralizing systems, to locate uranium mineralization, and to identify promising targets for detailed uranium exploration.	Camp-scale geological mapping, ground geophysical surveying, radon surveying, sampling, trenching, drilling with a sparse drill hole spacing, geochemical assaying, geological modelling and mineralogical characterization.
Stage Gate: promising targets identified and high-grade mineralized intervals intercepted		
Detailed Exploration	To identify significant uranium mineralization, to define Mineral Resources, to obtain information on the recovery of uranium from its hosting minerals, and to understand deposit's likeliness of economic success or failure at very high levels.	Prospect-scale geological and geophysical surveying, intensive drilling with a dense drill hole spacing, downhole radiometric probing, sampling, geochemical assaying, bulk density measurements, Mineral Resource estimation (typically Inferred Resources), mineralogical characterization, metallurgical test work, and the completion of the Preliminary Economic Assessment (Scoping Study).
Stage Gate: economic viability of the uranium deposit understood at very high levels based on the positive outcome of the Scoping Study		

TABLE 5.1. (cont.) MAIN OBJECTIVES AND TYPICAL ACTIVITIES OF EACH EXPLORATION PHASE, AND STAGE GATES BETWEEN THE EXPLORATION PHASES

Exploration Phase	Main Objectives	Typical Activities
Advanced Exploration/ Deposit Studies	To increase the levels of geological and metallurgical knowledge, to define Mineral Resources at the high confidence levels, to develop metallurgical flowsheet, to develop Ore Reserves, and to understand economic viability of the deposit.	Deposit-scale dense grid drilling, downhole radiometric probing, sampling, geochemical assaying, bulk density measurements, Mineral Resource estimation (upgrading of the Inferred Resources to the Indicated and Measured Resources), bulk sampling, metallurgical flowsheet development, pilot metallurgical testing, development of Ore Reserves, Pre-Feasibility Study, infrastructure investigations, environmental impact assessment, mining planning, geotechnical tests, evaluation of the capital and operating costs, reclamation plan, project infrastructure, and the completion of the final economic assessment (Feasibility Study).
Stage Gate: economic viability of the exploitation of the uranium deposit confirmed based on the positive outcome of the Feasibility Study		
Mine Development	To start mining and mineral processing to extract uranium from the deposit in an economically viable, environmentally sustainable and socially acceptable manner with the ultimate objective to produce uranium concentrate to the global uranium market.	Development of the mine, mine design, procurement, engineering work, construction of the mine, processing plant and tailings management facility, testing, and commissioning of uranium production.

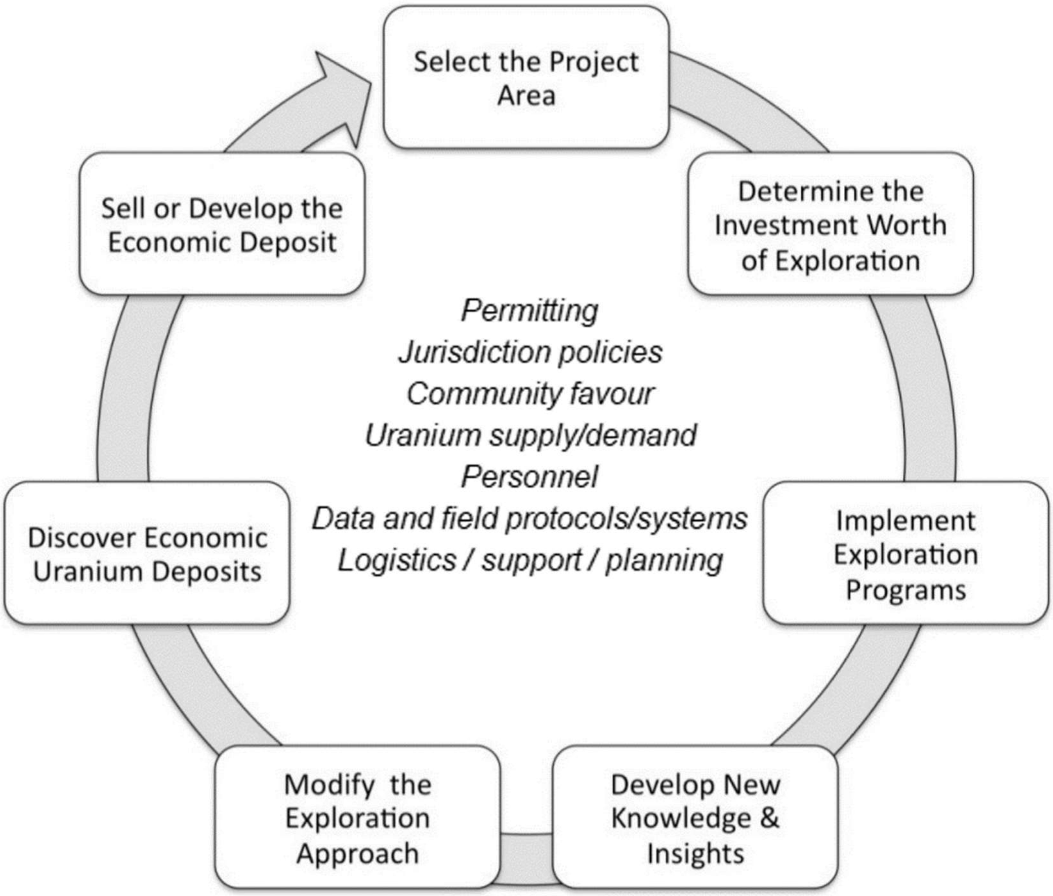

FIG. 5.2. The exploration programme management cycle (Reproduced from IAEA Ref. [5.2]).

An exploration organization should pay special attention to legal, regulatory, political, social, economic, and environmental aspects during the exploration planning and area selection phase. Additionally, a variety of prearrangements are required, such as the preparation of a data management plan, acquisition of exploration licenses, and setting up a camp, offices, and other exploration infrastructure. It is advised that exploration planning follows a systematic approach using key steps as depicted in Fig. 5.3. In practice, some of these individual planning tasks may be carried out simultaneously, such as the preparation of standard operating procedures and the development of the health, safety and environmental protection programme.

It is important that all management-related aspects, such as health and safety, data management, and quality control, are considered and planned in a comprehensive and detailed manner during the planning stage. These aspects should be planned during the first phase and updated as required since they are important in all operational phases from reconnaissance exploration to mine development. For example, initial budget and schedule are established during the first phase, but they are actively updated over the course of the exploration project as an integral part of exploration project management.

The main objective of the exploration planning and area selection phase is to achieve a good understanding of the exploration risks, prospectivity and explorability before starting actual exploration work in the field (Fig. 5.1 and Table 5.1). The desired outcome of this first phase is to ensure that prospective and favourable areas have been selected based on applicable deposit models, and that the exploration programme with suitable exploration methods has been developed. Exploration planning should include definition of all relevant management-related tasks including the roles and responsibilities in the implementation of the uranium exploration project. Prior to commencement of the actual field work, the exploration organization should also ensure that all risks have been evaluated and that sufficient risk management plans are in place. This is highly relevant to ensure that the uranium exploration project will be carried out in a safe, environmentally friendly, and socially acceptable manner so that the risks to worker and community health, and potential for environmental damage will be minimized throughout the exploration project.

Planning is part of all phases in exploration and should always include the assessment of country specific factors, prospectivity and explorability, review of existing data, and data management and quality control planning. It should be noted that a national, large exploration programme may include several subprojects (or subareas) undergoing various exploration phases depending on the maturity of individual areas, prospects, and deposits. To ensure consistency and good practices, such as health and safety, quality control and data management aspects amongst subprojects, planning should always cover the same aspects in a consistent manner.

Insufficient planning can result in a variety of challenges which are difficult to correct over the course of the exploration programme when the field work has already started. Therefore, management of all aspects such as explorability, policy factors, occupational health, data management, and quality planning should be an integral part of exploration planning as they are highly relevant for all the other exploration phases (i.e., reconnaissance, follow-up, detailed, advanced).

The first exploration phase consists of the broad categories depicted in Fig. 5.4. In practice, these aspects and sub-components are interrelated. Before progressing to the field work, the exploration organization should have a strategy to explore for specific uranium styles in specific regions of interest using an understanding of the targeted uranium deposit models.

5.2.1 Definition of the ownership of a uranium exploration project

Before starting exploration planning and area selection in detail, a Member State country needs to establish a clear policy regarding the ownership of a uranium exploration project. The project owner can be a national or state geological survey, a government-owned company, a government agency, a joint venture between a private and a government-owned organization, or a private uranium exploration company. The national policy may define uranium as a strategic commodity under exclusive national ownership [5.3]. In this case, only the government and its agencies are allowed to carry out uranium exploration and develop uranium deposits into production. In contrast, uranium may be considered in the national policy of a country as a commodity that can be explored by non-government (i.e., privately controlled) companies and this may even allow exploration companies from other countries to operate in the country. In either case, the Member State country should also have exploration and mining regulations with a clear path to mining in place before committing to exploration.

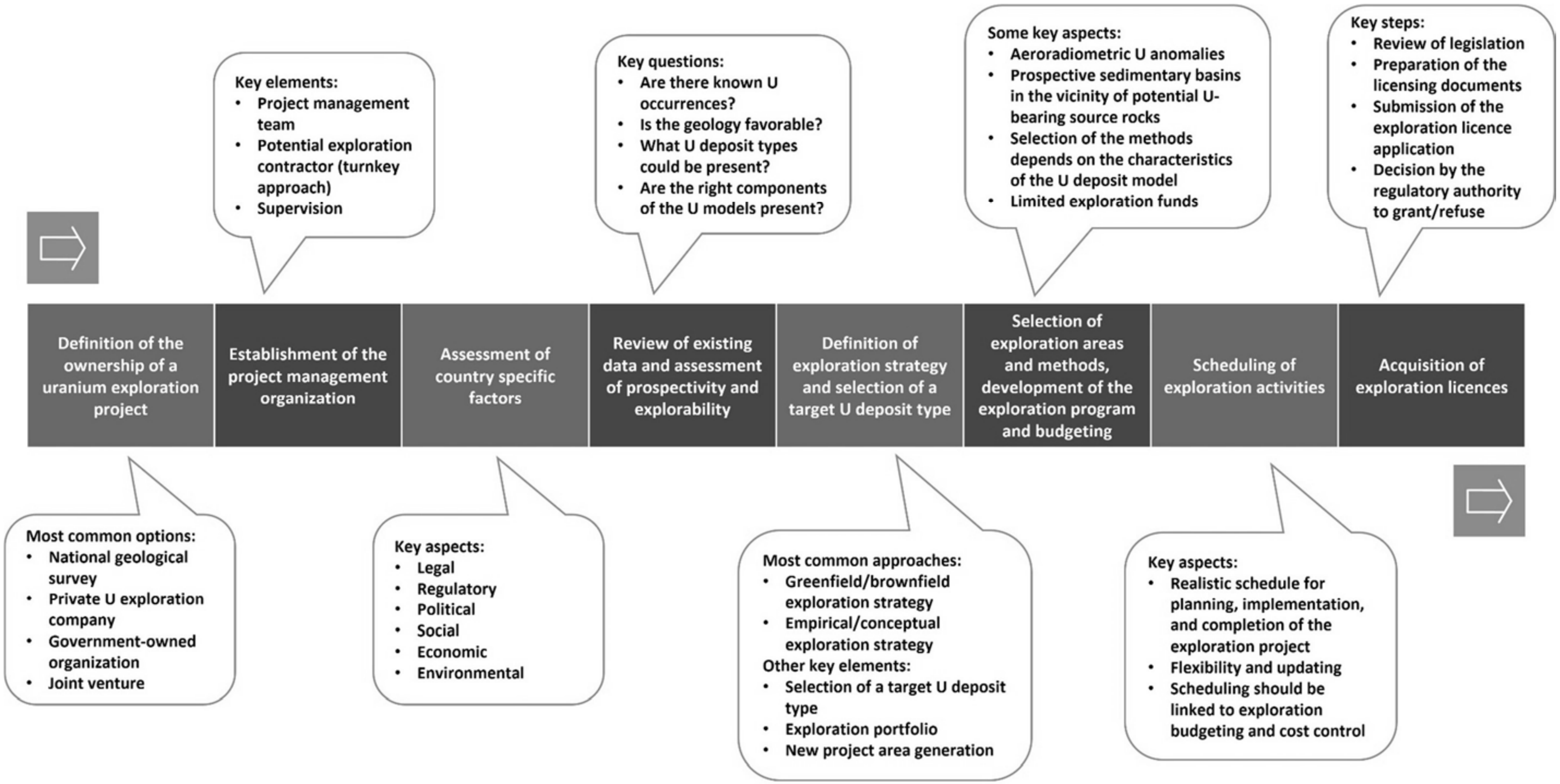

FIG. 5.3. Systematic approach to exploration planning.

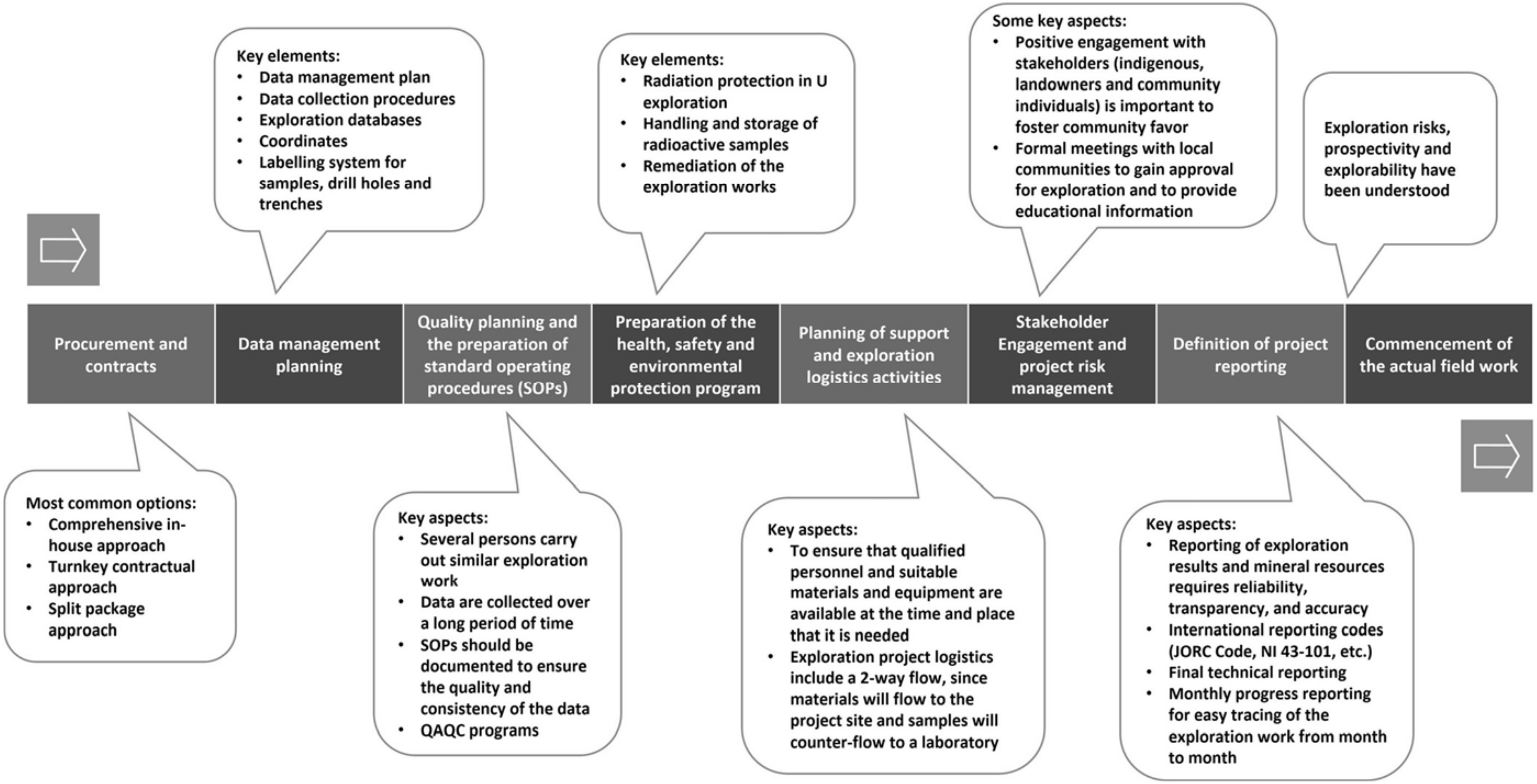

FIG. 5.3.(cont.) Systematic approach to exploration planning.

FIG. 5.4. Components of the exploration planning phase.

The project owner should have the leading role in project management and overall responsibility for the project in all exploration phases. The project owner will be responsible for budgeting, contractual items, procurement procedures, continuous planning, scheduling, cost control, risk management, information management, project communication, project implementation, supervision of quality control, and assessment of necessary changes, potentially supported by its contractors. All field and analytical work, technical studies and data management in an exploration project ought to be carried out under the supervision of the project owner. Typically, this exploration management organization (the project owner) is also the applicant for the exploration licenses and becomes the licensee of the exploration areas (see Section 5.2.8).

5.2.2 Establishment of the project management organization

The definition of the ownership of a uranium exploration project is usually followed by the establishment of the project management organization at the start of the planning phase. Proper project management is of crucial importance for implementing a successful uranium exploration project in a scientific and structured way with the goal to locate and define economically viable uranium deposits in a quick and cost-effective manner. Therefore, roles and responsibilities of project management in the planning and implementation of the uranium exploration project ought to be clear and well-defined.

It is important that the exploration management organization has sufficient geoscientific and technical expertise to support a uranium exploration programme. Moreover, efficient project management is needed to integrate all relevant disciplines (such as geology, geophysics, geochemistry) and existing data to identify and test exploration targets. All exploration work should be planned and carried out under the supervision of geoscientists who will be responsible for planning, implementation, and interpretation of all exploration activity in a uranium exploration project [5.4]. These geoscientists should be qualified by training and through experience in managing exploration projects to ensure that the exploration work is carried out using appropriate techniques and procedures. All technical information for an exploration project ought to be obtained under a formal quality assurance and quality control (QAQC) programme and reported under the supervision of the foregoing geoscientists.

5.2.2.1 Project management team

One of the very first tasks of the project owner is to establish the project management organization by appointing the project management team. Depending on the project, the size of the exploration organization may differ substantially, and in many organizations the project management team will be small and one person may carry out several roles within the team.

Figure 5.5 shows an example of an organizational structure for the project management team of an exploration organization. The project owner should appoint a single representative as its project manager because project management is a critical task that typically requires the full-time commitment by one person who concentrates exclusively on project management of the exploration project. In addition, it is advised to appoint a deputy for the project manager. The responsibility of the deputy project manager is to assist the project manager in managerial tasks, and to deputize for the project manager in their absence, such as annual leave and sickness leave, by taking over all managerial aspects of the uranium exploration project.

The project manager should understand the managerial, logistical, and administrative aspects of the uranium exploration project. The project management team, exploration team members and contractors should be made fully aware of their tasks, roles and responsibilities, and of the exploration services and equipment they are expected to provide [5.5]. The project manager should possess a variety of project management skills, such as leadership skills, planning, scheduling, organization, human relations and motivation, occupational safety, and quality control skills.

The project manager is responsible for administrative tasks and is typically an employee of the project owner or is outsourced using an expert who has experience in the management of exploration programmes and assessment of the investment worth of uranium exploration projects. The project manager should be experienced with uranium exploration in general and should be able to quickly recognize any potential problems and communicate them within the project owner organization. If readily available, the project manager can consider using project management software to plan and schedule all work items related to exploration field work, technical studies, analytical work, and project meetings.

The project manager decides how to best manage a uranium exploration project, and how risks, technical quality, schedule, and costs are controlled. The project manager ought to oversee each phase of a uranium exploration project from beginning to end to ensure that all tasks are completed correctly, on time and within budget. The project manager should actively communicate with the project management team, exploration team members, contractors and project owner's senior management. The key responsibilities of the project manager are monitoring of the exploration budget, solving any problems that occur during the exploration programme, and organizing the project meetings. Typical tasks include budgeting, scheduling, logistics management, camp management, supply chain management, contractor management, health and safety regulations, security, transportation, storage and handling of radioactive samples, land use, and indigenous rights [5.4].

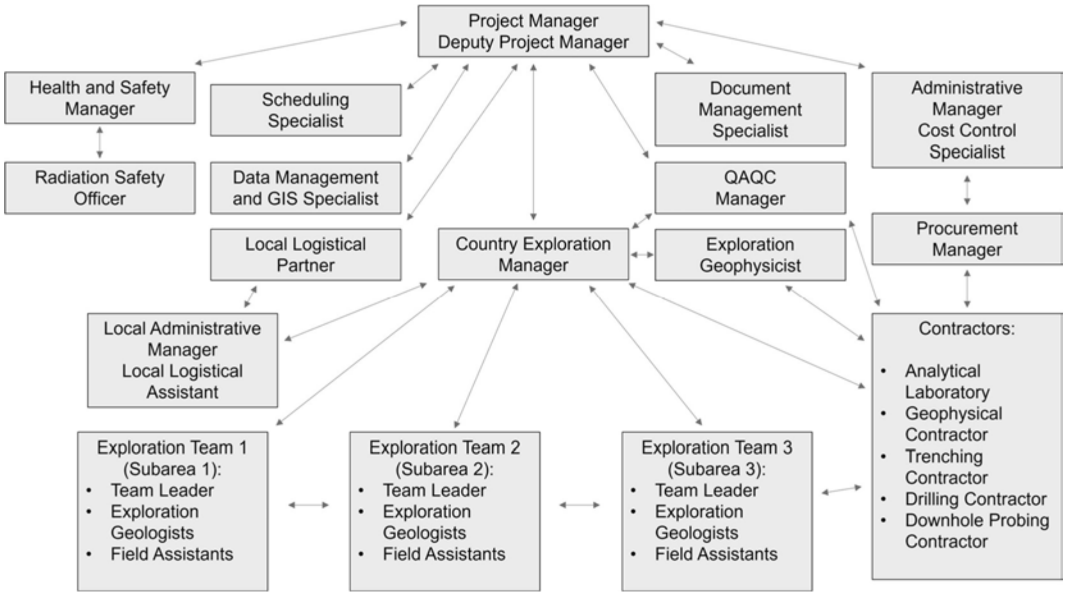

FIG. 5.5. Example of an organizational structure for the project management team of a large uranium exploration project which involves three subprojects (subareas).

The project manager might not be solely responsible for administrative tasks. Instead, the project manager and the deputy project manager can be supported by the administrative manager who takes over a major part of the administrative tasks, such as contractual items, procurement, invoicing, scheduling, cost control, information management and project communication. Involvement of a separate administrative manager enables the project manager to concentrate more on technical items, such as technical quality, staff selection, quality control, selection of exploration contractors, organizing and chairing the project meetings, and solving any problems that might be encountered during the project. In large national or state uranium exploration programmes, the project manager, deputy project manager and administrative manager can be supported by a variety of other management professionals, and these can include such positions as a procurement manager, cost control specialist, scheduling specialist, document management specialist, administrative assistant, legal expert, data management specialist, health and safety manager, and radiation safety officer (Fig. 5.5). Some of these tasks may be outsourced, such as a legal expert related to a requirement for legal consultation with respect to contracts, exploration licensing requirements, transferring mineral rights, transactions, establishing potential strategic joint ventures, and meeting regulatory terms.

5.2.2.2 Exploration contractors

The project owner might not conduct its own exploration work. Instead, it can retain a separate exploration contractor to provide exploration services for a project. If exploration results, mineral resources or ore reserves will be reported in accordance with a national/regional reporting code or standard (such as the Joint Ore Reserves Committee (JORC) Code, or National Instrument (NI) 43–101 [5.4., 5.6], an exploration contractor ought to provide its own Competent Person[1]

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[1] A Competent Person (known as a Qualified Person in Canada) is a minerals industry professional, who is a member or fellow of a National Reporting Organization, or of a Professional Organization , or of a Recognized Professional Organization with enforceable disciplinary processes including the powers to suspend or expel a member. A Competent Person should have a minimum of five years relevant experience in the style of mineralization or type of deposit under consideration and in the activity which that person is undertaking [5.6].

for a project. If several exploration contractors are retained, each of these contractors should provide its own Competent Person. In this case, the field work programme can be broken down into individual projects, each to be managed by a Competent Person of an exploration contractor. This would be beneficial from an exploration management perspective because a large national exploration programme can include a variety of different uranium deposit types. The distribution of different exploration areas amongst exploration contractors according to deposit types would also be in line with the guiding principles of the reporting codes and standards because a Competent Person should have a relevant experience in the style of mineralization and the deposit type in the activity which that person is undertaking and reporting [5.6].

If a separate exploration contractor will be retained by the project owner to provide all exploration services (i.e. a turnkey contract) for a project, the exploration contractor should accept the entire responsibility for the continuous exploration planning, implementation of the exploration work, drilling programme, the quality of the data, resource estimation, and reporting of exploration results, mineral resources and ore reserves even if some of these exploration activities are provided by its subcontractors.

Even for turnkey exploration service contracts, the project owner should establish efficient protocols for verifying the quality of the exploration work, sampling, analytical data, resource modelling, and reporting. This data verification can be done by constantly monitoring the performance of the exploration contractor through the review of the contractor's monthly progress reports (see Section 5.2.11), site visits, project meetings, spot check reviews of quality control data, and mineral resource audits. These reviews and audits can be conducted by the project owner itself, or by an independent, third-party contractor, such as a supervising contractor.

5.2.2.3 Supervision of a uranium exploration project

The project owner might not supervise field work, exploration procedures and mineral resource estimation by itself. Instead, it may retain a separate supervising contractor to assist it in supervising the quality control items, and to provide technical advisory for an exploration project. This kind of supervision can substantially increase confidence that the selected exploration contractors will collect accurate and reliable data. For example, a supervising contractor can assess and manage the risk of potential incorrect definition and reporting of mineral resources. In addition, a supervising contractor can provide the project owner with other advisory services, such as support for the uranium geology and exploration project management. In these instances, the project owner should make final decisions on exploration activities after completion of the review process by its supervising contractor.

Large national and state uranium exploration programmes may include a number of project areas and several subcontractors, and an exploration programme can benefit greatly from independent third-party review and quality control by a supervising contractor regarding the data collection, quality control monitoring and reporting to comply with industry good practices, and with reporting codes and standards (such as the JORC Code and NI 43–101). The role of a supervising contractor would be therefore to act as a quality control auditor in respect to how the uranium exploration project is executed and how results are reported, and may include the following tasks:

- Monitoring and review of exploration techniques and QAQC procedures to ensure compliance with industry good practices;
- Review of reporting to ensure compliance with a national/regional reporting code or standard (such as the JORC Code and NI 43–101);

— Review of data acquisition, data management and analytical procedures;
— Independent audit of any mineral resource estimates and ore reserve definitions completed in the project.

If a separate supervising contractor will be retained by the project owner, it will be important to ensure prompt implementation of corrective actions as advised by the supervising contractor. In this case, exploration contractors should not be allowed to apply their own preferred practices if such practices do not meet the objectives and interests of the project owner. It is therefore important that exploration contractors follow the advice of the supervising contractor to improve outcomes. Exploration contractors should not solely make major decisions on how to operate in the field. Instead, it ought to be the project owner who makes the major decisions in close cooperation with its contractors.

5.2.3 Assessment of country specific factors

The choice of country, or a region within a country (such as a province or state) for uranium exploration is one of the most important steps during the planning phase. The assessment of country specific factors and other risks is an integral milestone in the progression of an exploration project. It is a means for the project owner to evaluate, at very high levels, a project's likeliness of success in respect to a policy environment. Skipping this stage of evaluation may unnecessarily burden the exploration organization with the costs of starting exploration projects when such costs may not be warranted if policy factors are not favourable and predictable.

Economic considerations, geological aspects, and the potential for economic uranium deposits (prospectivity) are key factors in uranium exploration. In addition, policy of a country or jurisdiction region (such as province or state) is an important investment consideration. Prior to an exploration investment decision, all potential political, social, environmental, and economic risks associated with future mine development should be identified and clearly understood. Therefore, one of the first steps that the project owner should take is to assess all policy factors that affect investment decisions. Approximately 40% of mining companies' investment decisions are determined by policy factors [5.7]. These policy factors include taxation regime, regulatory environment (such as environmental and labour regulations), the legal system and jurisdiction policy, availability of land, infrastructure, socioeconomic conditions, trade barriers, political stability, the risk of nationalization, quality of the geological databases, security, supply of services, and labour and skills availability. Other factors that either encourage or discourage uranium exploration investment include prevailing uranium prices, foreseeable uranium market outlook (uranium supply and demand relationship), availability of funding, location of project areas, and the potential social and environmental impact of future uranium mining operations.

As a result of the assessment of country specific factors, the exploration organization should be ready to answer the following question: is there a reasonable chance that if uranium were found, it could be mined? If the exploration organization is sufficiently confident that the policy environment and regulatory environment are favourable in terms of exploration investment attractiveness, the organization may proceed to the next phase which is the compilation and review of existing geoscientific data to select areas for uranium exploration.

5.2.4 Review of existing data and assessment of prospectivity and explorability

One of the most rapid and cost-effective ways to identify prospective areas for uranium exploration is to use existing data. The review of existing geoscientific data will help an exploration team to gain a better understanding of the regional geology and structural architecture, identify radiometric anomalies and potential gaps in the knowledge base, generate exploration hypotheses, and select applicable uranium deposit models for exploration planning. Therefore, compilation of all existing relevant geoscientific data and the review of previous uranium exploration projects in a Member State are the first steps to evaluate the uranium potential and to determine the most prospective areas for a possible exploration project.

The main objective of the review of historical geoscientific data is to determine the investment worth of exploration, with the emphasis on the potential for the discovery of economic concentrations of uranium within the geological region [5.8]. During this initial stage of exploration, all publicly available regional reports and data are compiled by extensive desktop studies. These commonly include reports, databases, geological maps, geographic information system (GIS) datasets, field log sheets, drill core logging spreadsheets, geochemical assays and samples from previous exploration in a Member State. The majority will be sourced from geological survey organizations and other government agencies but may also include historical company exploration and from academic institutions, industry associations, and the IAEA. The IAEA global database of uranium deposits (UDEPO) provides useful information on known deposits throughout the world [5.9].

Identifying and understanding past and existing uranium exploration, prospects and deposits are central to informed exploration planning. In addition to identifying applicable uranium styles, it is important to understand their economic potential and technology to aid in the search and identification. During the previous exploration projects, large amounts of data might have been collected from different regions in a country and this data is often retained and made available by national or state geological survey organizations. The previous uranium exploration work might have resulted in the identification of key prospects having potential for uranium. Therefore, new exploration programmes ought to be built on a solid foundation of existing data, and the experience, results and previous findings of historical uranium exploration projects should be carefully taken into consideration. Exploration planning should build on the historical foundation of knowledge, recognizing its strengths, as well as fundamental flaws or deficiencies in the data, how the data has been obtained, and how it has been interpreted and utilized in the past.

During the planning phase of a uranium exploration project, for the country or regions within the country of interest, it is common to review airborne geophysical data if such data exist for the Member State country. For example, the review of airborne radiometric data is essential for discovery of deposits occurring at surface (see Section 5.2.5). However, historical airborne radiometric data might have been collected a long time ago. Therefore, it is worth noting that older airborne surveys might have certain limitations, such as the small crystal size, old sensor technology, wide flight line spacing, high flight altitude and poor location accuracy, and therefore future exploration planning needs to consider if it may be worthwhile to resurvey areas that might have been inadequately covered to improve the quality and extent of the information base.

In addition, historical information should be assembled and reviewed with a new perspective, considering for example alternative exploration models and integration of new data if available. Careful and continuous consideration of the existing knowledge in the planning process is essential to avoid situations where the new work essentially repeats what was done previously, or the approach taken previously. Therefore, the review of historical surveys is essential to reduce the risk that limited exploration funds would be wasted in repeating previous surveys with the same technology and in the same exploration areas with simply the hope for a better outcome.

The review of existing data should be integrally linked to the assessment of uranium prospectivity of an exploration terrain. The exploration organization should assess all geological, technical and economic factors that affect an investment decision to carry out exploration in a country or specific region within the country. These factors include existing knowledge base and the maturity of exploration areas, the historical discovery success, and the grades and tonnages of deposits that have been previously discovered [5.8]. Broad prospectivity assessment should synthesize the publicly available information in order to identify regions to focus on. These assessments can include quantitative and spatial evaluations of undiscovered uranium resources. Some examples of this are presented in a recent IAEA technical document [5.2]. Ideally, the assessment of prospectivity should lead to a sufficient understanding of the potential for economic uranium deposits within the country which essentially affects an exploration investment decision.

Although an area might have exploration potential, the explorability should also be assessed to confirm that exploration can be carried out efficiently and effectively, with reasonable grounds that economic uranium could be located and mined. Explorability means the practical ability to explore an exploration target in an economical, efficient, systematic, sustainable and socially acceptable manner. Therefore, in addition to prospectivity (uranium potential), the project management team should assess all factors that affect the explorability of a terrain to determine whether exploration can be conducted in a prospective region. Factors that affect the explorability include the location, infrastructure and physical accessibility of prospective terrains, social constraints, potential land use and environmental restrictions (such as nature conservation and cultural heritage areas, agriculture, farming and pastoralism, forestry, recreation and tourism), soil cover and vegetation, depth of cover if deposits are located in the subsurface, and the availability of service providers, logistics, equipment and staff.

When assessing explorability, it is particularly important to consider the depth at which a deposit is no longer economically viable. For example, deeply buried mineralized targets may have low explorability due to excessive depth of the cover even if the expected uranium grades are high. It is also important to assess whether the existing exploration and mining technology is sufficient, or if innovative technologies need to be developed [5.8].

In cases where the exploration organization is privately owned or is controlled by an out of country government, it is commonly worthwhile to carry out discussions with resident geoscientific specialists from national or provincial geological survey organizations to better understand the regional geology and uranium potential of the terrain of interest [5.8]. Moreover, this phase may involve field visits which are typically carried out with representatives from resident geological survey organizations. It is difficult to determine the investment worth of exploration without first seeing rocks in the field, or drill core and other data from past exploration projects.

As a result of the review of the existing geoscientific data and assessment of prospectivity and explorability, the exploration organization should be ready to answer the following questions:

- Are there known uranium occurrences?
- Is the geology favourable for uranium mineralization?
- What economic uranium deposit types and models could be present?
- Are the right components of the uranium models present?
- Can expected uranium targets be explored in an economical manner?

In summary, to assess the investment worth of the planned uranium exploration project, the policy environment and jurisdiction policy (see Section 5.2.3), uranium potential (prospectivity), and explorability (ability to explore) should be carefully considered by an exploration organization during the planning phase. If the exploration organization is sufficiently confident that the uranium potential of a country or a region within a country is favourable in terms of the possibility of hosting an economic uranium deposit, the organization may proceed to defining the exploration strategy, selection of target uranium deposit type models, and selection of exploration project areas.

5.2.5 Definition of exploration strategy and selection of a target uranium deposit type

An exploration strategy defines at very high levels an approach to developing either a greenfield or brownfield exploration programme, and whether the focus is on regional, widespread, and systematic collection of geological, geophysical, geochemical data to define theories on ore-forming processes based on field observations (empirical exploration strategy), or with the focus on theories on ore-forming processes with a goal of identifying and locating features which are indicative of a selected uranium mineralization style and deposit model in a specific exploration area (conceptual exploration strategy). It is advised that an exploration strategy be developed in tandem with the selection of target uranium deposit types and assessment of their applicability.

5.2.5.1 Key aspects of an exploration strategy

Exploration field activities should take place as part of a well-defined exploration strategy to locate and define economically viable uranium deposits. Following the review of existing data, an exploration organization typically defines an exploration strategy with a high-level strategic plan and goals. This phase may involve such activities as the selection of target uranium deposit type models, geoscientific synthesis, knowledge collaborations, metallogenic assessments, application of mineral systems approach, mineral prospectivity modelling, geological field visits and rapid terrain assessments, scientific studies, and economic geology. The focus of the foregoing activities should be directed at the evaluation of investment worth to support exploration strategy [5.2].

Detailed knowledge of the regional geology of an exploration area is critical for any uranium exploration project and often guides the initial exploration strategies and the selection of methods used to explore for a uranium deposit [5.8]. Therefore, it is important to review the existing geological data (see Section 5.2.4) from different perspectives such as the regional geology including structural systems, to increase the geological knowledge base within an exploration organization and to define an exploration strategy within a uranium mineral systems framework.

The regional geology can provide important information on the potential source of the uranium, the fluid pathways, and the traps necessary to form the uranium deposits [5.8]. An understanding of ore-forming processes that may lead to economic uranium concentrations is crucial in all phases of a uranium exploration project, and particularly when developing an exploration strategy and selecting a target uranium deposit type. Some of the key considerations for uranium deposit formation are optimum conditions including source rocks for uranium, mechanisms of transport and deposition of uranium, structural and physiochemical traps, preservation mechanisms, permeability contrasts and whether there is evidence for multiple events mobilizing and enriching uranium. When evaluating the potential of different types of uranium mineral systems (critical mineralizing processes), the following aspects should be considered:

- Availability of uraniferous source rocks (such as granites or rhyolites), to define the possible source regions for uranium and mineralizing fluids in hydrothermal systems;
- The geodynamic setting and tectonic events (such as the relation to the Great Oxidation Event at ~2.2 Ga, sedimentation in basins, or metamorphic history in orogenic settings), to define the nature and duration of the events affecting uranium mobility and concentration in the subsurface environments;
- The scale and structural architecture (such as faults) of the geological system, to define the possible fluid-flow pathways and permeability contrasts for uranium mineralizing fluids in hydrothermal systems, or regional structural features that control the distribution of intrusions in magmatic systems;
- Potential mechanisms of uranium transport, including the composition and chemical properties of fluids with uraniferous rock units. Considering properties such as the oxygen fugacity (f_{O2}) conditions, salinity, temperatures and composition of fluids in hydrothermal and other systems, or magmatic chemistry (such as aluminum saturation index and magma polymerization) and fractional crystallization in magmatic systems;
- Potential mechanisms and processes of uranium deposition caused by structural traps and physicochemical changes to uranium-bearing fluids, such as fluid interaction with the country rocks, changes in f_{O2} conditions, solution chemistry and pH, or mixing with reducing fluids;
- Preservation mechanisms, potential multiple superimposed events mobilizing and enriching uranium, and processes that might have modified the original uranium mineralized units, such as structural disruptions and redox-driven mobilization of uranium, and leaching or enrichment of uranium during younger hydrothermal or regolith (laterite) weathering events;

An exploration strategy should define the high-level goals of an exploration project and identify the most effective ways of achieving them. It is therefore an integral part of the exploration planning phase before progressing to detailed and more practical preparations, such as assessment of results in comparison to targeted deposit models which are part of the actual field work programme. An exploration strategy typically determines a high-level approach to exploration target generation describing general concepts to be applied by an exploration organization (empirical approach vs. conceptual approach). In addition, an exploration organization might also decide to focus on one country or a region within a country. An exploration strategy can be defined in tandem with the assessment of deposit models after the completion of the review of existing geoscientific data together with the assessment of prospectivity and explorability.

The concepts of greenfield exploration and brownfield exploration are also relevant when developing an exploration strategy. Greenfield exploration is carried out in areas where there are no pre-existing uranium mines or known uranium ore deposits, whereas brownfield exploration is conducted in historical uranium districts in the vicinity of existing or closed mines.

The two main types of exploration strategies are empirical using descriptive models and conceptual exploration using genetic models. Empirical exploration strategy searches for a theory to demonstrate that certain observations are relevant, whereas conceptual exploration strategy searches for empirical evidence to justify a theory [5.10]. Empirical exploration strategy (also known as prospector-driven exploration) is based on experience and field observations, whereas conceptual exploration strategy (also known as model-driven exploration) emphasizes metallogenic aspects, ore-forming processes, and uranium deposit models. Most mineral exploration projects employ elements of both conceptual and empirical approaches, and few actual exploration projects are characterized as purely one or the other [5.11].

The various models for uranium exploration include economic (grade-tonnage), descriptive, genetic, ore-forming and other predictive models that rely on probabilistic and spatial recognition methods. Combining these different models has the potential to improve discovery rates and quantify the overall investment worth which is depicted in Fig. 5.6. The investment worth should consider all exploration risks and likelihood of success along with foreseeable uranium market outlooks (i.e., uranium supply and demand relationship). Based on these criteria, exploration investment decisions can be made using a systematic, focused, and cost-effective approach to ensure an optimized project portfolio and sustained funding, preferably enabling new project area generation during the exploration project. As an example, an exploration strategy may define that the exploration will be concentrating only on deposit types with the highest economic potential, and that foreseeable marginal or presumably uneconomic deposit types (for example metallurgically complex peralkaline intrusion-hosted prospects, or low-grade phosphate and black shale prospects) are excluded from the exploration programme. However, this does not preclude exploration of deposits that have low economic potential, for example where exploration is for strategic reasons.

An exploration strategy may also encompass a high-level approach to collaboration and potential partnerships with other exploration companies through strategic alliances, equity holdings and joint venture arrangements. As an example, a national or state mining (or exploration) company may be partnered with a national or state geological survey to combine their knowledge base, national geodatabases, and technical and human resources to effectively serve the national interests of the whole Member State country.

An exploration strategy and the nature of a uranium exploration project can vary greatly from one project to another depending on the project owner. Governmental exploration organizations, such as national geological surveys, may concentrate on regional-scale uranium exploration programmes in areas that have the potential to host uranium deposits, with the goal to understand the geological context of a selected exploration area and scope for additional work [5.3]. Regional uranium exploration typically includes airborne geophysical surveying, remote sensing, geological mapping, geochemical bedrock sampling and soil sampling. Once prospects and targets are defined, further and more detailed work can be carried out by a private or government owned exploration company, or alternatively by the same national or state geological survey which conducted the early stages of the uranium exploration programme.

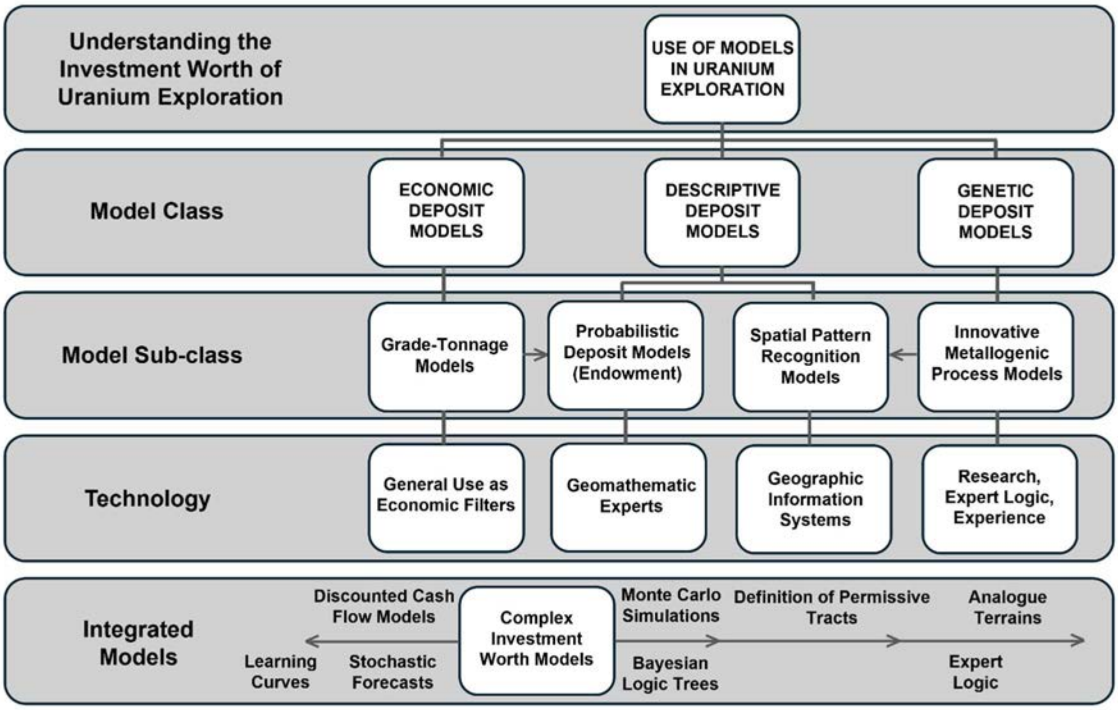

FIG. 5.6. Models used to understand the investment worth of uranium exploration (reproduced from IAEA Ref. [5.2]).

In contrast to a regional-scale or camp-scale approach (Fig. 5.1), an exploration organization might decide to concentrate on prospect-scale or deposit-scale exploration depending on the existing knowledge base and the maturity of exploration areas. Private exploration companies usually define their exploration strategy largely from an economic perspective motivated by the best return on investment and time [5.3].

5.2.5.2 Empirical exploration strategy

Empirical exploration strategy largely relies on data collection through field work, such as airborne geophysical surveying, geological mapping, regional geochemical surveys, and ground follow-up of aeroradiometric anomalies. A review of all relevant data and information in a Member State might result in the identification of new prospective areas with uranium potential. Regional or country-wide exploration programmes typically involve airborne radiometric surveys which usually result in the identification of large numbers of aeroradiometric anomalies. These widespread and systematic exploration techniques lead to an empirical prospect generation which tends to play a greater role in greenfield exploration programmes, where the levels of regional geological knowledge are much lower and applicable mineralization models are less well-defined compared to brownfield exploration programmes [5.11]. Typically, a large number of uranium targets are initially generated in greenfield exploration programmes, especially if extensive high resolution (low altitude, high density line spacing) airborne radiometric data are available.

5.2.5.3 Conceptual exploration strategy

In contrast to empirical target generation, conceptual target generation aims to integrate an understanding of the ore-forming processes with the regional geology to predict where economic uranium mineralization might be discovered. In conceptual, model-driven exploration, a smaller number of uranium targets are typically generated, but they are usually of a higher quality compared to targets generated by empirical, prospector-driven methods [5.11]. Conceptual exploration strategy largely relies on an understanding of ore-forming processes including source of the uranium, transport from source to deposition site, structural and physiochemical traps to promote uranium precipitation, and conditions preserving uranium mineralization to form an economically viable uranium deposit [5.8].

Conceptual exploration strategy commonly plays a major role where there are higher levels of regional geological knowledge and where the styles of uranium mineralization are well-understood through previous exploration projects and scientific investigations [5.11]. Uranium deposits tend to occur in clusters in prospective areas, and brownfield exploration is typically carried out in the vicinity of known uranium deposits. One of the best examples of brownfield uranium exploration is the current uranium exploration activity in Saskatchewan, Canada, which has led to a number of new large high-grade uranium discoveries in the Athabasca Basin in recent years [5.12].

5.2.5.4 Selection of a target uranium deposit type (uranium deposit model)

Before commencing any field work, an exploration organization should have a clear idea of what observable characteristics exploration geologists will be looking for in the field. These characteristics are largely dependent on the selected target uranium deposit type. The selection of the correct target uranium deposit type (also known as uranium deposit model) for an exploration project should be based on a careful geoscientific evaluation of the uranium potential [5.8]. The results of the review of the existing geoscientific data and assessment of prospectivity and explorability are crucial when assessing the applicability of a target deposit model. The potential for economic uranium deposits should be evaluated using comprehensive deposit models based on analogies with economic deposits in similar geological settings globally. When selecting a target uranium deposit type for an exploration project, it is important to understand favourable ore-forming processes that lead to economic uranium concentrations in the context of a genetic uranium deposit model. Prior to selecting a uranium deposit model, it is essential to assess whether a deposit model could be applicable in a prospective terrain, and especially whether it could indicate observable geological features in the field, or signatures in the geophysical data.

Uranium deposits are currently classified by the IAEA into 15 types [5.13] and are described in more detail in Chapter3.Ideally, the uranium deposit model should be chosen prior to commencement of field work because the selected deposit model is the target of exploration efforts. However, a comprehensive understanding of the regional geology, structural framework and stratigraphy, which may determine the correct deposit type to target, might not be possible before the reconnaissance exploration phase. The general geological setting may be permissive for the occurrence of uranium deposits but needs to be assessed by field visits and metallogenic evaluations founded on deposit models. This forms part of the assessment of the initial exploration hypothesis which should be based on the chosen uranium deposit type.

If the potential for unconformity-related or sandstone hosted uranium mineralization exists in a Member State country, it is important to focus on exploration for these deposit types due to their lower mining costs and higher grade compared to many other deposit types. However, exploration for sandstone and unconformity-type uranium deposits is typically challenging because they are usually located in the subsurface and are rarely exposed. This fact underlines the importance of considering the appropriate deposit models and exploration methods in a uranium exploration project. The benefit of including sandstone targets in the exploration portfolio is that sandstone uranium deposits typically have mineralogy (i.e., predominantly pitchblende and coffinite) which is favourable for uranium extraction [5.13]. Sandstone uranium deposits are also in many cases amenable to low-cost in situ recovery (ISR) mining, depending on water table depth and upon having the appropriate permeability of the host and permeability contrasts with the surrounding rocks. In addition, ISR amenable deposits can be brought to production in much shorter time frames, having significantly smaller scale operations, and lower costs with lower environmental and social impacts compared to many other uranium deposit types. ISR amenable uranium deposits are currently the world's lowest cost uranium producers (See Chapter 2, Fig. 2.5). Unconformity-type deposits are a desirable target due to their high grades which enables mining of lower total volumes of rock. Additional information on the characteristics of these types of deposits can be found in the IAEA publication, *Unconformity-related uranium deposits* [5.8].

5.2.5.5 Utilization of optimized exploration portfolio

Large national uranium exploration programmes are often broken down into individual projects and each project may contain one or more prospects [5.11]. Reviewing and revising as required, the entire exploration portfolio (individual subprojects or prospects within an exploration project) is often overlooked, but it is very important for exploration success. For example, some exploration areas or prospects may have been adequately explored during previous exploration projects in a Member State country. If these areas are ranked as having a low potential for discovery, further exploration in these areas may not be warranted. Instead, it may be prudent to focus on new but less explored sedimentary basins or cratonic shields in order to increase the probability of discovery success.

Exploration might be inefficient and wasteful, and field activities may be redundant if the exploration portfolio includes too many low potential subprojects with low investment worth. The number of individual projects in a uranium exploration programme may also have a significant role for exploration success because potential for discovery of an economic deposit is higher if the exploration funds can be allocated to a smaller number of prospective subprojects. This offers a more focused and cost-effective approach to exploration by concentrating on areas and deposit types with the highest economic potential. In this approach, low potential subareas, clearly uneconomic subprojects, and deposit types of a metallurgically complex and refractory nature (such as intrusive-type, peralkaline intrusion-hosted prospects) can be ignored. A smaller number of subprojects may expedite exploration through optimized project portfolio, sustained funding, adequate human and technological resources, and effective project management.

5.2.5.6 New project area generation

New project area generation is also an integral part of continuous planning during an exploration project. The number of anomalies and targets typically decreases during the exploration programme as field testing progresses. Therefore, there is the need to identify new subprojects and subareas using a project generation budget, especially in greenfield exploration programmes. This ensures that the exploration project portfolio has an adequate number of prospective subprojects and a pipeline of opportunities.

It is suggested that the investment worth of the exploration project portfolio is assessed frequently (semi-annually or annually) during the uranium exploration project to ensure optimal fund allocation to support economic discovery. Based on the results of these assessments, project areas (or subprojects) with low uranium prospectivity should be relinquished and replaced with new project areas with higher uranium potential. This kind of dynamic and optimized exploration project portfolio offers a more focused and cost-effective approach to exploration, concentrating on areas and uranium deposit types with the greatest economic potential. Replacement of the relinquished exploration areas with new subprojects increases the probability of economic discovery through consistent long-term funding of the national exploration programme or private company's exploration portfolio. It should be also noted that many large uranium producers have both mining and exploration operations, and therefore their high-level exploration strategy can emphasize the need to generate new prospective exploration areas to replace their current uranium production centers as mineral reserves are depleted by production in the long term.

5.2.5.7 Mineral prospectivity modelling

Before the selection of exploration areas, GIS-based mineral prospectivity modelling (also known as prospectivity analysis, spatial analysis, or mineral potential modelling) can be utilized to combine statistical models in a probabilistic and spatial manner. These help to combine diverse and broad geoscientific datasets in a quantified and time-efficient manner which allows modifications as further information is gained. The goal is to generate prospectivity maps which are maps of a region of interest that show estimated uranium prospectivity generated by automated GIS-based methodology. The assessment is broken down into observable and mappable features along with their relatively importance, which is sometimes referred to as a data-process-criteria predictive model. Examples of regional quantitative and spatial uranium prospectivity analysis are presented in a technical document by the IAEA [5.2]. Most use fuzzy logic to combine the observable and mappable features using mineral system understanding for an overall probabilistic rating of favourability or likelihood. For example, Fig. 5.7 shows input information used to assess the potential for sandstone-hosted uranium in Australia [5.2].

5.2.6 Selection of exploration areas, development of the exploration programme, selection of exploration methods, and exploration budgeting

On the basis of the exploration strategy, the selected targets, uranium deposit types and corresponding deposit models, the exploration organization can proceed to selection of exploration areas, development of the exploration programme, selection of exploration methods, and exploration budgeting.

5.2.6.1 Selection of exploration areas

An exploration area is a restricted geographical region which should have the possibility of hosting an economic uranium deposit. The selection of exploration areas is largely based on the deposit types with their corresponding models selected during the planning phase (see Chapter 3 and Section 5.2.5). The results of mineral prospectivity modelling, if available, can also provide valuable insights into the selection of exploration areas. It should be noted that the maturity of selected exploration areas can vary greatly from one exploration programme to another depending on the existing knowledge base and the outcomes of previous uranium exploration. A selected exploration area might have been explored using a variety of techniques and can contain several aeroradiometric uranium anomalies, outcropping mineralized zones, known uranium prospects, or even old uranium mines. On the other hand, the area might largely be based on geological ideas, conceptual approach, and genetic models, without any previous uranium exploration.

Areas for uranium exploration are often selected on the basis of aeroradiometric uranium anomalies if the selected deposit type and model (see Section 5.2.5) favours the possibility of exposed or near surface uranium mineralization. Typically, the selected exploration area includes the most promising aeroradiometric uranium anomalies which were identified during the review of existing airborne radiometric data (see Section 5.2.4) as part of the exploration planning process.

Airborne radiometric total count data, uranium channel data and ternary potassium, uranium and thorium maps are commonly used in area selection for uranium exploration. In addition, coloured uranium squared to thorium ratio (U^2/Th) grid maps are useful in the identification of aeroradiometric uranium anomalies and to particularly highlight areas of elevated uranium. This ratio is often used because it is an effective way to discriminate airborne uranium-dominated anomalies from anomalies which are also elevated in thorium [5.8].

The U^2/Th ratio is very useful in area selection because uranium and thorium commonly occur together, and they have a relatively constant ratio (Th/U = 3.8) in most upper continental crustal lithologies [5.14]. When reviewing airborne radiometric data for area selection, exploration managers should pay special attention to the geochemical characteristics of both uranium and thorium because thorium is more abundant in the Earth's crust than uranium, and these elements behave geochemically similarly in partial melting and fractional crystallization if key aqueous complexes are not involved in the magmatic processes. This is because uranium and thorium have quite similar crystal chemistry in their relatively insoluble tetravalent (U^{4+} and Th^{4+}) valence states and they both are strongly incompatible in all common rock-forming silicates due to their large ionic radius and high valence [5.15]. Therefore, both uranium and thorium typically become enriched in magmatic melts during partial melting and fractional crystallization. For example, the high degree of fractional crystallization of peralkaline melts can result in strong enrichment of both uranium and thorium, together with other incompatible high field strength elements (such as Ta, Nb, REEs, Zr), potentially leading to polymetallic mineralization (e.g., Kvanefjeld in Greenland and Ghurayyah in Saudi Arabia).

From a uranium exploration planning and area selection perspective, it is essential to highlight that uranium occurs predominantly either in the tetravalent (4+) or hexavalent (6+) oxidation state which have very different chemical behaviours. The tetravalent state has a low solubility but near-surface oxidation of U^{4+} to the hexavalent valence state U^{6+} results in uranyl $(U^{6+}O_2)^{2+}$ complexes which are highly soluble. The ability of uranium to form highly soluble uranyl complexes is crucial for most of the uranium mineralizing processes and deposit models (such as unconformity-related and sandstone uranium deposits). These geological processes include leaching of uranium from source rocks by oxidizing fluids, transportation of uranium in oxidizing uranyl-bearing solutions, followed finally by precipitation and deposition of uranium from mineralizing fluids due to the reduction of U^{6+} to U^{4+} at redox boundaries to form mineralized volumes in which uranium occurs predominantly in insoluble state U^{4+}.

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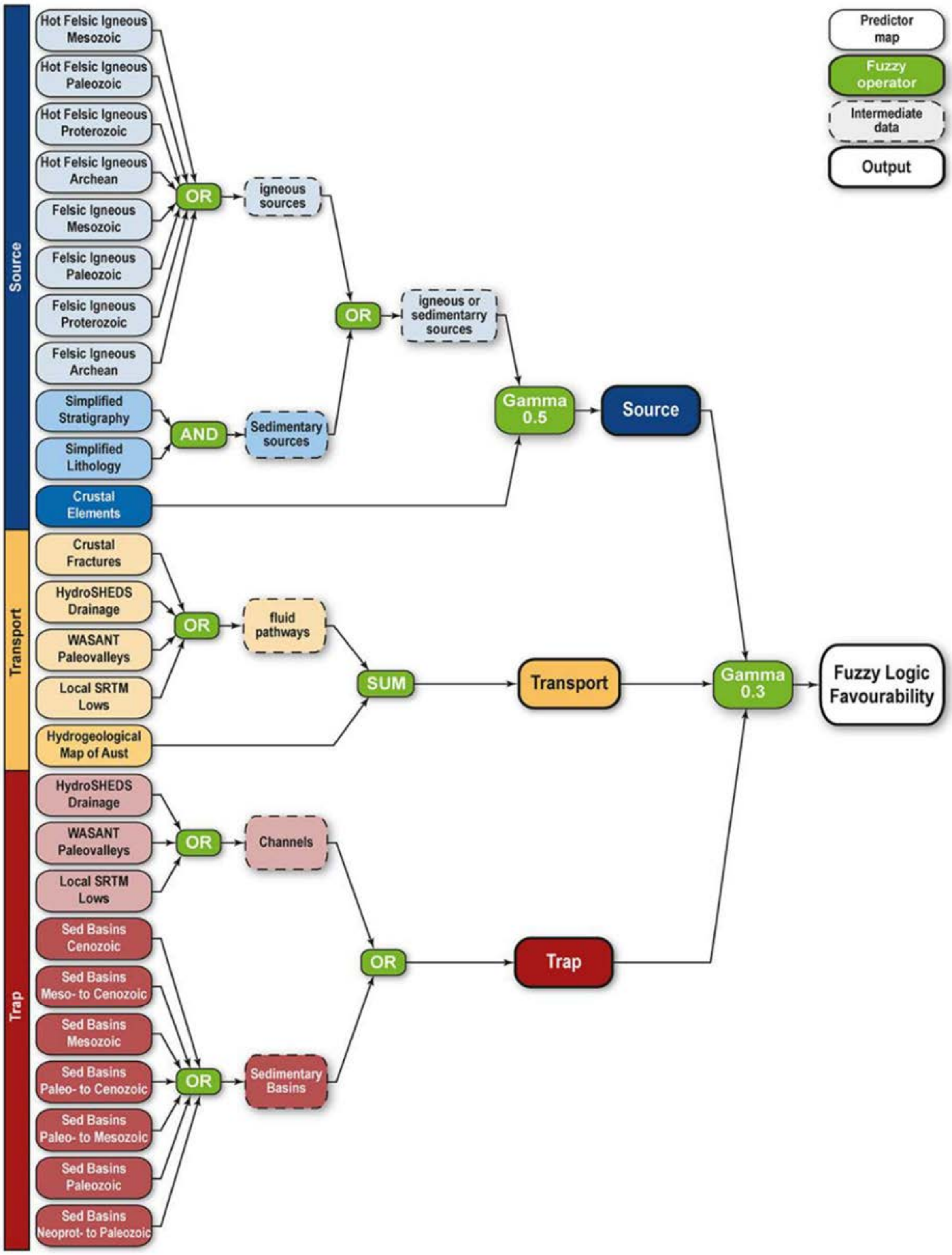

FIG. 5.7. Fuzzy-logic mineral prospectivity analysis for sandstone-hosted uranium deposits in Australia (reproduced from IAEA Ref. [5.2]).

It should be noted that the selection of exploration areas demands different approaches depending on each uranium deposit model. For example, in exploration area selection for sandstone uranium deposits, it is important to identify prospective sedimentary basins in the vicinity of potential uranium-bearing source rocks, such as intrusive rocks (typically granites) and volcanic rocks (typically rhyolites) with the elevated concentrations of uranium. In exploration for sandstone uranium deposits, the knowledge of the hydrogeological systems is essential. Similarly, in the selection of areas for exploration for surficial calcrete-type uranium deposits, special attention should be given to identify and locate drainage systems over areas where uraniferous source rocks (typically granites or rhyolites) are abundant, and where the drainage enters playas or sabkha areas where uranium precipitation might have taken place.

Once prospective exploration areas have been selected and agreed upon, exploration managers should carefully assess and identify suitable exploration technologies and their costs to develop an exploration programme and exploration budget.

5.2.6.2 Development of the exploration programme and selection of exploration methods

One of the most important tasks of the planning phase is to select the most appropriate and efficient exploration methods for the exploration programme. The most common methods used in uranium exploration are described in more detail in Chapter4. There are a number of management-related aspects which should be considered during the selection of exploration methods. Exploration managers should consider the advantages, limitations, quality, spatial resolution, scale, quantity and cost of each method. Table 5.2 presents a variety of factors which should be taken into consideration when the appropriate exploration techniques are selected for the exploration programme.

The uranium potential of the selected exploration areas needs to be assessed through a well-planned uranium exploration programme developed prior to commencement of field work. However, the nature of this original plan should not be locked into a course of action that is inflexible and inherently difficult to modify during the exploration programme. Therefore, continuous planning is also an integral part of a successful uranium exploration project and is important for all exploration phases.

Exploration methods may vary greatly depending on the maturity of the exploration areas and the nature of a uranium exploration project, and whether the focus is on regional-, camp-, prospect- or deposit-scale exploration work. For example, regional-scale airborne geophysical surveying, remote sensing, ground follow-up of aeroradiometric anomalies and radiometric boulder tracing are usually used to generate potential targets or focus areas for more detailed geological mapping or target investigation. Regional-scale, reconnaissance exploration work can include such activities as geological mapping, geochemical bedrock sampling and ground radiometric surveying, followed by more detailed prospect-scale geological mapping, ground geophysical surveying, radon surveying, sampling, trenching, drilling, downhole radiometric probing, and mineralogical characterization if promising targets are generated and delineated. All the foregoing stages typically include geochemical assaying performed by the analytical laboratories, but especially during the prospect-scale or deposit-scale work if the exploration project progresses into resource definition. It should be also noted that all technical information for an exploration project in all phases should be obtained using good practices under a QAQC programme and reported under the supervision of the skilled and experienced geoscientists.

Each deposit model demands different exploration approaches [5.1]. Therefore, the selection of the geological, geochemical, and geophysical exploration methods largely depends on the characteristics of the selected uranium deposit model [5.8], the maturity of exploration areas and the pre-existing knowledge base. If the selected deposit model and geological setting favours the possibility of exposed or near surface uranium mineralization, aeroradiometric surveying should be considered. For example, airborne radiometric data is very useful in targeting exposed or near surface uranium mineralization, particularly in exploration for intrusive, metasomatite, sandstone and surficial (calcrete) types of uranium deposits.

The selection of the most appropriate exploration methods should follow a systematic approach as the selected area becomes smaller as exploration progresses through the exploration phases. That is from early reconnaissance and follow-up phases of exploration to more detailed and advanced phases of exploration which require more detailed exploration methods, such as trenching and drilling.

Exploration managers should also ensure that the selected exploration methods are compatible and complementary, so that collected data can be integrated and interpreted in an efficient way to generate new knowledge, meaningful insights and conclusions. When selecting the exploration methods, it should be ensured that the selected areas will be surveyed in an efficient and cost-effective manner. For example, airborne geophysical surveying can be a cost-effective, quick, and reliable method. These may be combined and in particular the radiometric and magnetic surveys. Another example of an efficient and cost-effective approach is ground radiometric surveying which can be accompanied by geological mapping so that the level of radioactivity of the outcrops is measured at the same time as these outcrops are geologically mapped by a field team.

This allows the field team to delineate radioactive zones spatially and to identify their relation to lithology, mineralogy, structures, and alteration. In addition, ground radiometric boulder tracing of glacial erratics can be combined with these surveys in glaciated terrains. However, ground radiometric surveying may play a secondary role in exploration for sandstone and unconformity-type uranium deposits because they are usually located in the subsurface and are rarely exposed at surface. This aspect highlights the importance of understanding the deposit models and geological setting of the selected exploration areas (see Chapter 3 and Section 5.2.5) along with choosing the best exploration methods.

TABLE 5.2. TYPICAL PLANNING AND MANAGEMENT CONSIDERATIONS IN THE SELECTION OF EXPLORATION METHODS

Factors	Questions and Considerations
Concept	What is the style of uranium mineralization, and mappable characteristics?
	Is there likely to be sufficient physical property contrast for surveys?
	What is the target size, depth and is there cover - how do these affect the exploration technique?
	What are the desired outcomes?
	Who is managing the planning, acquisition, QAQC and interpretation?
	Who are the stakeholders?
Cost and Equipment	Does the approach provide appropriate value to warrant its use?
	Is there adequate funding (including processing and interpretation)?
	Are contracts in place with appropriate QAQC protocols?
	Are the instruments/contractors available for the activity?
	What are the deliverables and timing?

TABLE 5.2. (cont.) TYPICAL PLANNING AND MANAGEMENT CONSIDERATIONS IN THE SELECTION OF EXPLORATION METHODS

Factors	Questions and Considerations
Terrain	Does the terrain and accessibility impact the choice of ground vs. airborne surveying? Has topography, vegetation and climate factors been considered? Have seasonal variations been considered which may affect survey times including standby time? Could artefacts like powerlines and metal buildings impact on the survey or results? For sampling, is local drainage, surficial cover and transported media (glacial/water-born material) well understood?
Regulatory and Community	Does the activity comply with government agency regulatory requirements? Are special approvals or permits required to access the ground or fly over the ground? For low flying surveys, could it disrupt the natural environment including wild animals, livestock or communities? Is everything being done to maintain strong positive community relations? Are there timely/ongoing communications with stakeholders including results? Are there indigenous title, traditional owners, or archeologic sites to be avoided?
Environmental Aspects and Access	Has an early-stage environmental baseline study carried out prior to any field work? What is the location of the base of operations and infrastructure? Where is fuel being stored and how is it being managed? How is the activity area being accessed and what are the travel times from base? Is there adequate access for heavy equipment and fuel (across waterways, sensitive land)? What is the plan for rehabilitation of land disturbing activity (e.g., trenching and drilling)?
Occupational Health and Safety	Are occupational health and safety protocols in place? What are the emergency protocols and what is the distance to emergency facilities? Is personnel radiation monitoring required and in place?
Specifications	For grid-based surveys EW and NS are preferred but lines should be perpendicular to the features of interest for broad traverses. Does the survey outline extend beyond expected features (generally rectilinear)? Is there a balance between closer line spacing and desired resolution vs. cost? Is the flying height for air surveys as low as possible, depending on aviation regulations and land use? Is rain/snow being avoided which can affect the ground signal? Are drill holes perpendicular to target features and spacing determined by geology?

This allows the field team to delineate radioactive zones spatially and to identify their relation to lithology, mineralogy, structures, and alteration. In addition, ground radiometric boulder tracing of glacial erratics can be combined with these surveys in glaciated terrains. However, ground radiometric surveying may play a secondary role in exploration for sandstone and unconformity-type uranium deposits because they are usually located in the subsurface and are rarely exposed at surface. This aspect highlights the importance of understanding the deposit models and geological setting of the selected exploration areas (see Chapter 3 and Section 5.2.5) along with choosing the best exploration methods.

The quantity and quality of the available geoscientific data also plays an important role when developing the exploration programme and selecting the exploration methods. For example, a large number of aeroradiometric uranium anomalies may be identified during the review of the existing data. Therefore, it is suggested that the exploration managers prioritize sufficient time, field personnel and exploration funds for conducting a ground follow-up of aeroradiometric anomalies before selecting more detailed exploration techniques, such as detailed geological mapping, or radon surveying. Any of the aeroradiometric anomalies can potentially reflect uranium mineralization and should be regarded as a target to be followed up with a ground check and initial assessment in the field using handheld scintillation count rate metres or portable gamma ray spectrometers. However, relatively few aeroradiometric anomalies result in positive results and subsequent more detailed surveys. Therefore, the number of targets typically decreases during ground follow-up of aeroradiometric anomalies.

Even weak uranium anomalies should be checked carefully in prospective areas during ground follow-up of aeroradiometric anomalies because the aeroradiometric signal reflects only the uppermost portions of the ground. However, the bedrock or soil in this upper zone may not be representative of potential buried uranium-bearing horizons or mineralized zones at greater depths below the surface without any surface aeroradiometric expression. Although gamma radiation can travel long distances through air, the bedrock, soil, and water attenuate gamma rays effectively. The major portion of detected gamma radiation is derived from the uppermost (0–30 cm) part of the soil and bedrock [5.16]. Therefore, airborne radiometric surveying plays a less important role in exploration for unconformity-type uranium deposits because they are usually located in the subsurface at great depths. Instead, airborne electromagnetic data have played a significant role in the discovery of many unconformity-related uranium deposits within the Athabasca Basin in Canada [5.8]. This again underlines the importance of the deposit model when selecting the most appropriate exploration methods for the uranium exploration programme.

In many cases, the choice of a specific geophysical technique is made based on the options available, the known properties of the mineralization and its association with specific geological features. For example, induced polarization (IP) surveying is often useful for modelling the 3 dimensional (3D) characteristics of subsurface rocks, however, to be most effective, subsurface formations should contain a polarizable mineral and have resistivity contrasts. The presence or absence of such characteristics can be assessed based on field evidence. However, the selection of geophysical method is much more robust if the petrophysical properties of selected samples are systematically measured in a laboratory prior to commencement of field surveying. This is especially important where uncertainty exists regarding the choice of survey method and instrumentation. Optimal geophysical methods should be chosen based on the known petrophysical properties of different rock types, including mineralized rocks, host rocks and various country rocks, to ensure that the chosen methods can be effectively used to distinguish mineralized zones from barren rock types. For any petrophysical samples taken, the petrophysical properties should be systematically measured in a laboratory equipped for measuring radiation, density, susceptibility, remanent magnetization, electrical conductivity (galvanic and inductive), IP effects, seismic velocities, and porosity. Based on the results, the most effective geophysical methods for a target area can be decided before commencing any extensive field surveying.

It is important that future surveys do not essentially repeat the approach taken previously in the selected exploration area. For example, in conducting extensive geophysical surveys there should be sufficient justification at each exploration site to warrant the surveys. Ground geophysical surveying should be planned with emphasis on defining near-surface, rather than deep anomalies. For example, the reliance on audio-frequency magnetotellurics is questionable for shallow targeting, but may be appropriate for deeper, more regional to local basement geological interpretation. Depending on the petrophysical results, time-domain and frequency-domain electromagnetic methods can be considered especially for shallow targets. The configuration of measurements depends on the environment, contrast between mineralization and country rocks, and the depth penetration needed. In addition, reconnaissance geophysical profiles prior to any systematic measurements (sometimes referred to as orientation surveys) can be useful. Such geophysical profiles would allow field procedures to be modified as needed to best reveal anomalies related to mineralization or structures controlling it, thereby giving reasons to perform more systematic geophysical surveys.

After selecting exploration methods, the quantities of work will be estimated, so that a detailed budget can be formulated. For example, if airborne radiometric surveys are included in the exploration programme, it is important that total line-kilometers of airborne geophysical surveying are determined. If petrophysical characterization will be done, then the survey estimates might be contingent on the petrophysical results. The nature of this original plan cannot be locked into a course of action that is inflexible and inherently difficult to modify during the exploration programme. However, the quantities of work should be estimated, so that a detailed budget can be established. The exploration programme with the selected exploration methods is also the key basis for preparing tender documents for the bidding process to select the exploration contractor(s) for the uranium exploration project (see Section 5.2.9).

5.2.6.3 Budgeting

The selection of exploration methods is typically conducted in tandem with exploration budgeting and determination of staffing levels aligned with financial resources. Project costs depend on such factors as area, scale, resolution, selected exploration methods, staffing levels, location of exploration areas, and the duration of a project. Drilling is one of the most expensive and time-consuming exploration techniques used in uranium exploration, and hence drilling costs typically make up a large part of an exploration budget and are best conducted later in the exploration process once a smaller area of exploration has been selected.

It is advised that the exploration project budget is broken down into individual subproject cost estimates according to different exploration areas. Expenditure should be allocated for each of these exploration areas so that the total budget for the whole exploration programme can be reliably estimated. It may be that there is insufficient funding and resources to adequately explore all areas and so it may be prudent to select the most favourable areas to focus on, with the objective of assessment in a systematic manner. It is essential that a detailed cost breakdown is established to allocate the exploration project budget through individual exploration areas so that a budget worksheet is broken down into logical types of cost items including salaries, field survey expenses, trenching, drilling, downhole radiometric probing, core cutting, analytical costs, bulk density measurements, project management and administrative costs, equipment, support and logistics, and overhead costs.

Geographical and infrastructure factors should be taken into consideration in exploration budgeting. Remote exploration project areas, such as desert environments, equatorial rainforest, boreal forest (taiga) and arctic tundra may be difficult to access and explore. Poor infrastructure, logistical challenges and long distances from population centers increase exploration costs. In a remote location, there may be no local workforce, electric power supply, water supply, roads, houses, stores, or other infrastructure. All or some of these facilities might have to be built which increases cost. In addition, salary costs may be high to attract skilled geoscientists and other experienced workers to conduct a uranium exploration project in remote areas [5.17].

A typical problem with exploration project cost estimates is to ignore changes during the timeframe of the project due to unrealistic scheduling, price and inflationary effects, delivery bottlenecks of material, equipment and staff, logistics challenges, equipment failures, adverse drilling conditions, community interactions, regulatory hurdles, and unexpected natural disasters and emergencies, such as the COVID-19 pandemic, or war. Therefore, contingencies in the exploration budget should be used to account for these unforeseen possibilities to reduce the financial risks. Another way to manage additional costs is that an exploration organization may retain the right to reallocate work (such as drilling) to stay within the budget. If the rate of drilling is slowed, project management costs will typically rise. Therefore, an exploration contractor can retain the right to take exploration funds from the drilling budget by reducing the number of metres to be drilled to balance drilling costs against increased management costs. The only other way to stay within budget is to have a separate contingency budget or apply a significant markup in a bid as a contingency fund if exploration is carried out by a contractor.

Uranium exploration requires long timeframes to identify prospective areas, to delineate sufficient targets, to define mineral resources, and to develop ore reserves from a deposit with the ultimate goal of developing a mine and bringing these uranium resources into production. It can be problematic when policy changes or priorities impact on the long-term objectives of a project. In addition to a yearly budget there should be a budget that spans the expected life of the project. This should be aligned with the phases of exploration required to progress from each phase. The budget should pave the way for successful realization of the mineral potential whilst balancing the risks and potential changes in prioritize.

5.2.7 Scheduling of exploration activities

One of the first tasks of the project manager of the exploration organization is to develop a realistic schedule for the exploration project. This should include sufficient time allocation for planning, implementation, and completion of the exploration project in order to carry out all work in a comprehensive and consistent way while meeting accepted work standards to produce high-quality end products (i.e., data and technical reports).

The preparation of a detailed schedule with a realistic timeframe is one of the most important tasks for the project management team during the planning stage. However, not everything should be defined in advance by the exploration organization. The project should have the flexibility to respond to changes in circumstances. The project schedule should be updated and refined during the exploration project, and the schedule should allow the exploration organization to adjust its exploration programme and schedule based on new data being generated during the field work. In addition, exploration project scheduling should be linked to exploration budgeting and cost control because schedule changes typically impact costs.

Exploration schedules can vary greatly depending on the nature and funding of the project. Large-scale and regional exploration projects, that can consist of several target areas, usually require long timeframes, from less than five years to more than ten years. For example, country-wide or regional exploration programmes may involve airborne radiometric surveys which usually require long timeframes from conducting airborne surveys and interpreting airborne datasets to ground follow-up of aeroradiometric anomalies.

The project owner might not conduct all exploration work itself. In this case, the project management team should assign specific exploration activities, such as geological mapping, field surveying and drilling, to the appropriate contractors to be completed in a certain timeframe. The timeframes to start the actual field work after the contracts are awarded should be realistic, so that there will be sufficient time for mobilizing exploration crews, sourcing equipment, setting up a camp, offices and other exploration infrastructure, importing equipment, calibrating downhole gamma probes, satisfying regulatory requirements, securing exploration permits and approvals, securing environmental and heritage permitting, developing QAQC programmes and standard operating procedures (SOPs), developing a safety, health, environmental and data management plans, accommodating potential multiple languages, and developing radiation and environmental protection procedures and their monitoring programmes.

5.2.8 Acquisition of exploration licences

Once exploration areas and exploration methods are selected, the exploration programme is developed, and exploration budgeting and scheduling are completed, the project typically moves to its licensing (permitting) stage. An exploration licence (also known as an exploration permit) provides the licence holder with the exclusive right to explore for specified commodities within the exploration licence area, during the term of the licence [5.3]. Prior to commencement of field work, an exploration organization should typically obtain an exploration licence which is required under applicable legislation to enable an organization to perform its exploration activities in the field.

The requirements, definitions and regulations differ between countries and therefore exploration licences can vary greatly. An exploration licence does not allow mining, nor does it guarantee that a mining licence will be subsequently granted [5.3]. If the uranium exploration project results in the discovery of an economic uranium deposit, only a very small portion of land that is subject to an exploration licence is usually developed into a uranium mine. It should also be noted that rules for the repartition of the stakes in a potential future mining project is generally defined for the exploration licence [5.3].

The licensing process is an essential element of uranium exploration project management. This process typically includes the following steps:

- Review of applicable mining legislation and associated regulations and guidelines to ensure that the established regulatory criteria are met;
- Preparation of the licensing documents;
- Submission of the exploration licence application with the required appendices to a regulatory authority (mining authority, or similar);
- Decision by the regulatory authority to grant or refuse the exploration licence;
- Submission of activity reports to fulfil obligations set out in the exploration licence over the period of the licence;
- Termination (or cancellation), or retention (or extension/renewal) of the exploration licence depending on the results of the exploration project.

If uranium exploration leads to the discovery of an economic uranium deposit, then the exploration licensing process is finally followed by the submission of the mining licence application to a regulatory authority.

5.2.9 Procurement and contracts

Once exploration licences are secured, the project usually moves to its contracting stage. An exploration organization should pay special attention to the development of the procurement plan to ensure that the uranium exploration project will be carried out in a technically competent and cost-effective manner within the constraints of budget, schedule, and quality requirements which should be established during the exploration planning phase. The project owner (exploration organization) typically has the following three alternative options for a contractual approach:

1. Comprehensive in-house approach: the project owner is responsible for the overall exploration management and conducts all or the majority of exploration work. In this case, the organization already has the majority of the required personnel along with the exploration equipment (such as drilling rigs and geophysical instruments) to carry out the exploration programme. The project owner provides its own supervising geoscientist (Competent Person) for a project. One example of the comprehensive in-house approach is a large, experienced organization, such as a department or a subsidiary uranium exploration branch of a national nuclear corporation, a national geological survey, or a large governmental or private uranium mining and exploration company that can provide sufficient personnel and equipment to execute the uranium exploration programme. However, regardless of internal capabilities, geochemistry analysis is generally outsourced to independent laboratories due to the stringent QAQC requirements, protocols and accreditation.

2. Turnkey contractual approach: the project owner retains an exploration contractor to provide all exploration services. The overall exploration management is the responsibility of the main exploration contractor which provides its own supervising geoscientist (Competent Person) for a project. In the turnkey approach, a single exploration contractor or a consortium of exploration contractors takes the overall technical responsibility for the exploration work. The exploration contractor is contracted with the project owner by signing a turnkey contract. However, the main exploration contractor might utilize qualified subcontractors, such as drilling contractors, geophysical contractors and analytical laboratories which are contracted directly with the main exploration contractor. In the turnkey contractual approach, the project owner (such as a national ministry of mineral resources, or similar) might have the sufficient budget and financial capability for the exploration project but does not have sufficient human and technical resources to conduct a national uranium exploration programme.

3. Split package approach: the project owner assumes the overall technical responsibility for the planning and implementation of the uranium exploration project but the exploration activities are divided between the project owner and its contractors, such as drilling contractors, geophysical contractors and analytical laboratories which are contracted directly with the project owner. In a split package approach, the contractors under contract to the project owner should also set up their own project management organization when starting contract work. The project owner may perform certain exploration activities, some exploration tasks are conducted in cooperation with the contractors or project partners, while some exploration activities are carried out entirely and independently by the contractors (such as a drilling contractor and analytical laboratory). The project owner provides its own supervising geoscientist (Competent Person) for a project. The supervising geoscientist should supervise the overall technical performance of both the project owner organization and each contractor. The project manager of the project owner needs to supervise the execution of the contracts and delegate tasks between the project owner organization and its contractors. In the split package approach, the project owner is typically a private uranium mining and exploration company, or a junior uranium exploration company, which may be listed on a stock exchange.

Procurement procedures may differ between countries, and they will always take place according to a national, provincial or local legislation. The procurement department of the project owner is typically responsible for procurement procedures and tailors the procedures according to the size and nature of the project. For example, there might be a clearly defined commitment to purchase services based on the lowest evaluated price in the event where proposed services, materials and exploration techniques comply with bid specifications, commercial terms, and proposed delivery schedule.

The main tasks of procurement are to purchase exploration services, equipment and material as required for various exploration project tasks. These should be purchased from qualified contractors that offer services and equipment in a cost-effective manner, while meeting both the expected high-quality work standards, and compliance with the requirements for quality, competence, schedule, cost, and reliability. The project owner should pay special attention to negotiations with potential contractors to obtain the best possible exploration services and value for the project. Procurement procedures usually include the following main steps:

- Development of the procurement plan: procurement strategy, identification of needs, purchase/contracting packages, purchasing time schedule, preparation of the tender documents and bid specifications, and evaluation criteria;
- Bidding process and selection of the contractors: the identification of potential contractors (bidders list), signing a non-disclosure agreement with potential bidders, pre-qualification process, tender invitation (request for proposal), evaluation and comparison of proposals, identification of potential deviations from bid specifications, and cost evaluation including contract price and other associated costs;
- Contracting: contract negotiations (including the technical meeting with each bidder to review their technical proposal), contract awarding, contract signing, and purchase orders;
- Contract management: contract administration, invoice control, and recording of expenses;
- Monitoring, control, and expediting: evaluation of contractors' ability to perform work in accordance with the contract specifications and with the project schedule and quality requirements, management of the quality and schedule of exploration activities and deliverables (such as monthly progress reports), document management of contractors' deliverables, field inspection visits and on-site auditing to observe field work practices and QAQC procedures in action, real time monitoring of the status of the contract work, examination of exploration plans and the methods used, and enforcement of changes if the results do not justify the approaches taken by the contractor;
- Measuring and evaluation: evaluation of the contractor, feedback to cost estimating, the lessons learned, and continuous development.

5.2.10 Data management planning

Exploration data and technical reports are among the most important outputs of an exploration project. The degrees of data openness for sharing outside of the exploration organization vary, ranging from fully open to strictly confidential. The planning of data management reduces the risk of the loss of exploration data.

5.2.10.1 Data management plan

Before the execution of a uranium exploration project, a data management plan (DMP) should be created describing the data flow from the field to the final repository and specifying how data is handled during and after the exploration project. A DMP helps an exploration organization to save time and exploration funds, and it reduces the risk of losing valuable exploration data. It also supports an exploration organization to make the exploration data findable, traceable, accessible, consistent, interoperable and re-usable. By preparing a DMP prior to commencement of field work, complex data ownership and user rights issues can be avoided. A DMP is also relevant from a reporting perspective because primary data, data entry procedures, data verification, and data storage (physical and electronic) protocols should be described and summarized in the final technical reports [5.6].

Documentation and descriptive information on data types, file formats and conversion of the data types greatly increases the traceability of the project data. A DMP should include the documentation on the protocols used to ensure that the data is properly collected, handled, processed, used, and maintained. This kind of detailed and clear documentation of the project data, data processing and data conversion serves the project owner for future investigation and any further exploration work. In addition to the final technical reports, a major portion of the final value of the exploration project will be the geoscientific data generated which should be of exceptional quality and should be securely stored in the databases. It is vital that various fields of expertise within the project management team (geologists, geophysicists, data management specialists) contribute to the preparation of the data management plan.

The data management plan should include the following information, describing how the exploration organization will create, protect, and share the exploration project data:

1. General description of data and file formats:
   - What data types will be collected and produced?
   - Previously collected existing data which will be reused in the project;
   - Rough estimate of the size of the data to be collected and the required storage space;
   - List of data to be collected over the project (such as geological, geophysical, geochemical, drill hole, remote sensing, mineral resources);
   - List of the file formats for each exploration dataset;
   - List of software to be employed in viewing and processing the data (such as database, GIS, geophysical, drill hole, image, audio);
   - How will the consistency and quality of data be controlled?;
   - The data collection, analysis and processing methods, and the risks related to data accuracy;
   - Data quality control procedures in handling, converting and transferring of data to ensure that the original data is maintained in all data conversions;
   - Documented, clear and concise file naming conventions for all data, records, and files;
   - List of data dictionaries to describe terms, rock names, codes, and abbreviations;
   - List of internationally accepted rock classification standards to be used;
   - Descriptions on how the data will be collected, including detailed description of the workflow for all planned exploration surveys;
   - Metadata for all data to be collected;
   - Instrument calibration descriptions.

2. Storage and backup procedures, and archive and preservation plan:
   - Where the data will be stored and how they will be backed up during the project;
   - Digital repository for the final datasets;

— Repository for all survey data (field books, working files);
— Security plan to ensure storage and backup during collection;
— Proprietary software or formats not based on open standards that would diminish the long-term viability of the data;
— When converting data from one format to another, identification of the procedures to ensure completeness and accuracy of the data being converted.
  - Data access policies;
  - Sensitive information that would require confidentiality protection;
  - Copyright ownership of data.

3. Data use, sharing and distribution:
   — Procedures for partner access to all data (such as remote sensing, geological, geophysical, geochemical, drill hole, mineral resources);
   — Proprietary data that are not available to partners.

5.2.10.2 Data collection procedures

The information from the uranium exploration project is collected and stored on paper and/or in digital format. The most appropriate way of recording information should be defined prior to commencement of field work. Data collection procedures should ensure clarity and consistency of exploration data. In large national uranium exploration programmes, it should be ensured that the data conforms with long term national data management schemes and objectives, so that project data are intelligible and accessible to future users. Consideration ought to be given to this before commencement of the exploration project, and a decision made as to whether the project owner will be the designated final custodian of samples and project data, or whether some other national agency will have ultimate responsibility for management and storage and ensuring compliance with data strategies and policies (see the previous Section on the data management plan).

Collection of exploration data with paper forms requires that data need to be transcribed which always involves the risk of incorrect data entry and data loss due to an unforeseen disappearance of paper forms. Alternatively, data entry can be undertaken using a data collection application which is a computerized system for the collection and storage of qualitative and quantitative data in an electronic form. The benefit of using a data collection application is that it eliminates the use of paper forms and allows data to be quickly exported to the project database and GIS software for data review and reporting. Data collection applications make it possible to collect data on a mobile phone, tablet, or rugged laptop. It is generally desirable for the data collection application to be capable of gathering data offline in the field which allows the geologists to enter data directly on their mobile device and upload it into the project database and GIS software at an exploration camp or office.

In outcrop geological mapping, the use of mobile phones, tablets or rugged laptops with a data collection application allows the geologists to enter relevant data fields in real time, and each device is then synchronized with the master database at the end of each field day if areas are remote from effective internet access. This to some extent avoids the risk of errors in data transfer, allows backups and ensures that the data fields are standardized (see the next Section on data dictionaries and pre-defined dropdown pick lists).

Mobile phones and tablets also have built-in cameras which means that it is easy to take photographic images of outcrop, which can be regarded as valuable virtual samples. Photographs can thus be considered as samples and should always be linked to the coordinates of the observation point, or drill hole depth. In-built global positioning system (GPS) can facilitate geotagging of photographs, so the coordinates are automatically embedded into the photograph.

5.2.10.3 Data dictionaries and pre-defined dropdown pick lists in the exploration databases

Constrained predesigned domain lists improve the quality of exploration data. A data dictionary and hierarchical vocabularies using separate and standardized database fields should be developed to describe, define, and constrain terms, such as rock names. It is advised that pre-defined dropdown pick lists (lookup tables, also known as domain lists) are used in the exploration databases for lithology (rock names), alteration, colour, texture, grain size, analytical method, and instrument. Pre-defined dropdown pick-the lists greatly improve data integrity, conformity (e.g., spelling), usability (e.g., search commands) and validity across the databases to ensure that all data can be utilized, queried, exported or converted into other useful formats. When for example a rock name is inserted into the lithology data field, only pre-defined rock names can be entered. In this case, dropdown list for entering lithology is gathered from lithology domain list and there is no way to enter any other value for that field. This approach creates more integrated data, and the vocabulary file can be defined in several languages when domain lists are in use.

However, the use of standardized data fields can pose a potential risk that geologists might tend to simplify outcrop observations when unable to describe freely and qualitatively. Therefore, data entry interfaces with structured database templates should also contain database fields for free-format description to allow for detailed plain-language descriptions.

5.2.10.4 Coordinates

Coordinate systems need to be clearly specified for acquisition, data delivery, reporting and storage. The coordinate system depends on the scale of the exploration area and the type of data being used. In an established mining district, local mine grids may be in use. The choice of a national grid datum is obvious and standard practice, and most software will provide algorithms for conversion for example from longitude and latitude degrees to universal transverse mercator grids.

Accuracy of the desired sample locations depends on the scale being utilized. In reconnaissance mapping and sampling, most hand-held GPS devices (mobile phones, tablets, and rugged laptops) ought to suffice for accuracy, routinely providing 1–10 m accuracy. High-precision differential GPS measurements can be desirable and are becoming more freely available but can add extra time and cost and are typically used during the detailed and advanced stages of exploration.

During geological mapping, it is also good practice to record GPS routes (GPS tracking) to indicate locations that have been traversed even if no useful information was collected or record. This can help with planning for future investigations. A record of the route also provides a cross reference in case there is some uncertainty with observed and recorded locations.

5.2.10.5 Recording anomalies and targets

Exploration involves the application of many different methods at a variety of scales in order to identify new anomalies and targets. This is an iterative process requiring skilled geoscientists to process, model and interpret the data. Effective exploration generally requires the integration of the different methods. Identified anomalies are generally variations from the normal background response of a singular dataset, which does not necessarily relate to a uranium mineralization process or warrant field checking. On the other hand, targets are considered more prospective, ideally derived from more than one dataset, and generally require field checking. It is important for these to be recorded in reports and in a centralized GIS database which can be updated regularly as the exploration evolves.

To help guide field assessment priorities, any target file should incorporate a ranking system. A central target file should:

- Identify exact locations of interest;
- Share information with the broader team and across disciplines;
- Preserve observations and ideas;
- Describe the characteristics (e.g., method, size, shape, intensity);
- Identify the geological context (e.g., lithology, structure, morphology, alteration);
- Record ancillary information;
- Rank the features:
  - Prioritize field work;
  - Identify low priorities to be checked if in the area (but may not warrant a special trip);
- Record field follow-up results (which upgrades or downgrades the target).

Any target ranking system should be agreed upon by the exploration team and should incorporate a multi-disciplinary approach. It should be based on the deposit style mineral system characteristics and processes, which may evolve during the exploration work as the knowledge and understanding of the target is better understood. Some characteristics may be considered more important than others and therefore attract an increase in weighting. Situations often exist where characteristics are not known, for instance where cover obscures the geology. In these instances, the ranking system should not penalize the overall score but instead preserve a ranking to highlight the requirement for further work or possible favourability.

5.2.10.6 Labelling system for samples, drill holes and trenches

There are obviously multiple ways of labelling, with the most important aim of being clear, simple, and consistent. All samples should be collected using the packaging and labelling of samples in such a manner as the sample numbers are unique and indelible (permanent). It is proposed that pre-numbered sample tags should be enclosed in every sample bag. For drill core sampling, there are well-established procedures for assigning unique labels for drill core and quality control samples (standards, blanks, duplicates). Conventionally, this can be written into custom-designed field notebooks that also have a detachable tag to insert with the relevant samples. The use of a spreadsheet for capturing these data could be problematic because there is always the risk of error in transferring to the database, or if the user modifies the spreadsheet structure and it is still necessary to attach a sample label for analysis.

Exploration projects might also include reassessment of sites with historical data from outcrop observations and sampling from exploration trenches. The numbering system in the database needs to take these into account, which may also involve some work in checking coordinates and sample accuracy.

It is important to label drill holes and trenches in a logical manner which is unique and reflects the geographic area. One option is to label drill holes with an abbreviation to denote the project name (usually a geographical place name, or a company name), type (e.g., DD for diamond and RC for reverse circulation and TR for trench) and sequential number. Other options for the labels are to incorporate the map sheet or year.

For occupational safety reasons, as well as for obvious uranium exploration interest, it is necessary to clearly label the presence of radioactive samples using standard symbols (see Section 5.2.13 on radiation protection in uranium exploration).

5.2.10.7 Data verification and database quality control

Exploration data should go through sufficient stages of quality control measures to avoid any errors or omissions, such as mislabelled or duplicate fields, ambiguous terminology, non-lithological names, spelling errors, missing data, and null fields in the project databases. All project databases should be carefully checked and corrected by the exploration organization in terms of potential errors, omissions, incorrect data entries and spelling mistakes. This kind of rigorous quality control reviews of the datasets should be carried out before posting data to the final repository, such as the government server. This is important to ensure the data is reliable and suitable for the next development stage or any other exploration purposes in the future. Any potential deficiencies in the existing databases should be checked and corrected before starting the next exploration stages.

It should be noted that the national and regional reporting codes and standards (such as the JORC Code, or NI 43–101) are guidelines, suggestions and minimum standards for reporting and they do not regulate the procedures used by an exploration organization to measure and record geoscience and exploration data. For example, the Competent Person takes responsibility for the data validation and measures taken to ensure that data has not been corrupted by transcription or keying errors between its initial collection and its use for Mineral Resource estimation purposes [5.6]. For the purposes of the JORC Code, these items should be discussed in the technical report and if it is not discussed then the Competent Person should explain why it has been omitted from the documentation.

5.2.11 Project reporting planning

Reporting of exploration results, mineral resources and ore reserves requires reliability, transparency, and accuracy from an exploration organization [5.3]. It should be noted that many Member States do not have their own national codes for reporting their exploration results. However, governmental uranium exploration organizations can also report their results using the widely known reporting codes and standards, such as the JORC Code, or NI 43–101. These reporting codes and standards set out minimum standards, suggestions, and guidelines for reporting of Exploration Results, Mineral Resources and Ore Reserves [5.6] and have been developed in accordance with the reporting template of Committee for Mineral Reserves International Reporting Standards (CRIRSCO), with the objective to promote reliability, transparency, and high standards of reporting of exploration results, mineral resources and ore reserves [5.18].

The adherence to a reporting code or standard of the CRIRSCO-family standards is highly advised for Member States which have identified the need for attracting investments from foreign exploration and mining companies that might see a considerable advantage if reporting is carried out in accordance with a well-known reporting standard. In these instances, international investors can make more reasoned and well-informed investment decisions based on a reporting framework which transparently describes all relevant aspects, uncertainties and risks relating to the results of a uranium exploration project [5.3].

If Exploration Results, Mineral Resources or Ore Reserves will be reported in accordance with a CRIRSCO-aligned reporting code or standard (such as the JORC Code, or NI 43–101), an exploration organization ought to provide a Competent Person for a uranium exploration project. It should be noted that the reporting codes and standards are not guideline documents specifying procedures to be followed in exploration projects. For example, they do not specify how to collect samples. The Competent Person, who takes responsibility for the compilation and reporting of Exploration Results or Mineral Resource estimates, is the authority for making such choices and should have sufficient experience in a deposit type, the style of mineralization, exploration methods, sampling, and analytical techniques relevant to the deposit under consideration, as well as being aware of potential problems that could affect the reliability of exploration data [5.6]. All these aspects need to be carefully explained and described in the technical report, together with a comprehensive review and appraisal of any previous exploration activity, or metallurgical and economical assessments in the case of more advanced uranium exploration projects. The Competent Person is expected to carry out such work in accordance with industry good practices and should disclose the reasons for any deviation from accepted practices. The reporting codes and standards are therefore written for the Competent Person to disclose and report all the material facts rather than being a practical guide to execute the exploration work. In other words, the reporting codes and standards do not prescribe exploration procedures, protocols and resource estimation practices but rather refers to them in respect to how they should be reported.

The CRIRSCO-family reporting codes and standards cover the reporting of exploration results from all stages of work from reconnaissance to advanced exploration, stressing the importance of the following principles [5.18]:

- Transparency: All information contained in the Technical Report should be disclosed in a manner that is sufficient, complete, unambiguous, and easy to understand such that the report is not misleading;
- Materiality: The Technical Report should contain all information that would be expected and reasonably required by an investor or by its investment advisor relevant to making a reasoned and balanced judgment regarding an investment decision;
- Competence: The exploration work should be carried out under the supervision of a Competent Person who bears the responsibility for the quality of the work performed and the compliance of the Technical Report, and whose actions are subject to an enforceable professional code of ethics.

5.2.11.1 Monthly progress reporting

As described in Section 5.2.5, large national uranium exploration programmes may be broken down into individual exploration areas and subprojects, each active exploration area led by a team leader (see Fig. 5.5). It is advised that each active exploration area will be reported individually each month. A standardized monthly report format would allow for easy tracing of the exploration work from month to month. It would also simplify reporting since each team leader (or site leader, or similar) would be responsible for generating its own report. The suggested outline and chapters of a monthly progress report are:

1. Summary of the geological target;
2. Plans for the month;
3. Work accomplished (e.g., drilling cross sections);
4. Work not done and reasons;
5. Major observations;
6. Conclusions;
7. Plans for the next month.

These monthly progress reports should describe geological observations that are material to the ongoing project. The content should not be an exhaustive record of the work carried out however senior management of the project owner should be able to identify incremental additions to the knowledge base for each exploration area. Additionally, there might be a need for subdivision both on the basis of different mineralization styles and the designation of distinct regions containing exploration targets to allow the senior management to understand how each exploration area progresses during the exploration project.

Unnecessary repetition between the monthly progress reports should be avoided so that it is easy to understand what new information has been added in the reports, and what has been done during the reporting period. The progress reports should also give sufficient information on future plans for the exploration areas, including suggestions concerning the justification for continuing exploration or what work might be planned. In addition, there should be a detailed summary of the arguments for such areas where there is a suggestion to discontinue the exploration work due to low uranium potential.

In addition to technical reporting, an exploration organization should plan how the exploration activities and results will be communicated with the local community (see Section 5.2.15).

5.2.12 Quality planning and standard operating procedures

The selected exploration methods should follow the industry good practices. Therefore, quality planning is one the most important tasks during the planning process of the uranium exploration project, especially because several persons typically carry out similar exploration work and data can be collected over a long period of time. Through careful quality planning, an exploration organization can ensure that the data being produced over the course of the uranium exploration project is consistent and of high quality. From a practical perspective, this quality planning is implemented by developing and documenting SOPs during the exploration planning stage. The SOPs are documents that provide practical guidelines and step-by-step instructions to the field personnel in the execution of the exploration work. The SOPs should give sufficient information on the QAQC programme and procedures for chemical analysis, drilling specifications, drill core sampling, drill core logging, site security and the storage of core trays. It is suggested that the SOPs will be developed on the basis of generally accepted industry good practice guidelines which are summarized in this subchapter.

The written documents (i.e., SOPs) do not solely guarantee that the actual field work will be carried out in accordance with industry good practice guidelines. Therefore, the supervising geoscientist (also known as a Competent Person) should also check and control the exploration procedures at regular intervals to ensure that practical guidelines are followed by everyone in the field and core logging facility [5.4]. This is also important in relation to the use of agreed and standardized names for lithological or stratigraphic units in geological mapping and geological diamond drill core logging.

Quality planning should be done prior to commencement of the field work. As exploration planning can be followed by any kind of exploration phase (reconnaissance, follow-up, detailed, or even advanced exploration/deposit studies), the SOPs can vary greatly depending on the maturity of exploration areas and the exploration phase in question. The guidelines and suggestions in this chapter are general in nature and should not be considered too prescriptive for quality planning. They do not address all procedures and protocols for carrying out specific field work, surveys, or practices in data collection during the exploration project. Rather, these suggestions address general approaches that enhance the quality and consistency of exploration data to avoid common deficiencies which can be encountered during the field work and surveys.

5.2.12.1 Drilling procedures, hole locations and deviation surveys

Drilling is one of the most important exploration techniques in uranium exploration. It typically starts during the follow-up exploration phase and becomes the major exploration activity in the detailed and advanced exploration/deposit studies phases when the main goals are to identify significant uranium mineralization and to define uranium resources.

In general, drilling becomes denser and more detailed as exploration progresses through the exploration phases. A typical progress can be outlined as follows:

- Reconnaissance exploration: commonly no drilling, but in some cases the possibility of carrying out a limited amount of drilling may be considered to evaluate and verify the deposit model;
- Follow-up exploration: drilling with a sparse drill hole spacing with the objective to locate and intercept high-grade uranium mineralized intervals for detailed uranium exploration;
- Detailed exploration: prospect-scale intensive drilling with a dense drill hole spacing with the objective to identify and delineate significant uranium mineralized zones, to establish the geological and grade continuity of the uranium mineralization representing the discovery of a deposit, and to define Mineral Resources (usually at the confidence level of Inferred Resources);
- Advanced exploration/deposit studies: deposit-scale dense grid drilling with the objective to define Mineral Resources at the confidence level of Indicated and Measured Resources.

The priority and amount of drilling can also vary depending on the uranium deposit type in question. For example, the primary method suited for the exploration of sandstone deposits is drilling. Therefore, the main emphasis of exploration for sandstone deposits should be on delineating targets for drilling through geological mapping and downhole geophysical surveying by identifying the potential strata and conditions for the development of redox fronts. Diamond drilling is commonly needed for most uranium deposit types because it provides a means of verifying the data obtained from other exploration methods and provides the ability to revisit and sample the drill core for further investigations such as mineralogical characterization [5.8].

Exploration should be done in a logical manner and targets for drilling should be identified after finishing comprehensive field exploration programmes, data compilation and systematic evaluation of the results of the preceding work before drilling, such as ground follow-up of radiometric anomalies, regional and detailed geological mapping, geochemical surveying, radon surveying, geophysical surveys, trenching, mineralogical studies and chemical analyses. Based on these exploration results, and the conclusions made from them, targets with the greatest potential should be chosen for detailed work and drilling. The geologists are encouraged to prepare a working cross section of the drill holes showing the expected target location for every hole drilled. The cross-sections should be updated on a regular basis as the drilling programme progresses.

The appropriate exploration drilling techniques are generally limited to diamond core drilling, reverse circulation (RC) drilling and rotary drilling methods, and the choice between these three will depend on the need to recover a representative sample and the degree of consolidation of the formation being drilled. In some cases, the upper part of deep drill holes may be drilled using RC equipment with a change-over to diamond core drilling above the target zone to ensure optimum sample recovery. It should be also noted that the radiation aspects vary depending on the drilling method. Diamond drilling is conducted wet and therefore it generates only little dust. Rotary drilling methods are also used for sandstone uranium exploration. However, percussion rotary air blast (RAB) drilling uses air as the primary flushing medium, and as a dry drilling process it can generate significant amounts of airborne dust which could result in internal radiation exposure from the inhalation of long-lived radionuclide dust [5.19].

The drilling procedures should be standardized so that the highest quality of core or other samples will be ensured. The selected drill hole diameter should provide sufficient representative sample material for geological description, geotechnical characterization and chemical analysis. The core recovery should be close to 100%. In a hard and competent rock mass this is not particularly difficult to achieve but in fractured zones and in soft and unstable or poorly consolidated formations high core recoveries could be more difficult to meet. Therefore, wireline triple tube core barrels or larger core diameters should be considered. However, the SOPs should not provide overly prescriptive requirements for the minimum recovery percentage because occurrences of low drill core recovery can be encountered in some intervals due to high degrees of alteration or structurally damaged rocks with abundant fractures associated with faulted zones.

Core losses should be accurately reported in the driller’s logbook or by other means metres of core that have been lost, and from what depth, should be clearly stated and marked in the core tray. The drillers should be instructed to minimize the manual breaking of drill core to fit it in the core tray. These breakages should be avoided to the extent possible.

The amount of error related to the planned azimuth and inclination should be kept to a minimum. This can be accomplished by avoiding the use of worn-out drill bits and reaming shells which should be replaced as soon as they lose the ability to maintain the gauge of the drill hole. The drilling contractor should be encouraged to use a stabilized core barrel which essentially has additional diamond-impregnated reaming rings to maintain the diameter of the hole, thus enhancing the circulation of drilling fluids and reducing friction between the rock wall and drill rods. For deeper holes, wedges can be used to redirect deviating holes to intersect targets in some circumstances.

The drilling method should be appropriate to the lithologies being investigated, the objectives of the drilling programme, and local drilling conditions. Caution needs to be taken when holes are planned, to ensure that all geological factors are considered. Vertical holes are advised primarily in sedimentary systems if bedding is flat and there is no need for core orienting and structural measurements. If the bedding or mineralized structure is inclined, a series of inclined holes should be planned to be drilled perpendicular to the orientation of the target. Precautions should be taken when drilling in areas with the potential to intersect artesian water aquifers, or zones of hydrocarbons.

The planned drill hole location, azimuth and inclination should be systematically verified before drilling. In order to achieve sufficient azimuth accuracy, a GPS instrument may be used to measure the location of a drill hole with pickets (poles) established by compass to indicate the direction of the hole with the angle measured by a clinometer. For infill or detailed drilling projects where a higher level of accuracy is required, a differential global positioning system is suggested to provide cm-scale accuracy for the collar location, or alternatively the location may be measured with a total station or similar instrument relative to an established benchmark.

Drill hole deviation surveys should be undertaken at regular intervals, downhole, using techniques and instrumentation suited to the hole size, angle and length of holes, and the magnetic nature of the host rocks. For instance, a gyroscope instrument is not affected by magnetic interference and can thus be used for measurements inside wireline drill rods and steel casing. A gyroscope instrument can also be used in vertical holes. Drill holes should be systematically measured by deviation surveys before removing the casing from the collar.

Core drilling is normally carried out by the wireline method wherein a core barrel is locked in place at the bottom of a drill stem. The core-filled core barrel is removed from the drill hole at fixed intervals (nominally three metres unless a blockage occurs), and the drill core is removed from the core barrel and placed in rigid and durable core trays (wooden, metal, plastic or waxed cardboard), depending on availability and suitability to prevent deterioration. The hole number and tray number should be marked on the upper left-hand side of each core tray.

In core drilling, the drill core is to be placed securely in each core tray in order from shallow to deeper, left to right from top to bottom. The core height should not be above the tray height. The core should fit into the row in the tray with ease, but not too loose, to avoid excessive sideways movement. Depth blocks (such as labelled wooden blocks marked with the hole depth) should be placed within the core tray between drill core to identify the end of each drill run (core run) and to prevent sample movement and mixing within a row in the core tray, especially when there is core loss or core recovery is poor. The drill hole number, core tray number, and contained metre interval (the start and end depth) should be marked by a weather resistant means in each core tray. Once the tray is filled with core, it is stacked prior to transporting to a secure location where a detailed geological examination and sampling of the core will be carried out.

Drill hole locations should be systematically positioned in the field using a handheld GPS or differential global positioning system for increased accuracy which is particularly important when undertaking deposit studies. In some instances, entire drill holes, or uranium mineralized intervals, will be closed by plugging and cementing to prevent water incursion into future mining operations and to prevent environmental contamination. The latter may be a regulatory requirement, and accurate documentation is suggested in these instances.

5.2.12.2 Downhole radiometric probing

Downhole radiometric probing (also known as borehole gamma logging) is an indirect measurement of uranium grade, requiring rigorous attention to calibration and correction factors along with sufficient QAQC protocols to establish the accuracy of results. Downhole radiometric probing can be undertaken on open holes after drilling or within drill rods immediately following termination of a hole. Caution should be exercised if the total count gamma probing data are used to measure the equivalent uranium content because thorium and potassium can also contribute to the gamma ray activity of the rocks. Nevertheless, where uranium mineralization occurs, the contribution of other radioelements is generally negligible or can be accounted for by simple corrections. Downhole radiometric probing can guide core sampling and if the deposit is in equilibrium, then there are several potential benefits over geochemistry, for utilization of probing alongside geochemistry including:

- High spatial coverage (readings collected at 5 cm intervals);
- Results are available on site in the field;
- Represents a broader volume of material (~30 cm radius);
- Potentially cheaper than chemical assaying;
- Not as affected by poor core recovery or core loss (especially important in fracture zones);
- Preserves samples and core (rather than destroying it for geochemical analysis).

The only reliable way to determine uranium content is to obtain a geochemical analysis which measures uranium content directly and is not affected by the proportions of its daughter nuclides present. If downhole gamma probing data is used for resource estimation purposes, the validity of calculated equivalent uranium should be confirmed and demonstrated with chemical assay determinations. Otherwise, the equivalent assay data cannot be merged with chemical assay data and cannot be used for resource estimation.

Gamma ray emissions of the uranium decay series are mostly generated by radium (98%), not by uranium itself (2%), and therefore any disequilibrium problems affect downhole radiometric probing [5.20]. Uranium in its hexavalent state (U^{6+}) is mobile in the geological environment (see also Section 5.2.6) and as a result, the radioactive equilibrium between uranium-238 and radium-226 in the uranium-238 decay series is often disturbed, leading to radioactive disequilibrium. Equilibrium is attained in the uranium-238 series when all the daughter nuclides (such as radium-226) decay at the same rate that they are produced from the parent nuclide (uranium-238). It takes approximately 1 million years for radioactive equilibrium to be established [5.20]. At equilibrium, each of the daughter nuclides of the uranium-238 decay series are present in a constant proportion to its parent nuclide (uranium-238). The loss or gain, by geologic processes, of any of certain nuclides during the more recent part of the existence of a uranium-bearing mineral causes disequilibrium in the proportions of the parent nuclide to its daughter nuclides [5.21]. In the case of radioactive disequilibrium, downhole gamma probing may not be a reliable measure of uranium concentration. Correction for radioactive disequilibrium can be applied based on laboratory analyses for both uranium and radium content [5.20]. Alternatively, if the uranium deposit exhibits significant disequilibrium, it would be best to use probes that are unaffected by radioactive disequilibrium, such as a prompt fission neutron tool to directly determine the concentrations of uranium.

Corrections are required for estimating equivalent uranium from total count gamma rays [5.22]. Key corrections are for the casing (if collected within drill rods), water presence, drill hole diameter, size of detector, detector deadtime and the Z-effect. The Z-effect is the absorption of gamma rays by the uranium minerals, which is increasingly important for high-grade zones, and in these situations, Geiger-Mueller and shielded probes are sometimes employed. To apply appropriate corrections, probes should be regularly calibrated at a facility of known grades, which appropriately replicate the field situations, and gamma ray transport modelling may be employed to account for the variations not readily replicated by calibration facilities.

5.2.12.3 Geological logging and drill core preparation prior to core sampling

Drill core sampling should be carried out after the core is washed, core depths are verified, core recovery and radiometry are recorded, oriented core measurements are taken, geological and geotechnical logging are completed, and core photographs are taken for each drill hole. Drill core should be retained and protected so that it can be revisited in the context of new information or the need for additional sampling.

Drill core should be transported in standard sealed core trays from the drilling site to the project core logging and storage facility in a secure location which may be near the drilling site or at the project office. Once there, the core trays should be moved to the core logging and sample preparation room or to the core shed for core washing, core depth and recovery verification, core logging, radiometric scanning, and geochemical sampling.

Core should be pieced together to replicate the drill hole, preferable using an orientation rack attached to the roller logging table. If core is oriented, a bottom of hole mark can be transferred along the length of the core run by matching broken ends on an orientation rack. An orientation rack will ensure that the oriented core samples can be marked in a uniform manner. Core depths need to be verified and metre intervals should be systematically marked on the drill core trays. This procedure ensures that each drill run will be checked and instantly corrected in case of error. This will also make it possible to carry out different measurements and sampling according to uniform use of metre intervals, while reducing the risk of human error, which is obviously far greater if metre interval markings of core are missing.

Drill core should be systematically measured to determine core recovery on a per metre basis. Core recovery should be calculated and recorded in a logging spreadsheet (such as MS Excel) or entered directly into the database. Core loss needs to be marked on the core tray too, for example on wooden blocks (depth markers) between core runs.

Drill core logging should be done systematically by qualified geologists and overseen by the supervising geoscientist (a Competent Person). All geologists involved in core logging should agree on a consistent nomenclature for identifying lithologies. All drill core logging information should be digitally recorded and stored in a structured digital database or a spreadsheet (such as MS Excel) during the core logging process so that data can be used easily in any GIS or geological modelling software. In national uranium exploration projects, it is important that the data are also transferable into the national geological database structure, usually maintained by a national geological survey. To ensure data integrity and minimize spelling errors, rock naming and coding should be clearly defined and consistent, using coded values with pre-defined domain lists (‘vocabulary files’) working as ‘drop-down’ pick lists in the databases (see Section 5.2.10 on data management planning).

Any mineralized section should be more carefully observed, described, and recorded, and compared with the section of non-mineralized rocks. Geologists logging the core should be encouraged to record details rather than brief notes for mineralized sections. Radiometric gamma scanning using handheld scintillation count rate metres or portable gamma ray spectrometers should be conducted on the core to define which part of the core will be sampled for chemical analysis. If uranium mineralized core or samples are viewed and handled, external radiation exposure of the workforce could result from the direct external gamma radiation from mineralized core. This should be always considered in radiation protection measures for the workers handling, logging, sampling, cutting, storing, and transporting drill core and samples because these activities may bring workers into close proximity with the radioactive samples (see Section 5.2.13).

During geological logging, lithological intervals should be recorded and stored in the database for all holes. Once the core is radiometrically scanned, the drill core should be logged by geologists recording their observations on field log sheets or directly in the database. Appropriate software should be used to input raw data for geological recording of drill hole data as a strip log. This can be done using commercially available proprietary logging programmes or a spreadsheet custom designed for the purpose. In commercially available software, appropriate scales can be chosen, and a symbol library is available for rock types. At the start of the drilling programme, parameters regarding rock naming and descriptions should be established. Software should also allow for detailed, plain-language descriptions in addition to pick lists.

Information captured during the core logging should include the drill hole number, length of hole, azimuth, dip, drill hole completion date, lithological descriptions, mineral composition, porosity, grain size, textures, alteration features, colour, structural features, the presence of sulphides and carbonaceous material (important especially for the sandstone exploration projects), estimated mineral contents, descriptions of mineralized intervals (uranium, and other minerals of interest), a descriptive log of the core, oriented core measurements (alpha and beta angles), and any other noted physical and geotechnical characteristics (recovery, maximum grain size, friability, and fracture density). These data are then transferred from the field log to computer and imported into the drill hole database. In commercially available software, selected components of the downhole electric log including gamma radiation values can be imported and displayed beside the geological strip log. A geological strip log can be used for both core and RC drilling.

All information on the level of radioactivity, style of mineralization, lithology, structural features, lithological boundaries, mineralogy and alteration should be collected and used in interpreting the mineral system. These observations and assay data are essential for geological modelling, understanding the geometry and continuity of the mineralization, and the resource estimation. All records, regardless of the type of data, should be in a standardized and easily accessible format. The drilling results may be viewed in a 3D environment as part of geological interpretation and monitoring of drilling quality.

As part of the logging process, rock-quality designation (RQD) should be measured on the drill core. RQD is a rough measure of the degree of jointing or fracture in a rock mass, measured as a percentage of the drill core in lengths of 10 cm or more. High-quality rock has an RQD of more than 75%, low quality of less than 50%. RQD also allows the drill core to be checked for completeness and any errors such as core spillage, and the improper placement of core markers.

Core radioactivity should be recorded generally, and especially within the mineralized intervals, preferably with equally calibrated gamma ray spectrometers dedicated to the task to ensure consistency for all loggers. In terms of uranium mineralized intervals, gamma values in counts per second can also be marked on the core tray.

It is suggested that core orientation surveys are included in drilling campaigns. Oriented core measurements provide valuable information on structural trends in cases where a strong structural control is exerted on mineralization. The ability to record fracture and vein orientations provides a great deal of information assisting the interpretation of potentially important uranium mineralized structures, in addition to geotechnical information on fracture density and rock quality. Core orientation surveys using orientation tools are carried out and supervised by the drilling contractor, whereas oriented core measurements (transfer of a bottom of hole mark along the length of the core run by matching core pieces on an orientation rack, and alpha and beta angles) are taken and recorded by exploration geologists who conduct the core logging. There are several techniques to provide oriented core during drilling and it is important to perform sufficient quality control on this activity. Orientation tools determine a bottom of hole position on a portion of the core which is still attached to the bedrock in its original orientation [5.11]. This orientation of core needs to be known and marked before core is cut out and dragged from the ground. A bottom of hole mark is transferred along the length of the core run by matching core pieces on an orientation rack. On the basis of oriented core measurements (alpha and beta angles) and drill hole deviation surveys (hole azimuth and dip), the exploration geologist can measure the original orientation of structures and mineralized veins.

It is important that geological and geotechnical logging are fully completed prior to sampling and core cutting. In addition, all drill core trays should be systematically photographed (usually both wet and dry) prior to core cutting at a drill core logging facility for future review and documentation. Core photography provides significant benefit in case of mishaps during handling of core trays or accidents during transport. This allows independent verification of the labelling of core trays and shows where core has been sampled. Detailed core photos should also be taken to illustrate specific features, such as characteristics of mineralized core.

5.2.12.4 Drill core sampling for chemical analysis

All sampling in a uranium exploration project ought to be carried out using well-designed and uniform sampling practices to ensure that the analytical results are representative and reliable. A geoscientist should supervise the sample collection, sample security and sample transportation to ensure that a Chain of Custody[2] of the project samples is established and recorded. The preparation of samples for chemical analysis should be supervised by a geoscientist to ensure that any work by employees, contractors, researchers, or consultants is carried out by competent personnel, and that appropriate QAQC programmes and sample security procedures are followed for analytical work [5.4].

After the drill core is logged and the information recorded, any mineralized intervals should be marked for sampling based on radiometric and geological data. The core should be sampled entirely across the mineralized interval and extend at least one metre beyond the mineralized zone. Sampling should not cross lithology boundaries or contacts. Core segments with uneven mineralization and different radioactivity intensity should be sampled according to radioactivity levels. Sampling length should be a maximum of 1 metre. Sampling intervals should be marked on the core at the start and end of each interval and a duplicate sample numbering tag should be inserted into the core box at this location and marked with the start and end of the sampling interval.

When sampling, the core is cut in half by a core saw. If structure is present in the core, the plane of the cut should be along the axial plane of the structure such that the cut surfaces of the two halves are mirror images of each other. One half of the core will be placed in a polyethylene or other suitable bag for chemical analysis at the analytical laboratory. The geologist should ensure that the half-core submitted to the analytical laboratory for analysis is as representative as possible. The second half of the core will be retained in the core tray for future reference. The side of the core sampled, left or right, should be consistent across all samples within an interval sampled. To obtain a field duplicate sample, the core sample will be cut further (i.e., cut into quarters). However, all the drill cores should not be cut into quarters, only in half as already noted. In general, the larger the sample delivered to the laboratory for analysis, the more representative that sample will be because the irregularities in the distribution of mineralization will be averaged within a larger sample volume.

[2] The term Chain of Custody refers to the written record of the collection, handling, packaging, storage, transport, and receipt of samples.

Accurate and complete sample documentation is essential for verifiable and compliant reporting of results. Sample lists and filling of ticket books are important documentations for providing an audit trail as a means of checking the analytical database for errors and ensuring data quality. Samples should be sequentially numbered and data recorded for hole number, start depth and bottom depth for each sample interval, sample weight and radioactivity in counts per second.

Occurrences of low drill core recovery can be encountered in some uranium-mineralized intervals due to high degrees of alteration or structurally damaged rocks with abundant fractures associated with faulted zones. For mineral resource estimation, wherever core recovery is less than 75%, the radiometric downhole probing equivalent uranium values should be substituted for chemical assays where possible [5.23]. However, the validity of equivalent uranium (eU) values measured by spectrometric downhole gamma probing should be confirmed with chemical assay grades in areas of good core recovery such that a direct relationship between radiometric values and geochemical values can be demonstrated.

5.2.12.5 Sample security, transportation and chain of custody

Sample security, sample transportation and aspects of Chain of Custody should be carefully planned already during the exploration planning phase. The security of samples is a vital component of the sampling process to ensure the Chain of Custody. The term Chain of Custody refers to the written record of the collection, handling, packaging, storage, transport, and receipt of samples. This means that the possession of samples all the way from the collection at the field to the receipt of samples at the analytical laboratory should be conducted under a strict and traceable Chain of Custody protocol. The collection and packaging of samples for shipping should be taken by field personnel under the supervision of an exploration organization’s site managing geologist.

Drill core is typically transported from the drill site to the core logging and storage facility in core trays on a regular basis. Drill core trays should not be left unattended at the drill site in the field until such time as the drilling of a target is completed. This practice would introduce concerns about the security of the drill core since the core would not be guarded and would be vulnerable to damage by passing domestic animals, human tampering or even destruction by individuals who may oppose uranium exploration in their territory. Good practice is to cover the trays and seal them shut with strong wire. A secure drill core tray storage facility, such as a fenced area, storage room or container under lock and key, should be arranged to ensure sample security.

Core samples collected from drill core should be always bagged and stored in a secure storage facility until shipment to the analytical laboratory. Once sampled, core trays should be stored in a core storage facility with core trays being covered to further aid in preservation of the core. Samples should be bagged, systematically labelled with the sample number and temporarily stored in a secure sample storage facility (e.g., fenced area, storage room or container under lock and key) in order to ensure sample security until shipped by truck to the analytical laboratory that carries out the sample preparation and chemical analyses. There are also conditions related to radioactivity, especially in the case of export and delivery of samples (see Section 5.2.13).

Individual sample bags should be securely closed, preferably with tamper-proof seals that have a predetermined number that can also be used as the sample number. Alternatively, the sample number may be on a weatherproof tag included in the bag and with the number inked on the outside of the bag. If possible, a bar-coded sample tag may be stapled on the outside of the bag and a duplicate sample tag inserted into the sample bag. When an interval is sampled, a duplicate sample tag for that interval should be affixed to the core tray, also for future reference. In addition to regular samples, field duplicate samples (the quarter of the core), certified reference materials (CRMs) and blanks are inserted into the sample at regular intervals by field personnel (see subsequent Section on QAQC programme). Groups of consecutive samples should be shipped together in a sealed container which could be a polystyrene rice bag or some other container to which a numbered seal can be attached.

Samples should be stored in a well-ventilated, secure location before transport to prevent contamination and damage. Samples should be bagged or trayed for shipment with sample numbers marked on the outside of the shipping container. Instructions for analysis should be included with the shipment. Sample shipments should be transported to the analytical laboratory by a bonded carrier or by trusted project personnel and the analytical laboratory should be alerted to the shipment of the samples and the requested analytical method.

Samples should be shipped on a regular basis to an analytical laboratory. Upon receipt by the laboratory, the seals should be checked to ensure they are intact, and the samples should be logged in and checked against an exploration organization's sample submittal form included with the samples and delivered electronically to the laboratory for any discrepancies.

During final technical reporting, it is important to provide clear and comprehensive information on sample security and Chain of Custody to ensure that all relevant details are documented accurately as it both increases the confidence of the reader in the quality of work done, as well as providing essential information should there be a need in the future to review the results of specific analytical batches. This is a fundamental aspect of the transparency embedded in the reporting codes and standards (such as the JORC Code), designed to ensure accountability at all stages from sampling through analysis and the reporting of analytical results. Even simple details, like dispatch and laboratory return dates could prove important if in the future it were discovered that a particular laboratory had some instrumental drift or calibration error at this time. There are many reasons why this is important. It is much easier to provide all of this information in the technical reports appendices, than for someone in the future being compelled to either exclude the results because of inadequate documentation or contact the laboratory at their own expense. It is essential that this information is reported clearly and accurately in reports as this could cause considerable confusion or at worst, exclusion of analyses from the database, if it were shown later, for example, that there were calibration or analytical bias in a laboratory at this particular time. Reports should also include documentation describing storage and security provisions during the transport of samples from the field to the laboratory.

Additional information on the transport of radioactive materials can be found in the IAEA Safety Standards, *Compliance Assurance for the Safe Transport of Radioactive Material* and *Radiation Protection Programmes for the Transport of Radioactive Material* [5.24] and *Radiation Protection Programmes for the Transport of Radioactive Material* [5.25]. Additional information on the security of radioactive materials can be found in the IAEA Nuclear Security Series, *Security Management of Radioactive Material in Use and Storage and of Associated Facilities* [5.26].

5.2.12.6 Reverse circulation (RC) drilling sampling

In RC drilling a continuous stream of drill cuttings from a drill hole are sampled at a specified interval (e.g., 1.5 m) and collected in a cyclone at surface. In the cyclone the cuttings are mixed, water is removed if present, and the sample is dumped into a riffle splitter or other sample divider to reduce the amount of material and produce a representative sample of approximately 1 kg of material that is sent for analysis. With some drills, the sample is collected in a bucket and manually put through a Jones sample divider by the drilling crew. Depending on the outside diameter of the drill bit the cuttings from a 1.5 m interval can weigh 25 kg or more, so most of this material is necessarily discarded. For QAQC purposes, a field duplicate sample should be collected and analyzed to measure sampling variance.

It is essential that the drill geologist observes the sampling process to ensure that the sample dividing equipment and procedures do not introduce a bias into the material being retained for analysis. It is essential that the sample is homogenized before it is divided or at a minimum that the system does not allow gravity to separate light and heavy minerals and vary how they are directed through the divider.

The RC cuttings should be placed in a bag which allows any moisture present to dry out during transport. Sequentially numbered bar-coded sample tags are placed in each bag and a second tag attached to the outside of the bag. As well, the sample number can be written with a permanent marker on the outside of each bag. Field duplicates, blanks, and standards (certified reference material) should be inserted into the sample stream.

The above description is based on continuous sample of a hole from top to bottom. It is likely that all samples from the top to the bottom of the hole need to be collected during initial uranium exploration. During follow-up uranium exploration, sampling can be more selective, and the entire sample sequence does not have to be shipped for analysis.

From each interval, a geological sub-sample will be collected in a plastic chip tray by the on-site geologist, who studies the washed chips, often using a binocular microscope, and records the information available. Each chip tray should be marked with the hole number and the start and end of the drilled interval within each tray. Geological contacts are usually approximate based on RC drilling and may be amended if downhole geophysical probing is available.

5.2.12.7 QAQC programme for chemical assaying and quality control samples

The purpose of the QAQC programme is to monitor and control the quality of sampling, sample preparation and sample assaying by using quality control samples in the sample streams which are processed through the analytical laboratory. The only way to do this is to constantly monitor the performance of quality control samples (QC)as the sample stream is processed through the laboratory. Laboratory reporting and the results of quality control samples should be evaluated by the exploration personnel to establish acceptable levels of accuracy and precision, and to detect any potential contamination. Any problems should be recognized and acted on with immediate corrective actions taken to fix sampling, sample preparation and sample assaying procedures to make sure that the system is always in control. The QAQC programme should be an integral part of a uranium exploration project in all exploration stages, and especially during the detailed and advanced exploration phases when one of the main objectives is to define mineral resources of a uranium deposit.

The laboratory's own in house QAQC programme should never be the only means for checking laboratory performance. Instead, the exploration organization should use its own QAQC programme to systematically monitor and evaluate sample collection and handling from the field to the assay laboratory. The purpose is to prevent mishandling of samples and eliminate potential sources of uncertainty and issues in the final assay results.

An adequate set of QC samples need to be inserted into analytical sample batches by the exploration organization's personnel prior to sending sample batches to the analytical laboratory.

These QC samples include standards, CRMs, duplicate samples (also known as duplicates) and blank samples. Standards, field duplicates and blanks are typically inserted into sample batches at the project core logging and storage facility, which may be near the drilling site or at the project office. All QC samples ought to be blind (anonymous) to the laboratory, and therefore QC samples should be submitted to the analytical laboratory without any identification marks apart from the sample number (also known as the tag number).

If analysis of the QC samples identifies a failure within a sample batch, action should be taken by the exploration organization and analytical laboratory to investigate and establish the source of the quality control failure. If the results indicate analytical or contamination related errors, the exploration organization should communicate these QC failures with the laboratory personnel immediately after the QC failure is known.

Quality control samples are typically used in the sample stream at a minimum insertion rate of 1:10 insertion rate, representing at least 10% of the total samples. The insertion rate can also be higher depending on the characteristics of the uranium deposit and the maturity of the deposit definition stage. For example, commercial CRMs (standards) can be used with 1:20 insertion rate, representing 5% of the total samples [5.27]. Field duplicate samples can be inserted into the sample stream in every 40 samples, representing 2.5% of the total samples. One blank sample can be included with every 40 samples (2.5% of the total samples). Additionally, pulp duplicates can be analyzed in every 40 samples, representing 2.5% of the total samples. In other words, in an analytical run of 40 samples, two samples will consist of CRMs, one will consist of a blank, one will consist of a field duplicate, and one of a pulp duplicate sample (5 quality control samples and 35 regular samples included in every 40 samples). The foregoing procedure would ensure that quality control samples (CRMs, blanks, field duplicates and pulp duplicates) represent about 12.5% of the total samples which exceeds the industry standard of 10%. In addition to one blank sample included with every 40 samples, blank samples should be inserted within and at the end of the uranium mineralized zone, so the percentage of blank samples should be higher in the sample batches which represent mineralized intervals. It should also be noted that standards, field duplicates and blanks are inserted into the sample stream with regular project samples at the exploration site, but pulp duplicates are obtained by the laboratory from samples already pulverized, and then these pulp duplicates are analyzed with regular samples.

Drill core samples should not be left in the exploration site or sampling site until such time as the drilling or sampling of a target is completed. In addition to creating potential security problems, this would interrupt the sample flow to the laboratory, preventing the exploration team from having the option of adjusting its work programme based on the availability of new data generated during the project. In terms of the QAQC programme, this would introduce significant delays in the receipt of analytical data in respect to QC monitoring, such as in recognizing any potential sampling errors in a timely manner. Therefore, it is suggested that samples should be shipped to the laboratory frequently and in small batches so that an exploration organization is able to identify potential sampling errors, analytical errors or contamination early enough to systematically monitor the accuracy and precision of the chemical assay data, and to immediately react and adjust its procedures as the sampling, sample preparation and sample assaying processes are ongoing.

The approach to an evaluation of the quality of the analytical data should be clearly documented by an exploration organization. A supervising geologist should verify that the approach will not lead to the acceptance of the failed quality control samples. The results should be summarized in a final technical report accompanied by a control chart illustration with a discussion to clarify whether there is any evidence of improper sampling procedure, cross-contamination during sample preparation, or laboratory bias that affects the analytical results in a significant and material manner. Before any sampling and analytical work commences at a uranium exploration project, the exploration organization's QAQC programme and the approach used to evaluate the results should be well-planned, fully completed and assessed by a supervising geologist to ensure that the QAQC programme meets internationally acceptable standards to assure an exploration organization and other potential investors that the assay data are reliable.

5.2.12.8 Standards (Certified Reference Materials)

Standards (CRMs) are samples with known uranium grades that are certified by laboratories within a specified range of confidence. They are inserted into the sample chain as a test for accuracy of the analytical results. Accuracy refers to how close a laboratory measurement value is to the true grade of the sample [5.27]. Standards should be selected to represent the type and grade of mineralization. Most importantly, data should be generated from similar digestion and analytical methods to determine certified values and standard deviations. If data from different digestion and analytical methods are combined, then there will always be a bias in comparison of certified values with laboratory results. Certified values and standard deviation values, specified according to a digestion method and analytical technique, are shown in each CRM certificate provided by a supplier of the CRM. Prior to acquiring the project's CRMs, it is highly important to make sure that the CRMs have been digested and analyzed during the certification process in the same way as the exploration project samples will be analyzed to allow a full comparison. For example, if the project samples will be decomposed using four-acid digestion prior to analysis, the exploration personnel should not use a CRM which is certified only for aqua regia digestion. Some of the individual CRMs are certified for several digestion methods (aqua regia, four-acid and fusion) which can be beneficial when choosing CRMs for an exploration project. Good practice is to insert standards with a close match to the matrix of the project samples and with grades that are similar to the expected uranium grades in the samples from the interval being tested.

It should be noted that the use of the CRMs is the only way to confidently identify the error in QC data as laboratory measurement error. Otherwise, the exploration organization will be fraught with uncertainty as to the origin of the error. It is suggested that commercially available CRMs are acquired to ensure that only high-quality CRMs will be used. The most important properties of a high-quality CRM are the accuracy of the certified values, low but realistically achievable standard deviations, homogeneity of the certified uranium values with a negligible or very small range of uranium content, well-constrained tolerance and confidence intervals, packaging durability, proper storage, and quality of documentation in the CRM certificate.

When monitoring analyses on CRMs, the upper and lower control limits (the confidence limits) for each CRM are typically set at 2 and 3 standard deviations. The standard deviation (SD), reported in a CRM certificate, provides the control limits to which laboratories should perform during analyses. Plus or minus two or three standard deviations, as reported by the manufacturer of the CRM, from the certified value is generally considered acceptable. In QC monitoring, two or more analytical results lying outside the 2SD window is generally regarded as warning or rejection, and rejection for single results lying outside the 3SD window.

When analytical results are returned from the laboratory, the CRMs for the sample batch should be checked by the exploration personnel to ensure that the reported results fall within 2SD or 3SD of the certified value reported on the CRM's certificate. If a CRM falls outside of the 3SD of the certified value (Fig. 5.8), the analytical laboratory is typically requested to re-assay, at its own cost, 5–20 samples on either side of the CRM along with re-assaying of the CRM itself, to ensure that the assays for the sample batch are not overstated or understated. Similarly, if two adjacent CRMs are greater than 2 SD from the certified value, and on the same side of the mean (Fig. 5.8), the analytical laboratory is typically requested to re-assay all samples between the failed CRMs along with re-assaying of the CRMs themselves, and also 2–5 samples on either side of these failed CRMs. An alternative action in the event of QC failures of CRMs is that the analytical laboratory should re-assay the entire sample batch. The exploration personnel should communicate the CRM sample failures with the laboratory personnel immediately after the CRM failure is known so that potential laboratory measurement errors could be investigated and corrected without delay.

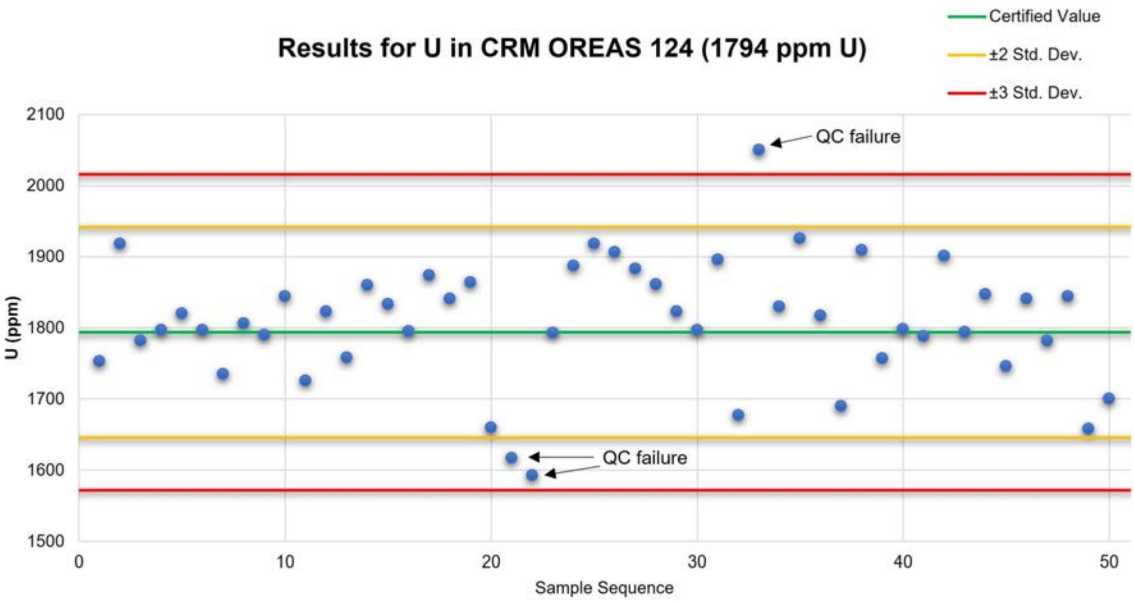

FIG. 5.8. Example of a standard control chart showing one, 3SD (+/- 3 Std. Dev.) outlier and two, 2SD (+/- 2 Std. Dev.) outliers (QC failures). The certified value of this CRM is 1794 ppm U.

In final technical reporting, an exploration organization should explain what actions were taken if results fell outside the range of plus or minus two or three standard deviations from the certified value of the CRM, as well as provide information on how the samples were reprocessed and re-analyzed to ensure that the required quality limits were met. In addition, any discernible patterns, such as consistently higher or lower grades, cyclical increasing or decreasing grades, grades trending up or down (see a sample sequence 25–30 in Fig. 5.8), increasing or decreasing variability in the uranium values, or CRMs returning identical values should be examined carefully and documented in the reports. There should be always a clear documentation of follow-up procedures to investigate the CRM failures, in particular, an assessment of whether or not the other results reported for the sample group are representative, or if they contain other data that are inaccurate.

5.2.12.9 Blanks

Blanks are inserted into the sample batches to detect the presence of any contamination introduced at the laboratory during sample preparation. Poor sample preparation can result in a significant source of bias especially in mineral resource estimation. Therefore, sample preparation methods (such as drying, crushing, splitting, pulverizing, homogenization, mixing, cleaning) should be selected as carefully as the actual digestion methods and analytical techniques. Particularly, sufficient cleaning methods (such as compressed air, sand cleaning, water cleaning, use of blank samples) in sample preparation are important to minimize cross-contamination between subsequent samples.

Blanks should consist of material that are guaranteed not to contain any significant amount of the elements that are of major interest, in this case uranium. Any significant amount of uranium reported by the laboratory in blanks is therefore a red flag to the QAQC manager or supervising geologist indicating that contamination occurred at the sample preparation facility due to improper cleaning of the crusher and pulverizing equipment between the samples. High-quality blank rock material should be utilized to ensure the blank material passes through the same process as the regular samples. Analytical good practice requires that a blank sample should be inserted into the sample stream especially within or at the end of a higher-grade uranium-mineralized intersection to check for potential carry-over contamination during sample preparation.

It should be ensured that only high-quality blank material will be used. In-house blanks can be prepared from a rock type known to be barren based on QAQC testing at a minimum of three laboratories on a quarterly basis to ensure the blank material is of suitable quality. For example, a barren limestone, diabase, or basalt can satisfy the need for blank material in uranium exploration.

When analytical results are returned from the laboratory, the blanks for the sample batch should be checked by the exploration personnel. Blank control charts should include an acceptance line (failure limit). Typically, if a blank gives a result more than 5 times the detection limit (QC failure) of uranium, these sample failures should be discussed with the laboratory personnel immediately, as the failure may be a result of potential contamination due to improper cleaning of the crusher and pulverizing equipment between the samples. If this is the case, the analytical laboratory should be requested to interpose more efficient cleaning methods for the crusher and pulverizing equipment between the samples to avoid any further cross-contamination.

5.2.12.10 Duplicates

Field duplicates (also known as core duplicates for drill samples) are taken and inserted into sample batches to monitor for improper sampling procedure and as a test for precision (also known as reproducibility or repeatability). Precision refers to how close sample values are to one another [5.27]. This quality control measure involves splitting of the whole core in half and one half further split to obtain a quarter core. The purpose of the secondary splitting is to obtain two samples that are similar in uranium grade, a goal that may be difficult to achieve if the mineralization in the core is irregularly distributed. In QC monitoring, the analytical result of the second sample (field duplicate) is expected to be similar to that of the primary sample. When a large variance occurs, the exploration personnel should re-examine the drill core to determine the degree of irregularity of the uranium mineralization within the rock.

Pulp duplicates are used to check for improper mixing at the laboratory. Pulp duplicates are obtained by the laboratory from samples already pulverized. In other words, pulp duplicates are not inserted into sample streams at the sampling site in the logging and sample storage facility, instead pulp duplicates are produced at the analytical laboratory so that both regular sample pulp split and another split (pulp duplicate) will be analyzed. Therefore, there is no physical pulp duplicate sample at the sampling site because pulp duplicate samples will not be produced before sample preparation at the laboratory. In this regard, the laboratory should be clearly informed about the samples which need to be split into two subsamples to obtain both regular sample pulp split and pulp duplicate split. It is a common practice to affix an empty sample bag with the sample number to the regular sample bag so that the laboratory personnel will be aware that a pulp duplicate sample needs to be produced from a regular sample at the laboratory after pulverizing. In QC monitoring, the analytical result of the second sample (pulp duplicate) is expected to be similar to that of the primary sample. When a large variance occurs, the exploration personnel should request a remixing of the pulp samples and re-assaying by the analytical laboratory, or a check assay by a different laboratory (secondary laboratory).

5.2.12.11 External laboratory checks

As a further quality assurance procedure, a sufficient number of the sample pulps can be sent to a different laboratory (secondary laboratory) for assay validation and verification (external laboratory checks). This re-check process should cover different types and different uranium grade levels of the mineralization in question. Typically, approximately 4% of the sample pulps are sent to a reputable secondary laboratory for external laboratory checks. For external laboratory checks, the primary laboratory should be provided with a list of the samples to be re-analyzed and should be asked to ship the pulps directly to the secondary laboratory. The percentage difference between assay returns from both the primary laboratory and secondary laboratory should then be calculated and evaluated.

It should be noted that standards (CRMs) do not necessarily fulfil the requirement to be anonymous (blind) to the laboratory because they are commonly purchased as individual sachets. Therefore, the CRM identification should be removed from the CRM sachet prior to sending sample batches to an analytical laboratory. Otherwise, standards can be easily recognized in the sample batches, and therefore it is possible that these CRM sachets are treated more carefully by laboratory personnel in the sample assaying processes. To overcome this potential anonymity issue, some CRM sample pulps can also be analyzed in an external laboratory as a further quality assurance procedure [5.27]. The accuracy difference between CRM assay returns from both the primary laboratory and secondary laboratory should then be evaluated.

5.2.12.12 Laboratory audit

It is suggested that a primary analytical laboratory of the uranium exploration project will be visited and examined by the QAQC specialists of the exploration organization. The purpose of this laboratory audit is to examine the procedures employed for receipt of samples, sample security, sample preparation methods, cleaning methods, digestion methods, analytical techniques and QAQC protocol. After a laboratory visit, the QAQC specialists should prepare a laboratory audit report to provide suggestions for any potential corrective actions needed.

5.2.12.13 Geochemical laboratory analyses

Geochemical analyses are carried out in all uranium exploration phases to identify uranium and trace element anomalies (i.e., in mediums such as rock, soil, water, biological). From a management-related perspective and to comply with a requirement of the transparency principle, it is advised that the physical sample preparation, sample digestion and chemical analyses are carried out by an internationally accredited laboratory that complies with all requirements of common international standards. The contract between the exploration organization and analytical laboratory should include all relevant information on analytical schedules, possible delay penalties, the terms and quality control criteria for re-assays in case of QC sample failures within a sample batch (see previous Section on QAQC programme), transportation services, and coarse reject and pulp sample storage.

The only reliable way to determine the correct uranium content of a sample is to obtain a geochemical analysis, which overcomes the potential issues associated with uranium disequilibria in regolithic and surficial formations when using only radiometric measurements. Also, this determines uranium directly and is not affected by the proportions of its daughter nuclides present which should always be considered in gamma ray radiometric (spectrometer) surveying.

No single analytical method covers all types of geological materials for all geochemically relevant elements at all concentrations. Sample type, element of interest, geochemical pathfinders and the expected concentration levels of target elements should all be considered when selecting an appropriate digestion method and analytical technique. For the determination of uranium concentrations, it is important to decide how samples will be digested prior to analysis:

- Partial digestion by aqua regia or other weak acid leach techniques;
- Near-total digestion using a four-acid digestion which includes a combination of HCl (hydrochloric acid), HNO_3 (nitric acid), HF (hydrofluoric acid) and $HClO_4$ (perchloric acid);
- Total digestion using a sodium peroxide fusion or a lithium metaborate fusion.

Digestion methods and analytical techniques should be carefully chosen based on mineralogy and uranium grade of the samples. In general, aqua regia digestion readily dissolves many sulphide minerals, oxide minerals and carbonate minerals. Four-acid digestion quantitatively dissolves nearly all minerals, but it may sometimes be necessary to use even stronger techniques, such as fusion, to fully digest niobium, tantalum and REE minerals which may also incorporate uranium in their crystal lattices.
The choice between various techniques should be decided by the expected concentrations of elements of interest. If available, downhole radiometric probing data can be used to guide in selecting appropriate analytical techniques. The concentrations of equivalent uranium (eU) measured by surface and downhole gamma spectrometric probing should be carefully used as a guide in selecting analytical procedures, and the exploration personnel should inform the laboratory about the need for using different methods with a higher upper quantification limit of uranium for high-grade samples. This procedure avoids delays and unnecessary repeating of chemical analysis.

The choice between various techniques should also be appropriate for the mineral composition of the sample, including both the economic minerals and the matrix. Different digestions can have a major impact on the concentrations reported. Therefore, the field geologists who best understand the mineralogy and nature of the geological materials being analyzed need to be actively involved in respect to communicating with the geochemical laboratory.

Strong digestion methods, such as fusion, are needed to ensure complete dissolution of all uranium-bearing refractory minerals in cases where the mineralogy is of a complex and refractory nature. For example, total digestion using a sodium peroxide fusion method is suggested for intrusive uranium occurrences, particularly for peralkaline granite-hosted mineralization, to ensure complete dissolution of refractory minerals to accurately quantify total uranium in samples. It should be noted that weaker digestion methods, such as aqua regia or a 3-acid digestion, do not provide accurate information on the total recoverable uranium. For example, uranium leachable in aqua regia cannot be considered as a means of approximating the amount of uranium that might be recoverable in a commercial operation, and therefore a weaker sample digestion method does not provide the relevant information on recoverable uranium. Instead, recoverable uranium should always be determined by metallurgical test work. Comparison of in situ and recoverable resources is highly relevant for uranium deposits which are at the development stage. During the exploration stage however, it is suggested that chemical assaying provides total (in situ) uranium content in the sample. In this regard, reporting and mineral resource estimates should be based on total uranium content even though some deposits contain a significant component of refractory mineralization. Overall, uranium recovery factors can be determined only through comprehensive metallurgical test work to be done by metallurgists because recovery factors are dependent on different possible metal concentrates and the deportment of uranium during processing, and not simply on mineralogy. In fact, some refractory minerals may partly dissolve during the leaching circuit at the processing plant depending on an individual leaching process, and therefore metallurgical understanding is always needed to provide information on what is recoverable and what is not. However, a potential refractory nature of mineralogy should be described and presented transparently in reporting of exploration results and mineral resources.

It is suggested that initial exploration plans should not provide overly prescriptive definition for the digestion methods and analytical techniques for each exploration site because the methods should be carefully selected by the supervising geologist as the knowledge base evolves over the course of the uranium exploration project. There is a wide range of approaches to digestion and analysis that are possible depending on the mineralogy of the target which should be used as a guide to determine the best digestion method and analytical technique. As many approaches are possible, the optimum approach needs to be determined in discussions between an exploration organization and the analytical laboratory. Prior to commencement of any sampling or drilling programmes, the digestion and analytical methods should be reviewed and approved in advance by the supervising geologist of the exploration organization.

Analytical programmes should involve two or more independent laboratories; one acting as the primary laboratory, and one or more additional laboratories serving as the secondary laboratory for external laboratory checks (see previous section on QAQC programme). It is suggested that the secondary laboratory is not part of the same company as the primary laboratory. The complete laboratory process from the arrival of the samples at the laboratory to final reporting as well as QAQC procedures need to be well documented for future review.

5.2.12.14 Bulk density measurements

Bulk density information should be collected in the detailed and advanced exploration/deposit studies phases when the main goal is to define uranium resources. The three main geological inputs of mineral resource estimations are grade, volume and bulk density. Therefore, the reliable estimation of the bulk density is an important component in the preparation of an accurate tonnage estimate for both the mineralized volumes, and the adjoining non-mineralized or weakly mineralized volumes.

The choice of bulk density measurement method is the responsibility of the supervising geoscientist and depends on the sample material and the physical characteristics of a uranium deposit [5.4]. The bulk density should be measured and recorded at appropriate drill core intervals by a method that adequately accounts for void spaces (such as porosity and vugs), moisture and differences between the mineralized material and adjoining non-mineralized material within the deposit [5.6]. The commonly used methods for determining the bulk density of a deposit include wax immersion, caliper, water immersion, gas pycnometer, vacuum-packed water displacement and geophysical methods.

Special attention should be given to the determination of the volume of specimens that have irregular shapes, are friable, soft, or porous, such as in exploration for calcrete-hosted uranium deposits. It is suggested that bulk density measurements are carried out in an external laboratory that is certified and accredited for the measurement methods used. It is also essential that sufficient number of bulk density samples are taken and measured to obtain a good representation for all geological material types across a uranium deposit.

In terms of bulk density measurements of core samples, the site geologist of an exploration organization should select the actual piece of core to be measured for bulk density to ensure a representative sample of the interval. The sample to be measured for bulk density is typically temporarily taken out of the bag containing other core to be chemically analyzed after bulk density measurements. Therefore, a logical practice is that both the bulk density measurements and geochemical assaying are carried out by the same accredited laboratory. In addition, appropriate quality control procedures should be used to assess the quality of bulk density measurements.

5.2.12.15 Geological modelling and resource estimation

Mineral Resources and Ore Reserves are the key assets in the exploration and mine development projects. The key factors in a mineral resource estimate are the verification of the geology and modelling of geological continuity, grade continuity and grade distribution within a uranium deposit.

In general, geological modelling and resource estimation become more detailed as exploration progresses through the exploration phases. A typical progress can be outlined as follows:

- Reconnaissance exploration: commonly no drilling and geological 3D modelling, but in some cases the possibility of carrying out a limited amount of 3D modelling may be considered if previous drilling data are available;
- Follow-up exploration: the drilling results are viewed in 3D environment as part of geological interpretation and monitoring of drilling quality;
- Detailed exploration: 3D modelling of the deposit especially for the higher-grade zones which are extended for any significant distance. Modelling of the resources can be carried out only if the drilling and sampling provide sufficient evidence of geological and grade continuity. Mineral Resource estimation is usually carried out at the confidence level of Inferred Resources;
- Advanced exploration/Deposit studies: 3D modelling of the deposit based on deposit-scale dense grid drilling and sampling (possibly supplemented by downhole radiometric probing) with the objective to upgrade the confidence level of Inferred Resources to Indicated and Measured Resources with the ultimate goal to develop Ore Reserves.

There are a number of aspects and parameters that should be considered when preparing a Mineral Resource estimate. These include data verification and data adequacy, mineralization controls

and geological model, Mineral Resource estimate data analysis, Mineral Resource classification, reasonable prospects for eventual economic extraction, and reporting of the Mineral Resource estimate, risks and uncertainties.
It is crucial that a supervising geoscientist has relevant experience in the style of mineralization and the deposit type in the activity which that person is undertaking and reporting [5.6]. The supervising geoscientist should carefully consider the style of mineralization and cut-off grade when assessing geological and grade continuity for the purposes of Mineral Resource classification. The determination of the economic cut-off grade is a complex process that involves the integration of geological, economic, and engineering factors. Cut-off grades chosen for the estimation should always be realistic in relation to the style of mineralization and the anticipated mining and processing development options [5.6]. The basis for defining a cut-off grade should always be explained and presented in the technical report on resource estimation.

Data verification and data adequacy for the use in the Mineral Resource estimate include such parameters as Chain of Custody, sampling, sample preparation, sample security and analytical procedures, analysis of the results of QAQC, and downhole radiometric probing data and its QAQC results. In reporting of mineralization controls and geological model, some key parameters include geological and analytical datasets used for the Mineral resource estimate, surfaces, volumes, and other features used to constrain the Mineral Resource estimate, and methodology of modelling of geological domains. Mineral Resource estimate data analysis includes sample support, treatment of outliers, continuity analysis, and rock density. In addition, block model parameters and interpolated variables, interpolation methodology and resource model validation are the key parameters for Mineral Resource estimation and classification.

A Mineral Resource, according to the CRIRSCO template, is a concentration of solid material of economic interest in such form, grade, and quantity that there are reasonable prospects for eventual economic extraction [5.18]. Therefore, mineralization that does not have reasonable prospects for eventual economic extraction (RPEEE), should not be included in a Mineral Resource. The CRIRSCO-aligned codes and standards require that all publicly declared mineral resources have RPEEE. In other words, a Mineral Resource cannot be an inventory of all mineralization regardless of economic viability because the CRIRSCO-aligned codes or standards prohibit the disclosure of estimates regarding the quantities of mineralization that lack economic viability.

The basis for the assumption of RPEEE is always a material matter and should be disclosed and discussed by the supervising geoscientist within the technical report (also known as the Competent Person's Report). The disclosure of RPEEE should also include a discussion of the technical and economic support for the cut-off assumptions applied [5.6]. These assumptions involve various aspects, such as potential mining methods, metallurgical considerations, cost assumptions, uranium prices, and constraints applied the Mineral Resource estimate. Reporting of the Mineral Resource estimate should also include a sensitivity analysis utilizing different cut-off grades, the methodology employed for uranium equivalent grades, the quantity and grade of each resource category, and a comprehensive discussion of all risk factors and uncertainties associated with the Mineral Resource estimate.

In terms of the polymetallic uranium deposits, co-products or by-products may add value to the asset portfolio and support the economic extraction of the deposit. To qualify as a Mineral Resource however, reasonable expectations of commercially viable production for all metals disclosed as a Mineral Resource should be demonstrated. For example, incorporation of thorium into a disclosure of Mineral Resource requires special attention. If there is no expectation that the thorium could become economically viable within a reasonable timeframe, then it cannot be classified and reported as a Mineral Resource because there is currently no significant demand or market for thorium. Mineral Resources, even where several metal commodities are present, should be defined according to a single cut-off grade based on an evaluation of the primary metal commodity which is usually the one that contributes the most to the overall value of the deposit. Hence, the economic model and the primary value component should be defined, whether it be uranium or another metal, in the planned plant output. The technical report, disclosing a Mineral Resource, should present elements as a single deposit, employing a single cut-off grade for the primary metal (uranium or another metal), providing a singular tonnage estimate, and specifying individual grades for each commodity (uranium and any other elements).

The single cut-off value applied in the Mineral Resource estimate determines both the quantities and grade values of other elements in the case of polymetallic uranium deposits. This approach is adopted to avoid reporting resources using separate cut-off grades for different elements, as decisions related to mining co-products or by-products are generally contingent on the viability of the primary commodity. The selection of a single cut-off grade based on the primary metal commodity is a reporting and communication convention that aids in standardization and comparability among different projects. During the production stage, mining companies have the option to implement additional cut-off grades for secondary commodities. This becomes relevant, for instance, when there is the need to strategically manage stockpiled material to enhance profitability, or in the case of sub-economic material, currently of lesser value but with potential future profitability. The decision depends on mineralogical, metallurgical, and processing conditions that are case-specific and contingent on the type of mineralization. It is essential to conduct a thorough economic and technical assessment, considering the distinctive characteristics of the deposit, the broader market context, and the company’s operational and environmental considerations. Given the high variability of mining projects, the assumptions made should closely align with the specific circumstances of each case.

All figures in the Mineral Resource estimate table within the technical report should be rounded to an appropriate number of significant figures, aligning with the relative accuracy of the estimates. In terms of the technical implementation of resource modelling, CRIRSCO-aligned reporting codes and standards, do not prescribe specific resource modelling procedures. Instead, they grant designated Competent Persons the freedom to exercise discretion, emphasizing their experience and case-specific considerations. Resource modelling nevertheless should still accord with generally accepted industry good practice guidelines for the commercial sector. These are in turn monitored by government regulators and major financial institutions, and deviations from such practices will result in the rejection of technical reports that are found to be non-compliant. Failure to comply with regulatory requirements or reporting standards could result in regulatory sanctions or legal consequences for Competent Persons. To achieve the objective of facilitating market-related disclosure and supporting requests for financial investment, it is essential to adhere to the fundamental principles of transparency, materiality, and competency set by the CRIRSCO-aligned standards and codes. This means that sufficient supporting information ought to be provided to enable the reader to evaluate and assess the risk associated with a reported Mineral Resource.

An effective Mineral Resource and Ore Reserve quality assurance is needed to assess and manage the risk of potential incorrect definition and reporting. This has an impact on investment decisions, reporting accuracy, reputation, and investor confidence. The resource modelling specialist should keep an audit trail documentation that covers all technical details of the resource estimation process to allow constant review of procedures for improvement and reporting of deviations from planning. Transparent, concise, and comprehensive documentation of the various procedures used, assumptions made, and parameters selected, is essential in the preparation of a

Mineral Resource estimate. In addition, the independent reviews and audits of competency, processes and systems are highly advised to increase the confidence level, transparency and quality of the resource estimation process.

5.2.12.16 Mineralogical characterization and metallurgical test work

The mineralogy of a uranium exploration target is a very important factor which essentially impacts the economic viability of a uranium deposit and requires careful consideration in all phases of exploration. Mineralogical studies from a beneficiation perspective are always advantageous and highly relevant to decision-making processes concerning further exploration. Early attention to mineralogical characteristics and uranium-hosting minerals facilitates a robust, geoscientific approach to the evaluation of the economic potential of exploration targets. For instance, during the follow-up exploration phase, promising targets could warrant assessment of mineralogy and uranium-bearing minerals. This is indeed highly relevant for the systematic 'stage gate' approach because a decision to progress to the next exploration phase always requires sufficient information on mineralogical characteristics of the uranium exploration targets. Although uranium mineralization might be encouraging, further exploration may not be warranted for targets where uranium is predominantly incorporated in metallurgically complex minerals of a refractory nature.

Similarly, metallurgical test work should be started early enough to systematically investigate potential metallurgical flowsheet options. This work should be carried out by an internationally recognized testing facility. However, before any metallurgical test work, a comprehensive mineralogical characterization should be carried out. This characterization work is particularly important if it is expected that the identified uranium targets contain metallurgically difficult and complex refractory uranium minerals. If the mineralogical paragenesis is understood and uranium-bearing and associated minerals are identified, much better-informed decisions can be made with respect to different metallurgical options.

Mineralogical characterization and metallurgical testing should always be carried out in tandem with chemical assaying because the evaluation of uranium exploration targets is largely based on three main factors which are uranium grade, dimensions and extension of the mineralized zones (geological and grade continuity), and mineralogical characteristics (simple and non-refractory mineralogy, or complex and refractory mineralogy). It is suggested that mineralogical characterization is carried out by experienced mineralogists, metallurgical testing by expert metallurgists, and chemical assaying by independent and accredited analytical laboratories. It should be noted that the requirements, specifications and measurement methods for mineralogical characterization should be planned and determined in collaboration with the project exploration geologists, mineralogists, and metallurgical specialists to identify and quantify the main uranium minerals and associated gangue minerals.

In general, mineralogical characterization, metallurgical test work, and flowsheet development become more detailed as exploration progresses through the exploration phases. A typical progress can be outlined as follows:

- Reconnaissance exploration: visual observations on mineralogy in the field;
- Follow-up exploration: bedrock sampling and other surface sampling followed by mineralogical characterization such as petrographic observations, identification of uranium-bearing minerals, and examination of a mineral paragenesis using optical

microscopy (polished thin sections) and X ray diffraction to yield valuable information on the mineralogy of uranium and associated metals of economic importance;

- Detailed exploration: drill core sampling for more detailed mineralogical characterization, such as optical microscopy, X ray diffraction, scanning electron microscopy, mineral liberation analysis, and electron probe microanalyses, followed by limited, laboratory-scale metallurgical test work and preliminary flowsheet development to provide mineral processing assumptions and other input parameters for the Preliminary Economic Assessment (Scoping Study);
- Advanced exploration/Deposit studies: drill core and bulk sampling for detailed mineralogical characterization (using mostly the same methods as in the detailed exploration phase) to represent all major mineralized types that have been identified within a defined uranium deposit, followed by comprehensive metallurgical test work (conducted on a bulk sample and/or composited drill core samples), definitive metallurgical flowsheet development, and pilot metallurgical testing to provide critical input parameters (such as process design and equipment selection) for the Pre-Feasibility Study and the Feasibility Study.

5.2.13 Health, safety and environmental protection

In addition to economic and technical parameters of the exploration project, the management of health, environmental and social aspects should be carefully planned before commencing any field work. Any person in authority in an exploration organization should be aware of the laws and regulations that cover occupational health and safety in the region where the uranium exploration programme takes place [5.28]. A written health, safety and environment programme and its training programme ought to be developed by an exploration organization to ensure the safety, security, and health of the workers and any subcontractors involved in field activities. In addition, clear environmental protection guidance to the workers should be provided. It is highly advisable that a health and safety representative will be assigned to the project. In large national uranium exploration programmes, this person can act as a full-time site health and safety representative (health and safety manager, radiation safety officer, or similar), also being responsible for development of the environmental protection and remediation of the exploration works, such as exploration trenches, test pits and drill sites. This health and safety specialist should also conduct periodic health and safety performance appraisals and inspections for all employees and sub-contractors (e.g., drilling contractors) involved in field activities. The health and safety representative should also be responsible for implementing corrective actions in case of any individual health and safety performance deficiencies observed during health and safety performance appraisals.

5.2.13.1 Radiation protection in uranium exploration, and handling and storage of radioactive samples

Uranium exploration may cause a health hazard due to the exposure of the exploration personnel to natural radiation. Therefore, the radiation protection aspects of uranium exploration should be carefully considered in the exploration planning phase, especially if it is expected that highly radioactive samples will be handled. The main purpose is to limit radiation exposure of the personnel during the field work, sampling, sample handling and storage of radioactive samples. An exploration organization should determine the potential radiation exposure pathways which may occur during the programme and assess the encountered radiation exposure.

Whenever possible, the exposure to radiation should be limited and an appropriate radiation protection programme should be implemented to reduce radiation doses. As part of this work, an exploration organization should carefully review applicable national legislation for radiation safety, and its requirements (usually known as the Radiation Act, or similar), before starting any field work or relogging and sampling of historical drill cores.

Prior to commencement of the exploration project, an exploration organization should prepare a written radiation protection programme document (also known as radiation safety guidance, standard operating procedure, or similar) which describes the radiation safety measures, methods and precautions to be used in the field work, and in the handling and storage of radioactive samples. The objective of a radiation protection programme is to provide practical guidelines to the exploration staff to limit radiation exposure. The radiation protection programme should be applicable to the handling and storage of all radioactive samples, including bedrock samples (e.g., grab samples) taken with a rock hammer from the surface of outcrop, drill core, RC samples, soil samples, and stream sediment samples. It is highly advisable that the radiation safety instructions will be developed by the competent radiation safety specialist (usually known as the radiation safety officer) of the exploration organization, preferably in consultation with a radiation safety expert from the national radiation safety authority, if possible.

In many jurisdictions, there are no specific regulatory guidelines in place that would deal specifically with uranium exploration, core logging and storage facilities, drill core libraries, or other premises where naturally radioactive samples are handled and stored. General guidelines on radiation protection are provided in the IAEA Safety Report Series, *Occupational Radiation Protection in the Uranium Mining and Processing Industry* [5.19]. The procedures and exposure levels specified in a radiation protection programme should provide a practical solution to minimizing the radiation exposure. Radiation dose (the amount of radiation exposure) generally means the effective dose which is used to assess the effects of radiation detrimental to human health. The unit of the effective dose is sievert (Sv). Its multiples, mSv and μSv, are often used: 1 Sv = 1000 mSv = 1 000 000 μSv.

The total effective dose assessment method is the sum of the dose from the following exposure pathways:

- External gamma radiation;
- Inhalation of long-lived radionuclide dust;
- Inhalation of radon and radon decay products;
- Ingestion, wound contamination, and absorption.

If uranium-rich rocks are largely exposed at surface, the field work in these mineralized areas can result in increased external radiation exposure of the workforce caused by direct external gamma radiation from mineralized outcrops. Another significant source of external gamma radiation is the mineralized drill core during handling, logging, sampling, cutting, storage, and transportation of drill core because these activities bring workers into close proximity with the radioactive material. It is also noted that some downhole probes rely on radioactive sources for measuring physical properties, and therefore these sources require careful handling and storage.

Dust generating activities, such as pitting and trenching, require special attention in the development of a radiation protection programme because these activities can result in increased internal radiation exposure due to the inhalation of long-lived radionuclide dust in addition to external gamma radiation. Dust masks should be worn whenever there is dust generating activities, such as RC drilling, pitting and trenching, and when handling of friable samples (such as friable drill core and bedrock samples).

The inhalation of radon and radon decay products should be considered where there is restricted ventilation, in deep trenches and especially in sample storage facilities, such as in sample storage rooms and shipping containers. Very high levels of radon and its decay products can occur in these sample storage facilities if there is no ventilation [5.19, 5.24].

In order to prevent internal exposure from ingestion of radioactive material, the exploration staff should use protective clothing (e.g., cotton gloves, or disposable plastic gloves) and wash their hands after handling of radioactive samples and uranium mineralized core, especially before consuming any food. Any personnel with exposed wounds on any part of their body should cover the wound before handling any radioactive samples.

It should be noted that uranium exploration samples are transported to an analytical laboratory where receipt of samples, physical sample preparation (such as drying, crushing, splitting, pulverizing, homogenization, and mixing), sample digestion and chemical analyses are performed by workers who might not be aware of the presence of radioactive samples if the samples are not clearly labelled with a radiation warning sign. In addition, drill core trays containing radioactive core are usually shipped to a permanent storage (such as a national core library operated by a national geological survey) at the end of a drilling campaign. Therefore, it is highly important that the exploration personnel label any radioactive samples or any drill core tray containing radioactive core with a radiation warning sign (Fig. 5.9) prior to sending any sample batches to an analytical laboratory, or before shipping drill core trays to the core library (or any other permanent storage facility of core trays). In addition, the site geologists should always communicate with the laboratory staff and core library staff before shipping radioactive samples to an analytical laboratory or core library. The level of a radioactive sample should be also defined in a radiation protection programme document. For this purpose, it is suggested that contact dose rate (the level of radioactivity) is measured in µSv/h (microsieverts per hour) using a radiation detector at the surface of the drill core or other sample material. Typically, any drill core or other sample material with a contact dose rate more than 5 µSv/h is defined as radioactive sample [5.29] and should therefore be labelled with a radiation warning sign before shipment to an analytical laboratory or core library. It should be noted that exploration companies and organizations may use a different trigger level for a radioactive sample and for the action level for the initiation of radiation protection controls, ranging from 1–10 µSv/h measured on contact from drill core or other rock sample (contact dose rate).

FIG. 5.9. Radiation warning sign for a radioactive substance or ionizing radiation.

It is important to note that the shipment (import and export) of radioactive samples is highly regulated by carriers and countries following international standards for packing, labelling, shipping and licensing [5.24, 5.25, 5.30]. The IAEA safety standards establish fundamental safety principles, measures to control the radiation exposure of workers, measures to control the release of radioactive material to the environment, and requirements and controls for transport of radioactive samples. For example, the shipment of radioactive material is regulated and the dose rate at any point on the external surface of an excepted package should not exceed 5 μSv/h [5.31]. Detailed guidelines on the transport of radioactive materials can be found in the IAEA Safety Standards Series report, *Compliance Assurance for the Safe Transport of Radioactive Material* [5.24]. In addition, the long-term storage of radioactive samples may require the establishment of licensed storage facilities to mitigate hazards of radiation and radon gas exposure.

The specified dose limits to be defined by the exploration organization in a radiation protection programme should consider the actual contact time with radioactive samples and characteristics of work activities relating specifically to radioactive samples. Therefore, it is the responsibility of the exploration organization, preferably in consultation with the national radiation safety authority, to define whether regular radiation monitoring programme of exploration staff by personal radiation monitors is needed or not. An absolute minimum requirement is that the exploration personnel should be equipped at least with the handheld radiation detectors (scintillation count rate metres or gamma ray spectrometers) to measure and monitor the gamma dose rate at the exploration sites and in core logging and storage facilities. If it is expected that the annual effective dose from occupational exposure exceeds 1 mSv in addition to the background exposure, then the individual radiation monitoring and assessment of workers' exposure due to external radiation sources and from intakes of radionuclides are needed [5.32]. At the exploration stage, a radiation monitoring programme is typically implemented using portable individual thermoluminescent dosimeters (TLDs) for the assessment of individual gamma doses.

All exploration personnel and all workers who are involved in uranium exploration and in the handling of radioactive samples at the exploration sites, core logging premises and storage facilities should read and acknowledge the contents of the radiation protection programme document. In addition, radioactive material may need to be disposed of, for example returning the material to the point of origin [5.19], which also needs to be included in a written health, safety and environment programme that is prepared during the exploration planning phase.

5.2.14 Management of support and exploration logistics activities

Project support ensures that suitable and qualified personnel and supplies are available to allow the exploration work to be completed in an effective and timely manner. Logistical considerations are essential to the planning process to ensure the support required is available at the time and place that it is needed. In this regard, an exploration organization may be supported by a local logistical contractor which will be contracted with the project owner.

Uranium exploration projects require knowledgeable and skilled management that anticipates and plans the project with realistic expectations which bear in mind external drivers, such as stakeholders and weather. Choices should be made concerning the work programme and scheduling in such a way that initial results can be used to guide decisions later in the project. For example, an initial programme of bedrock sampling or radiometric surveying may generate data which can immediately be used as a guide in locating trenches to be excavated. The value of the initial surveys is weakened if the equipment for trenching is present on-site and if work will begin at the same time the surveys are completed. Therefore, support for the project ought to be timely and should also be appropriate for the area being explored.

Long travel times in an exploration area may require establishing a base camp to support the project, however the base camp itself will then require support in the form of ensuring the provision of adequate supplies of water, food and energy and that adequate facilities are provided for communications, human hygiene, and waste disposal. Depending on the exploration area, provisions may also be required to ensure the security of the camp. All these factors add costs which should be evaluated against the cost saved in travel time. Where distance and time is not a factor, local hotels, guest houses and apartments may provide a suitable option which is less onerous on logistics.

Exploration project logistics involves the management of materials and support services to the project site, and the flow of data and information from the project site to senior project management of the project owner organization. The goal is to align the flow of materials, personnel, and subcontractors with project demands. Communication is the key element to ensuring that these demands are met. A last-minute demand for a drill rig on-site cannot be satisfied if the need has not been scheduled and properly communicated, or the only drill available is not suited to the task required. Exploration project logistics include a two-way flow, since materials will flow to the project site and samples will counter-flow to a laboratory.

The project manager ought to view logistical planning as a critical element of the supply chain. It begins with comprehensive project planning in terms of tasks and schedules, identifying the personnel and materials required and then assessing inter-dependencies to identify critical points that may substantially impact completion and cost elements. This is often referred to as strategic planning. All service providers should be in the communications loop and the information flow should be routinely renewed on a weekly basis. It may be prudent to immediately alert all parties to the project of a failure in the supply or service pipeline for critical items. Where possible, standby equipment or replacement parts should be available to prevent a failure from substantially impacting the completion of an exploration project. This may require treating suppliers and subcontractors as a partner in the project rather than a subordinate such that the contractor understands the key metrics affecting the project.

The logistical requirements provide a valuable opportunity to build short and long-term relationships and good favour with the local community members, suppliers and stakeholders. It is important to understand the priority of these relationships, which should be considered alongside the other more traditional decision driving forces such as cost, timeliness and efficiencies. In some instances, it might be cost effective to source logistics from abroad but in the long-term it might be more beneficial to use local support. Building up and supporting local logistical support might be an investment into community relationships and infrastructure required as the exploration progresses towards mining.

As critical as the flow of materials and equipment is to the exploration site, the flow of information back to senior management should also be managed in an efficient and regularly scheduled manner. As described in Section 5.2.11, exploration organization’s monthly reports should give important information to allow management to grasp the essential aspects of the project: i.e., what work was planned for the month, what work was completed, the reasons for any departure from the plans, what results were achieved or conclusions were made, and what work will be planned for the next month. This basic information is needed by senior management to allow it to measure progress, and that ability is lost if a reporting trail cannot be followed from one month to the next.

5.2.15 Stakeholder engagement

General guidelines and information on stakeholder engagement can be found in the IAEA Nuclear Energy Series publication, Stakeholder Engagement in Nuclear Programmes [5.33]. Stakeholders affected by exploration may include indigenous, landowners and the community individuals or groups. Positive engagement with these parties is important in order to comply with legislation and to foster community engagement and favour. These aspects start during the reconnaissance exploration phase and the follow-up exploration phase involves increased engagement with the community and local stakeholders including landowners. These interactions should be carefully managed and a history recorded to support future social impact assessments (if a discovery is made and mining considered). Stakeholder engagement becomes more important when progressing through the phases, as mining and development becomes more probable, especially when input is required into decisions that are being made.

The exploration organization project manager should develop engagement guidelines which should clearly identify how, when and what stakeholder engagement will occur. The process will need to be flexible as projects develop particularly in relation to the level of impact and degree of community interest. Underlying principles should be grounded on integrity, trust, respect, effective communication and transparency. The guidelines should consider:

- Who are the stakeholders;
- Information and analysis on attitudes and expectations;
- What previous engagement activities have been conducted;
- The type of engagement level (e.g., inform, consult, involve, collaborate or empower);
- Form of engagement (e.g., verbal, formal, printed);
- Engagement objectives;
- How to record engagement;
- Who is to undertake engagement.

Exploration organizations should be prepared to educate local communities and individuals regarding the impact of exploration activities, radiation safety and potential mining. There may be a requirement or need to have formal meetings to gain access and approval for exploration and provide educational information.

All personnel and contractors should seek to foster positive relationships and communicate effectively with the public. This might involve considering local requests regarding land access routes and timing for instance to avoid disrupting farming activity. It can be beneficial if there is an individual assigned as the primary point of contact who can speak on behalf of the exploration organization and be purposeful with fostering the relationships.

Environmental and community impact statements require the exploration organization to demonstrate long-term trustworthiness, community engagement and development. Therefore, during exploration it is prudent to document any relevant activity including interaction with stakeholders and suppliers. Typical records may include:

- Date;
- Location;
- Organization;
- Nature;

— Concerns and complaints;
— Importance;
— Action points.

5.2.16 Project risk management

Every exploration project has risks, which range from policy environment, geological interpretation and metallurgical challenges to occupational health and social aspects, which also dictate the attractiveness and economics of an exploration project from an investor's perspective. A uranium exploration project should be carried out in a safe, environmentally friendly, and socially acceptable manner, requiring special attention from the project management team throughout the uranium exploration project. Therefore, the risks of the uranium exploration project to worker and community health, and potential for environmental damage should be assessed during the exploration planning phase.

Based on the risk assessment, a risk management plan should be prepared during the planning phase, and then updated over the course of the exploration project. It is also important that all risks are managed and transparently communicated with all workers, partners, contractors, and stakeholders, and that corrective actions to mitigate a variety of risks will be taken by the project management team in a timely manner.

5.2.17 Outcome of the exploration planning and area selection phase

The first gate to the reconnaissance exploration phase opens if favourable areas are identified for exploration. It should be noted that the exploration planning and area selection phase (phase 1) does not always progress to reconnaissance exploration if sufficiently prospective areas are not identified during the planning phase, or if the policy environment, regulatory environment, or explorability are not favourable for starting uranium exploration. In addition, the reconnaissance phase does not automatically follow the exploration planning and area selection phase because phase 1 can be followed by any kind of exploration phase (reconnaissance, follow-up, detailed, or even advanced exploration) depending on the maturity of exploration areas based on past exploration projects and their results.

5.3 PHASE 2 – RECONNAISSANCE EXPLORATION

Reconnaissance exploration represents the phase when the actual field work is carried out in a selected exploration area. It commences after the following key criteria are reached:

— Exploration risks, prospectivity and explorability have been understood;
— Prospective and favourable areas have been selected based on the applicable uranium deposit model;
— Exploration programme with suitable exploration methods and QAQC programmes have been developed;
— Project management organization has been established, and roles and responsibilities of project management in the planning and implementation of the uranium exploration project are clear and well-defined.

Reconnaissance exploration is carried out on a regional scale with the following main objectives:

— To define the geological context of selected areas;
— To confirm that the uranium deposit model selected during the exploration planning and area selection phase is applicable to the selected exploration areas;
— To identify viable anomalies for more detailed, follow-up uranium exploration;
— To acquire sufficient information for the assessment of the investment worth of the selected exploration areas.

After choosing the area to be explored, typically an application will be made for the exploration permits or licences from the regulatory authority, which according to the legislation of a particular Member State can be at national, provincial, regional, local or departmental levels, or a combination of these (see also Section 5.2.8). The exploration rights granted by the regulatory authority are an unequivocally necessary step before proceeding to physical exploration for uranium. In addition, the duration of exploration rights, exclusivity of the claimed area for exploration activities and the legislation for mining rights are important considerations for an exploration organization at this stage [5.3]. At this point the presentation and approval of the corresponding environmental and social impact assessment reports may be required. Although, for reconnaissance exploration, it is expected that the socio-environmental impacts are low.
Throughout the entire exploration process, it is just as important to rule out areas with low mining potential as it is to define a target of interest on which to focus the investment efforts during the next exploration stage. Therefore, the number of prospective anomalies and targets typically decreases during the reconnaissance exploration phase as they are discounted by field assessment.

Following the application and approval of exploration permits, and the analysis of all of the pre-existing information, exploration techniques of low cost per surface unit are applied. Exploration areas in the reconnaissance stage are large, typically more than 100 000 km^2. Typical exploration activities of the reconnaissance phase encompass regional airborne and ground geophysical surveys, remote sensing, regional geological mapping with ground follow-up of regional airborne radiometric anomalies, and baseline geochemical bedrock and soil sampling [5.34].

5.3.1 Regional airborne radiometric surveying

Regional airborne radiometric surveying is one of the most important techniques in uranium exploration during the reconnaissance phase. It provides a quick, cost-effective and reliable method for collecting radiometric data over a large area. The most important goal of airborne radiometric surveying is to identify uranium anomalies which may be followed up by ground checking. Since the gamma-ray response is due to the uppermost part of the soil and bedrock, it is important to consider whether the targeted uranium is likely to occur at the surface, which depends on the degree of cover material and depth of burial which is particularly significant for basin-related uranium deposits.

Geological programmes at the country scale, commonly provided by national or provincial geological survey organizations, include magnetic, electromagnetic, and radiometric airborne survey data. At the reconnaissance scale, the airborne surveys typically use a wide flight line spacing (300–1000 m) and a relatively high flight altitude (60–100 m). Magnetic and electromagnetic data provide important geological and structural information, while radiometric data are interpretable in terms of surface geochemistry [5.35]. Typically, regional airborne radiometric data generates a large number of radioactive anomalies that should be checked carefully in prospective areas through ground follow-up during the reconnaissance exploration phase. Since the flight lines are likely to be sparse, care should be taken when utilizing gridded data which interpolates between readings, and it may be best to identify anomalies utilizing flight line data profiles. Interpretations should bear in mind whether significant anomalies could exist between sparse survey coverage.

Airborne radiometric surveying is typically combined with magnetic surveying due to their cheap cost and ready deployment. These may be combined with various other geophysical methods for simultaneous acquisition in order to save cost and time. The IAEA [5.20, 5.36] provides several guidelines on the acquisition, processing and interpretation of radiometric data. When planning airborne radiometric surveys, there is generally a trade-off to consider between cost and spatial resolution. Processing to equivalent radioelements should utilize modern good practice which includes spectral noise reduction, deadtime, cosmic and background radiation corrections, energy calibration, stripping and extractions of windows, height correction and levelling. The following specifications should be carefully considered when planning airborne radiometric surveys:

- Spectrometer recording stabilized full spectrum (256-channel or more);
- Large crystal volume (33 L or more);
- Close line spacing (25–400 m);
- Low flying height (30–120 m) appropriate for the line spacing
- Slow flying speed;
- Calibrated at a test range;
- Test line and pre/post flight ground calibration;
- Flown during a period without rain or snow.

Airborne radiometric surveying requires sufficient quality control procedures to ensure data quality by identifying any potential errors, spikes, gaps or other problems in the data, and by reducing statistical noise and instrumental effects [5.36]. For example, it is crucial to ensure that the final coordinates are correct and accurate for all geophysical components by eliminating any potential errors sourced by incorrect differential GPS base station coordinates, timing error in data acquisition, incorrect time difference between GPS and UTC time, incorrect locations of geophysical sensors, and incorrect coordinate transformations [5.16].

A fixed survey altitude should be maintained steadily throughout the airborne radiometric surveying programme. In hilly and rugged mountainous terrains, flights should be planned carefully because the altitude variations have a significant impact on the measurements. In these cases, pilots have to deviate from the nominal height for safety reasons. The survey aircraft should start climbing well before a steep mountain, and the increase of the altitude is typically 100 m vertically for every 1 km horizontal distance [5.16]. Similarly, the gradient of the descent and the speed of the aircraft should be kept reasonable when descending in a mountainous terrain. In steep mountain regions where regular grid flying is dangerous or impossible, flying can be carried out by following the contours of the ground [5.36].

5.3.2 Remote sensing

In reconnaissance exploration programmes, the geological mapping can be integrated with satellite-based remote sensing work in guiding uranium exploration on the ground. Multispectral remote sensing techniques constitute one of the most powerful data sources for the reconnaissance stage. In this respect, this technology applies to the identification of areas of interest at the level of metallogenetic provinces. Satellite image data (such as WorldView-3, ASTER, Landsat) can be used extensively and routinely by an exploration organization in geological mapping for defining lithological boundaries and interpreting structural patterns. An exploration organization can build a data library of spectral data acquired on the ground of alteration and mineralization types using a spectral radiometer. Having acquired such data, an exploration organization can then process these data to extract maximum value from satellite image data. If this kind of data is available, follow-up field work should not proceed before the remote sensing data are processed and interpreted to extract the maximum value from the satellite imagery, for example, by identifying alteration zones.

Depending on the nature of exploration work (regional-scale, camp-scale, prospect-scale, or deposit-scale), resolution of datasets should be suitable for the scale of work. In terms of deposit-scale work, high-resolution satellite imagery data (such as Worldview-3) can be used to provide useful datasets, whereas Landsat imagery data are more suitable for regional-scale work. Hyperspectral surveys can be also utilized as they use optical airborne sensors for the collection of surface reflectance data over exploration areas, generally at high spatial resolution for deposit-scale exploration.

The source, type, specifications, and integration of different datasets of the remote sensing data should be specified and documented by an exploration organization so that the quality of the data can be assessed by any future users. In addition, data correction and processing practices should be clearly reported. An exploration organization should also provide a list of generated data products, how they are used, and what they illustrate in various parts of the exploration area.

5.3.3 Regional geological mapping

Geological mapping (also known as bedrock mapping) is critical to exploration for any type of uranium deposit. The purpose of geological mapping is to increase the understanding of the local and regional geology together with the factors that control uranium mineralization. A high-quality regional geological map is a critical tool for exploration and can be initially prepared from satellite and aerial images, and together with cartographic sheets, it is useful for the delimitation of areas of interest at the reconnaissance stage. However, available known background geology typically requires field checks, additional geological mapping, and rock sampling.

As one of the main objectives of the reconnaissance exploration phase is to find out whether the selected deposit model is applicable to the exploration area, the field geologists should particularly search for the characteristics of the target uranium deposit type. Ground radiometric surveying is typically accompanied by geological mapping so that the level of radioactivity of the bedrock outcrops is measured at the same time as these outcrops are geologically mapped by a field team. Information collected from geological mapping usually includes the lithology, level of radioactivity, alteration, mineralogy, structural geology, relationship between rock types, and delineation of barren and uranium mineralized zones. If available, airborne and ground geophysical survey data should be utilized to support geological mapping. Airborne geophysical surveys can be of great help for geological mapping. Aeroradiometric data can be used to delineate lithologies that have different radioelement contents (a good support for lithological and alteration mapping), while aeromagnetic data can be used to identify fault systems and to extrapolate local structural measurements up to a strain field (a good support for structural mapping).

Geologists should observe and record information on lithological units, alteration, structural features, and mineralization styles in an exploration area. This information is typically compiled on a geological map, whose scale depends on the objectives defined at the planning stage of the uranium exploration project (phase 1). At regional and local scales, maps show the location of major lithologies, structures, alteration types, and any significant uranium mineralization.

Detailed geological maps typically display the lithology, alteration, and structural features of a small area such as an exploration trench or an individual outcrop.

Accurate, clear and understandable rock classification should provide information relating to the genesis of the target mineralization and the geological environment in which the uranium mineralization formed. The naming of rocks should follow standard classifications, such as the International Union of Geological Sciences classification for igneous rocks. The field geologists may collect a suite of hand samples that display representative characteristics of the host rocks, alteration styles, and mineralization types found in the exploration area for reference. These type samples are useful to ensure that geological mapping information is collected in a consistent manner by all members of the exploration team. To ensure data integrity, rock naming should be clearly defined and consistent. Unusual samples which lack an accepted name should be discussed by the exploration team in order to agree on acceptable interim name such that recurrences can be properly identified.

Geologists should have enough time to observe and map features of special interest, carry out detailed field measurements, and record observations. Structures should be measured in order to be represented on the geological map (i.e., use of compass, geometrical analysis, kinematics of the faults, typology. The focus should not be on collecting geological data at specific measuring points along profile lines. Producing a geological map from mere data points enters the strong possibility that unrelated features (points) will be connected, a flaw that is easily avoided by simply walking along the feature and ignoring the need to make notes at preselected stations. Restricting geological data to measuring points results in substantial risk that features relating to mineralization may not be fully recognized or fully represented as traces on the final geological map. Important features can be traced manually or digitally by GPS tracking and point data on profiles is much less important than the need to trace and outline geological features which can be entered as polygons into the GIS software. GPS tracking of structures or interesting zones provide important information on detailed geology such as where mineralization is structure-controlled and to document the relationship between uranium and mineralizing processes. The track function of GPS instruments can be used to selectively track the perimeter of outcrops, trace contacts and set waypoints for sites where notations are made, or samples are taken. This data can be uploaded to GIS software and processed to produce maps.

The geological maps should be drawn up in a clear and unambiguous manner. They should include the scale of the map, a north arrow, and a coordinate system. Map legends should be included to explain information depicted on the map such as rock names and structural symbols (i.e., lithological contacts, stratigraphy, foliation, fracture zones, faults). The use of distinctive colours or patterns to represent individual lithologies is suggested. A standard geological legend, encompassing all major lithological units and geological symbols should be applied in a consistent manner. Depending on the terrane, a structural map may be highly suggested.

All sample locations should be accurately recorded, however the level of accuracy needed depends entirely on the spatial density of samples being collected and the level of the exploration stage. Reconnaissance samples collected at hundred-metre spacing can be located with an acceptable level of accuracy using a GPS and its long-count, location averaging function. The sampling of a trench creates high-density data that requires a correspondingly high level of accuracy in recording the locations, preferably with a differential GPS.

5.3.4 Regional geochemical stream sediment and soil sampling

Reconnaissance-scale geochemical stream sediment and soil sampling can provide useful information on the potential enrichment or depletion of uranium and other associated elements in targeted areas. Likewise, lithogeochemical sampling is useful in the regional phase for the recognition of geochemical provinces and favourable host rocks. There is no specific sampling interval of geochemical surveys since it depends largely on the geological and geographical characteristics of the region studied. For example, a regional survey of stream sediments can include the collection of one sample per 50–200 km^2 and the analytical determination of about twenty elements.

5.3.5 Ground radiometric surveying

Ground radiometric surveying (also known as gamma ray surveying) through ground follow-up of radiometric anomalies using handheld scintillation count rate metres or portable gamma ray spectrometers is one of the most common techniques in uranium exploration. The level of radioactivity is measured at the surface of the outcrop by positioning these handheld instruments over a flat outcrop surface because the source-detector geometry has a significant effect on the readings. In uranium exploration, even weak anomalies should be checked carefully during ground follow-up of aeroradiometric anomalies because the aeroradiometric signal reflects only the upper portions of the ground and the material in this upper zone may not be representative of potential buried uranium-bearing horizons or mineralized zones at greater depths below the surface.

The measurement of gamma ray intensity for the estimation of uranium and thorium concentrations assumes that the respective decay series are in equilibrium. It should be noted that neither total count surveying (using scintillation count rate metres) nor gamma ray spectrometry (using gamma ray spectrometers) can compensate for radioactive disequilibrium [5.20]. As there is no absolute certainty that equilibrium conditions apply to a measurement, radiometric determinations of uranium and thorium abundance need to be identified as equivalent determinations. Therefore, ground spectrometric measurements of uranium and thorium concentrations need to always be expressed as the equivalent concentrations (as ppm eU and ppm eTh) to distinguish the results from the chemical assay data. Exploration trenches and pits are typically measured by handheld spectrometers and sampled. To overcome the potential issues associated with uranium disequilibria, such as in exploration for calcrete-hosted uranium deposits, sampling and geochemical assaying are essential to accurately establish the uranium content because the only reliable way to determine the exact uranium content of a sample is to obtain a geochemical analysis. This determines uranium directly and is not affected by the proportions of its daughter nuclides present.

It should also be noted that ground radiometric measurements should not be performed only with specific point densities or along profiles with standard point distances without taking into consideration geological aspects and factors that influence radiation levels in outcrops. Instead, geologists should trace interesting features and avoid collecting data only at predetermined stations because ground radiometric measurements limited to pre-established profiles pose significant risk of missing features that may be related to the uranium mineralization, and thereby not revealing the nature of the mineralization.

5.3.6 Verification of the deposit model and identification of viable uranium anomalies for follow-up exploration

The most detailed work taken into consideration in the reconnaissance exploration phase is to obtain additional geological, structural, geochemical, and mineralogical data to evaluate and verify the deposit model. This activity may consist of trenching to expose bedrock for mapping, structural measurements, rock sampling, and ground radiometric measurements to investigate mineralized zones at specific sites. The possibility of carrying out a limited amount of reverse circulation (RC) drilling or diamond drilling can be evaluated.

The desired outcome of the reconnaissance exploration phase is to select the most prospective areas along with radiometric anomalies and targets to be followed up by more detailed exploration work in the subsequent phase (i.e., follow-up exploration phase). Typically, the number of prospective anomalies and target areas decreases when progressing from the reconnaissance exploration phase to the follow-up exploration phase.

New anomalies are typically limited to a single dataset due to a change from the normal background response, which does not necessarily relate to a uranium mineralization process or warrant field checking. However, airborne uranium anomalies are generally considered to be targets for field checking since these may directly detect uranium mineralization and minor anomalies may represent significant buried mineralization masked by cover. Targets are considered more prospective and are ideally derived from more than one dataset, sufficiently significant to warrant field checking. During the reconnaissance exploration phase, it is suggested to initiate a central target file to record the details of anomalies and targets which can be updated as the exploration evolves. A target file should incorporate a rating system to help guide field assessment priorities initiated in the reconnaissance phase and a comprehensive part of the follow-up phase.

The reconnaissance phase reaches a critical decision point when it is determined if the deposit model is confirmed or needs to be adjusted or totally reformulated. The confirmed deposit model and the characteristics of the chosen subareas for follow-up exploration are important factors that will also help to guide exploration and to identify the most appropriate exploration methods to be used during the follow-up exploration phase. Otherwise, additional area selection and planning may be required to identify new exploration opportunities.

At the end of the reconnaissance exploration phase, the comprehensive analysis and interpretation of the pre-existing and surveyed geoscientific data are carried out to verify the existence of the different metallogenic components (i.e., source rock, transport, trap, deposition, preservation) of the mineral system formulated for a particular exploration programme to identify promising targets for follow-up uranium exploration [5.37]. The selection of areas for follow-up exploration should be based on the positive results of the analysis of geological, geophysical, geochemical, and remote sensing data [5.3].

5.4 PHASE 3 – FOLLOW-UP EXPLORATION

The follow-up exploration phase begins after the following key criteria are reached:

- Viable uranium anomalies have been identified in an exploration area;
- Applicability of the target uranium deposit model has been confirmed as a result of reconnaissance exploration.

Follow-up exploration is conducted on a camp scale with the following main objectives:

- To identify positive indicators of uranium mineralizing systems;
- To determine the extent of anomalies in the areas of interest and to develop anomalies to exploration targets which are tested by drilling;
- To locate and intercept high-grade uranium mineralized intervals by drilling for detailed exploration.

Typically, work in the follow-up phase is at what is commonly called the camp scale, an area ranging from 25 km^2 to 100 000 km^2. The follow-up phase of exploration commonly involves significant geological mapping, ground and airborne geophysical and geochemical surveys, ground and airborne radiometric measurements, radon surveys, trenching, limited widely spaced drilling, geochemical assaying, geological modelling, and mineralogical characterization.
The areas of the greatest interest defined during the reconnaissance phase are the objects of more detailed surveys and assessment during the follow-up exploration phase. Table 5.2 provides a useful framework to help consider any new survey plans and their application. Gamma-ray spectrometry surveys can encompass airborne, carborne, and ground surveying. In particular, airborne radiometric and magnetic surveys with greater spatial resolution may be flown with flight lines spacing of 100–500 metres and flight heights between 30–60 metres. The available geophysical data can be complemented with additional airborne electromagnetic surveys. For geochemical surveys, it is common to collect the same kind of material as used in the reconnaissance exploration phase, such as stream sediment, water, bedrock, and soil samples but at a closer spacing (i.e., 10–20 samples/km^2).

5.4.1 Ground geophysical surveying

The follow-up exploration phase typically includes intensive and more detailed ground radiometric surveying using handheld scintillation count rate metres or portable gamma ray spectrometers if the selected deposit model (see Section 5.2.5) favours the possibility of exposed or near surface uranium mineralization. Ground radiometric surveying can be supplemented by other ground geophysical surveying methods in the follow-up and detailed exploration phases. For example, ground electrical, and electromagnetic survey profiles can be carried out to further define the exploration targets. The selection of other geophysical exploration methods largely depends on the characteristics of the uranium deposit model [5.8]. When selecting other ground geophysical methods, petrophysical characterization may be warranted as a prelude to planning ground geophysical surveys to select the most appropriate geophysical methods (see Section 5.2.6).

It is important that geophysical surveys are carried out in a manner that complies with standard industry practices in terms of data acquisition and this should include technical procedures and quality control protocols to assure satisfactory data quality and repeatability of the various geophysical surveys. Part of this process is not only to confirm the validity of the measured data, but also to assess other factors that influence the effectiveness of the geophysical surveys conducted. In most cases, faulty or noisy data acquired during a geophysical survey cannot be improved or corrected through post-survey data processing, so it is vital that problems encountered in the field are corrected in the field.

5.4.2 Radon surveys

Since diamond drilling is expensive, the follow-up exploration phase generally relies on cheaper techniques, for example utilizing radon measurements to measure radon in the near-surface soil gas, to detect buried uranium occurrences, to define the extension of a uranium anomaly, and to delineate targets for follow-up drill hole testing. Given the mobility of radon gas and its short half-life (3.8 days), radon surveys are not often effective at pinpointing an exact source and location of uranium mineralization. However, radon surveys can be used as a guide to subsurface uranium mineralization.

The appropriate radon surveying techniques are generally limited to the alpha track method, the alpha card method, and the emanometer probe method, and the choice between these will depend on the required measurement sensitivity and the availability of sufficient time and human resources to conduct the surveying. For example, the alpha card method detects the radioactivity of radon solid decay products as they accumulate on an alpha card collector (a paper frame with a circular, aluminum-coated mylar collector), which is placed in a pit for 1–2 days [5.20].

The alpha track method measures a long-term sample of soil gas by recording radon alpha particles on a sensitive film which is attached to the inside of a plastic cup. These alpha track cups are placed in pits in a grid pattern at a depth of about 0.3–0.6 m [5.20]. These pits are then covered by soil and left buried for three to four weeks. The density of alpha tracks recorded on the sensitive film is a measure of radon in soil gas. After the cups have been buried for a period (typically several weeks), they are retrieved and sent to a laboratory for counting of the tracks created by alpha particles that have been released by the breakdown of radon in the enclosing cup over the survey period. Contouring of the resultant data should allow the indication of underlying uranium-bearing minerals. The alpha track method is more reliable and can achieve greater sensitivity than the emanometer method used for radon detection. However, alpha track surveys are labour intensive. Cups are commonly buried at 25 m intervals over a target area that can commonly be one square kilometre or more in size, necessitating the placement of more than 400 cups per km^2. Cups should be in place for three to four weeks before being collected, in order of placement. Deployment of cups may present security challenges in an exploration area since the cup locations need to be marked on the ground surface, and thus may be prone to tampering. Given the limitations on the number of cups that can be placed and retrieved in a day and the fact that the cups should then be shipped for analyses that can also take up to a month, such a survey can take many months from start to completion.

Radon surveys using emanometer probes (portable radon detectors) are significantly faster than the alpha track method as they yield immediate results. Therefore, the emanometer probe method can provide quite quickly and effectively valuable data for follow-up targeting on prospective areas. Emanometers measure the alpha activity of a soil gas sample which is typically taken from a depth of about 0.8–1 m [5.20]. Radon surveys, taken as kBq/m^3 readings, are conducted in the field along profiles, typically spaced 50–500 m apart, with individual readings taken along profile every 5–100 m. If promising radon anomalies are detected, more detailed measurements can be conducted over denser grids. The emanometer probe method is sensitive to atmospheric pressure and contamination. Emanometer base stations can be used to monitor diurnal background radon variations. Therefore, sufficient QAQC procedures should be in place and the documentation on the QAQC procedures ought to be reviewed by the project owner or its supervising contractor before the commencement of the field surveying if radon surveys are carried out by a subcontractor.

Although the accuracy of the radon cup method is probably higher, the emanometer probe method has the distinct advantage of obtaining quick results, which is important considering a potentially tight schedule of the uranium exploration project. The use of soil gas emanometers also avoids the time and cost of shipping a considerable amount of radon cups to the exploration site, followed by several weeks of measuring time, and then the costs associated with shipping the cups to the laboratory for measuring alpha tracks. In addition, the emanometer probe method does not require site signaling and security. For quality control purposes, it is also possible that the emanometer probe method is compared with the alpha track method (alpha particle detector mounted on a plastic cup), or with the alpha card method, to compare the performance, sensitivity and accuracy of these methods.

It is also possible that a soil sample for geochemical analysis is collected at the same time as radon measurements are conducted by a field team. This would provide useful information to supplement the radon survey. Samples collected for chemical analysis are particularly valuable in the exploration for calcrete-hosted uranium deposits due to potential issues of non-equilibrium relating to the semi-quantitative and unreliable spectrometer readings. Given the cost of placing the operating crews on site for the radon survey, geochemical sampling at the same time would be reasonable and cost-effective.

5.4.3 Identification of high-grade uranium targets by drilling or trenching

After a certain level of geological confidence is attained, widely spaced trenching and drill holes (e.g., 1 hole/2–5 km^2) can be completed to better understand the geological setting and to test anomalies and mineral systems (i.e., geological setting, lithological controls, structural trends, alteration features). Drilling depths can vary from tens to hundreds of metres depending on the geological type of uranium deposit.

During the follow-up exploration phase, as much as 90% of the initially selected exploration area may be eliminated, outlining remaining prospective areas of a few to perhaps 10 km^2 in extent [5.38]. If promising targets are identified with high-grade mineralized intervals from initial drilling (i.e., depending on deposit model), then these sites are considered a prospect and likely to be named for convenience, and an exploration organization may proceed to the next detailed exploration phase to continue the evaluation including follow-up drilling.

5.5 PHASE 4 – DETAILED EXPLORATION

The detailed exploration phase starts after the following key criteria are reached:

- Positive indicators of uranium mineralizing systems have been identified;
- Promising exploration targets have been determined;
- High-grade uranium mineralized intervals have been intercepted by drilling during previous exploration (follow-up phase).

Detailed exploration is carried out on a prospect scale with the following main objectives:

- To identify and delineate significant uranium mineralized zones;
- To establish and confirm the geological and grade continuity of the uranium mineralization representing the discovery of a deposit;
- To define Mineral Resources, usually at the confidence level of Inferred Resources;

- To obtain preliminary information on the ability to recover uranium from its hosting minerals;
- To carry out laboratory-scale metallurgical test work and preliminary flowsheet development to provide mineral processing assumptions for the Preliminary Economic Assessment (Scoping Study);
- To understand economic viability of the deposit at very high levels by completing the Preliminary Economic Assessment (Scoping Study).

The detailed exploration phase involves closely spaced drilling and sampling to identify and delineate significant mineralized zones. The exploration methods used in this phase may not differ significantly from those used in the previous phases, but the substantive change is given by the density required for the acquisition of new data. The density of drilling and sampling are determined by a deposit model and proposed mining method. The size of an exploration area is typically less than 25 km^2, and the data collected and evaluated during the detailed phase are usually compiled into maps at scales of 1:5000 or 1:1000.

Typical activities during the detailed exploration phase include prospect-scale geological and geophysical ground surveying, intensive drilling with a dense drill hole spacing, downhole radiometric probing, sampling, geochemical assaying, bulk density measurements, mineral resource estimation (typically inferred resources), mineralogical characterization, and metallurgical test work. Systematic grid-based trenching for surficial uranium deposits and grid-based drilling for concealed deposits are carried out. A significant amount of sample material will be collected, mainly from the mineralized bodies that will be the subject of petrological and mineralogical studies, chemical determinations, geological modelling, and bulk density measurements.

Different drilling methods will be utilized due to their differing approach. Chip-based methods are cheaper which is useful where a large number of drill holes is required to establish continuity and volume, but they do not provide the structural information about controls that angled diamond holes provide. A balance of these two approaches is generally required in order to estimate the contained uranium. Figure 5.10 depicts how initial drill hole intercepts might be progressively understood through increased drilling and structural information. 3D modelling of the deposit is carried out during the detailed exploration phase and is especially important if the higher-grade zones are extended for any significant distance. Modelling of the resources can be carried out only if the drilling and sampling provide sufficient evidence of geological and grade continuity.

At this stage, a distinction should be made between mineralization that may be of economic interest and that which, exhibiting low mining potential, should be discarded. In other words, in this phase, direct indications of an economic uranium mineral deposit ought to be duly located and proven. Due to the significant reliance on analytical results, a workflow is advisable so that modelling can be planned for at the appropriate time, which in turn provides feedback for follow-up drilling and sampling.

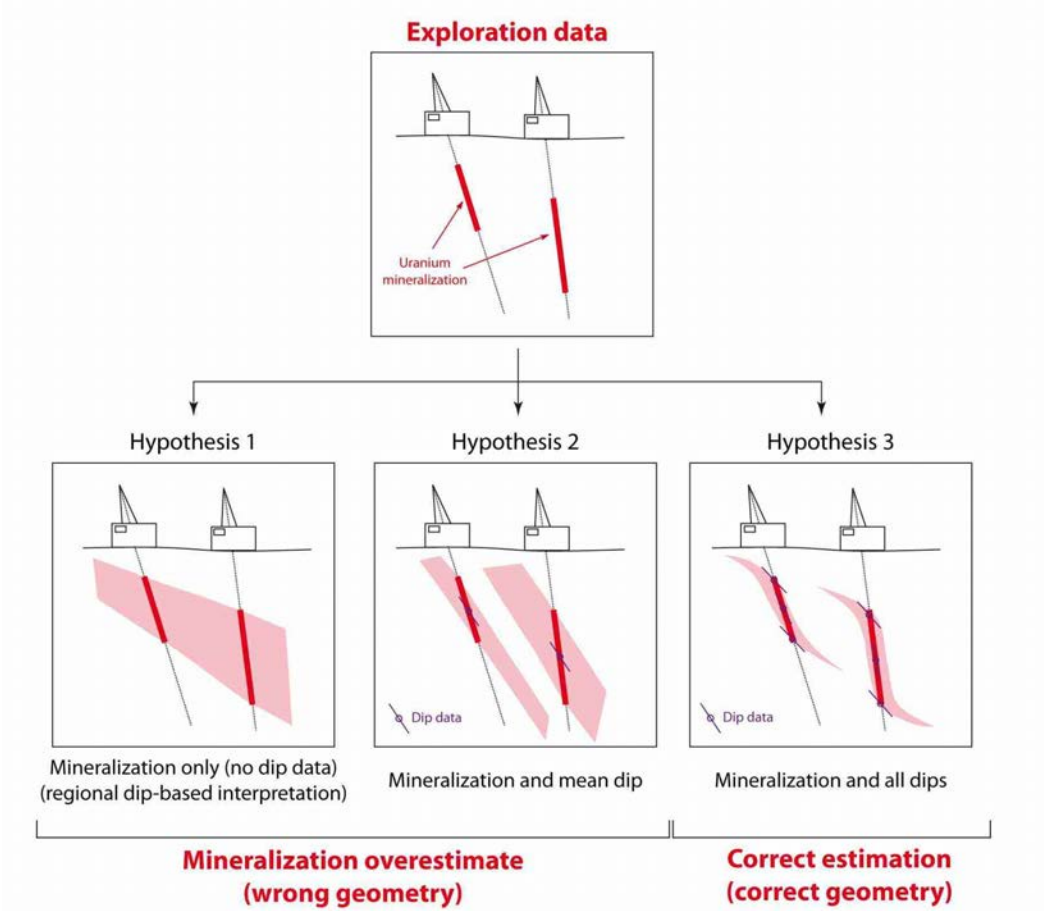

FIG. 5.10. Drill hole mineralization becomes more realistic and better defined with increased drilling and structural measurements. Mineral resources can be defined, and the Preliminary Economic Assessment (Scoping Study) can be completed.

If mineral resources can be defined at the end of the detailed exploration phase, a Preliminary Economic Assessment (PEA, also known as a Scoping Study) is the next logical step since it provides appropriate assessments of realistically assumed modifying factors together with any other relevant operational factors that are necessary so that advanced exploration/deposit studies phase can be reasonably justified. The outcome of a Preliminary Economic Assessment typically determines whether the stage gate opens or closes at the end of the detailed exploration phase. It should be noted that the definition of initial mineral resources does not alone justify progressing from detailed exploration to the advanced exploration phase. Instead, the PEA is a means for an exploration company to evaluate, at very high levels, a project's likeliness of success or failure. Skipping this stage gate of economic evaluation may unnecessarily burden a company with the costs of advancing marginal projects to the advanced exploration phase when such costs may not be warranted. Therefore, an economic analysis of the potential viability of initial mineral resources is needed on the basis of the Preliminary Economic Assessment to justify continued investment in the subsequent, advanced exploration phase.

5.6 PHASE 5 – ADVANCED EXPLORATION / DEPOSIT STUDIES

The advanced exploration/deposit studies phase commences when the following key criteria are reached:

— The geological and grade continuity of the uranium deposit has been confirmed and Mineral Resource (usually at the confidence level of Inferred Resources) has been defined;
— The outcome of the Scoping Study (also known as PEA) is positive in respect to economic viability.

Advanced exploration is carried out on a deposit scale with the following main objectives:

— To increase the levels of geological knowledge and confidence of the uranium deposit;
— To define Mineral Resources at the confidence level of Indicated and Measured Resources;
— To carry out metallurgical test work, to confirm the ability to recover uranium from its hosting minerals, and to develop metallurgical flowsheet;
— To develop Ore Reserves from Mineral Resources;
— To carry out economic and engineering studies to demonstrate economic viability of the uranium deposit by completing the Pre-Feasibility Study;
— To carry out infrastructure investigations, environmental impact assessment, mining planning, geotechnical tests, evaluation of the capital and operating costs, project infrastructure design and reclamation plan;
— To confirm economic viability of the uranium deposit and to show how the uranium mine will be built by completing the Feasibility Study.

The main objective of the advanced exploration/deposit studies phase is the confirmation of the economic potential of uranium mineralization by increasing the levels of geological knowledge and confidence. This is achieved through an increased density of sampling, typically achieved through detailed drilling follow-up.

During the advanced exploration/deposit studies phase, detailed geological, geochemical, and geophysical studies can be used to better define the mineralization at the local deposit scale. Mineral deposit definition drilling continues with additional drill holes to define the extent of mineralized grades and thicknesses, and the geological setting. Preliminary analytical studies of mineralization and rock qualities also continue, to support mining and metallurgical considerations. This information leads to a better understanding of the spatial distribution of the grade and tonnage of mineralized rocks, supporting the further definition of the mineral deposit, including the development of resource and ore reserve estimations, and mining, process, metallurgical, and hydrogeological studies. Hydrogeological and leachability studies are pertinent to assess mineralized settings that have the potential for in situ recovery (ISR), also known as in situ leach methods. Information is also collected to support early-stage environmental baseline studies.

Mineral deposit definition (deposit studies) involves more intense data gathering including the further identification of geological characteristics through the assessment of physical, chemical, and mineralogical properties. Bench-scale metallurgical tests, and further hydrogeological and leachability studies for ISR amenable deposits, are also warranted. Collecting additional information for resource calculations involves establishing mining cut-off grades and thicknesses, and calculating mineralized volumes, tonnage, grade, and metal (uranium) content. The appraisal and categorization of resources using conventional or geostatistical methods continue, with additional deposit definition drilling to further define grades and thickness, and the extent of the uranium deposit.

As advanced exploration progresses into mineral deposit definition, the 3D modelling of mineral resources continues, leading to the further classification of indicated resources and the identification of measured resources, thus informing the technical viability of the deposit. Next, probable and proven ore reserves are identified through the assessment of modifying factors that inform the environmental-social-economic viability of the mining project. These factors relate to mining, processing, metallurgy, infrastructure, economics, marketing, legal, political, social responsibility, and environmental sustainability. For further information including the various resource term definitions see JORC [5.6], CRIRSCO [5.18], and Fig. 5.11 below.

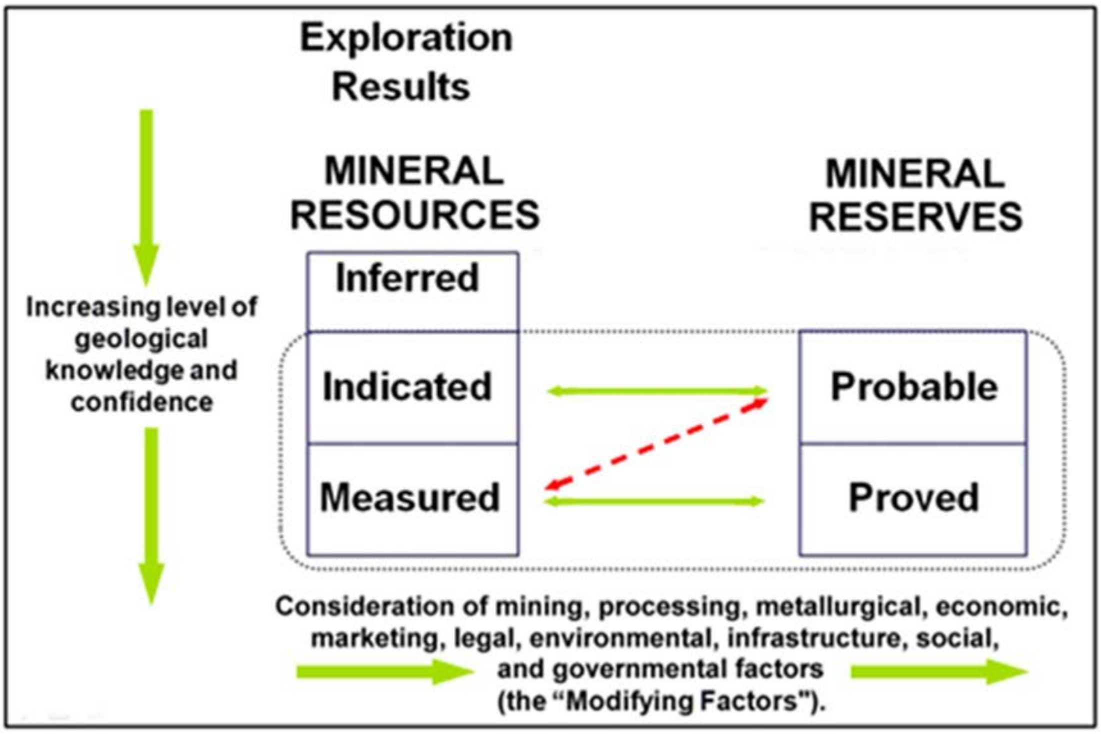

FIG. 5.11. Relationship between Exploration Results, Mineral Resources and Ore Reserves. After CRIRSCO [5.18].

Following the PEA, a Pre-Feasibility Study, and Feasibility Study are typically completed, if justified. These technical and environmental-social-economic viability studies include detailed engineering studies focused on how the mine will be constructed. The collection of a bulk mineralized sample, and the completion of a pilot plant test, or a pilot well-field test for ISR amenable deposits, are usually required to increase technical confidence. These studies inform investment decisions with increasing economic confidence, potentially leading to mining development and production.

At the advanced stage of exploration, engagement with affected stakeholders increases with a focus on social responsibility and environmental sustainability. An Environmental and Social

Impact Study is typically required before mining development to support the Feasibility Study [5.3, 5.39, 5.40].

REFERENCES TO CHAPTER 5

[5.1] MARLATT, J., KYSER, T.K., Paradigmatic shifts in the uranium exploration process: knowledge brokers and the Athabasca learning curve, Soc. Econ. Geol. News. **84** (2011).

[5.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantitative and Spatial Evaluations of Undiscovered Uranium Resources, IAEA-TECDOC-1861, IAEA, Vienna (2018).

[5.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of National Infrastructure for the Uranium Production Cycle, IAEA Nuclear Energy Series No. NF-G-1.1, IAEA, Vienna (2023).

[5.4] CANADIAN INSTITUTE OF MINING, METALLURGY AND PETROLEUM, CIM Mineral Exploration Best Practice Guidelines, CIM (2018).

[5.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Project management in nuclear power plant construction: guidelines and experience, IAEA Nuclear Energy Series No. NP-T-2.7, IAEA, Vienna (2012).

[5.6] JOINT ORE RESERVES COMMITTEE, Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves, JORC, Carlton (2012).

[5.7] YUNIS, J., ALIAKBARI, E., Fraser Institute Annual Survey of Mining Companies 2020, Fraser Institute (2021).

[5.8] INTERNATIONAL ATOMIC ENERGY AGENCY, Unconformity-related uranium deposits, IAEA-TECDOC-1857, IAEA, Vienna (2018).

[5.9] INTERNATIONAL ATOMIC ENERGY AGENCY, World Distribution of Uranium Deposits (UDEPO), IAEA-TECDOC-1843, IAEA, Vienna (2018).

[5.10] WOODALL, R., Empiricism and concept in successful mineral exploration, Australian Journal of Earth Sciences **41** 1 (1994) 1–10, https://doi.org/10.1080/08120099408728107

[5.11] MARJORIBANKS, R., Geological Methods in Mineral Exploration and Mining, Springer, Berlin Heidelberg (2010), https://doi.org/10.1007/978-3-540-74375-0

[5.12] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2020: Resources, Production and Demand, OECD, Paris (2020), https://doi.org/10.1787/d82388ab-en

[5.13] INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Classification of Uranium Deposits and Description of Selected Examples, IAEA-TECDOC-1842, IAEA, Vienna (2018), http://dx.doi.org/10.13140/RG.2.2.36449.56162

[5.14] RURNICK, R.L., GAO, S., "Composition of the continental crust", Treatise on Geochemistry, Vol. 3 (HOLLAND, H.D., TUREKIAN, K.K., Eds.), (2003) 1–64, https://doi.org/10.1016/B0-08-043751-6/03016-4

[5.15] HAZEN, R.M., EWING, R.C. and SVERJENSKY, D.A., Evolution of uranium and thorium minerals, American Mineralogist (2009) 1293–1311, https://doi.org/10.2138/am.2009.3208

[5.16] AIRO, M., Aerogeophysics in Finland 1972-2004: Methods, System Characteristics and Applications, Geological Survey of Finland, Special Paper **39** (2005).

[5.17] MOON, C.J., WHATELEY, M.K. and EVANS, A.M, Introduction to Mineral Exploration. Blackwell Publishing (2006), https://doi.org/10.2113/gsecongeo.102.1.161

[5.18] CRIRSCO, International Reporting Template for the public reporting of Exploration Targets, Exploration Results, Mineral Resources and Mineral Reserves (2019).

[5.19] INTERNATIONAL ATOMIC ENERGY AGENCY, Occupational Radiation Protection in the Uranium Mining and Processing Industry, IAEA Safety Report Series No.100, IAEA, Vienna (2020).

[5.20] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in airborne and ground geophysical methods for uranium exploration, IAEA Nuclear Energy Series No. NF-T-1.5, IAEA, Vienna (2013).

[5.21] ROSHOLT, J.N., Natural radioactive disequilibrium of the uranium series. U.S. Geological Survey, Bull., 1084-A (1959), https://doi.org/10.3133/b1084A

[5.22] DICKSON, B., BECKITT, G., The application of Monte Carlo modelling to downhole total-count logging of uranium: Part I – low grade mineralization and Part II – high grade mineralization, Exploration Geophysics (2018), https://doi.org/10.1071/EG12068

[5.23] SORBA, C., VERRAN, D., LEUANGTHONG, O. and KELLER, D., Technical Report with an Updated Mineral Resource Estimate for the Midwest Property, Northern Saskatchewan, Canada, Denison Mines Corporation (2018).

[5.24] INTERNATIONAL ATOMIC ENERGY AGENCY, Compliance Assurance for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. SSG-78, IAEA, Vienna (2023).

[5.25] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection Programmes for the Transport of Radioactive Material, IAEA Safety Standards Series No. SSG-86, IAEA, Vienna (2023).

[5.26] INTERNATIONAL ATOMIC ENERGY AGENCY, Security Management of Radioactive Material in Use and Storage and of Associated Facilities, IAEA Nuclear Security Series No. 43-T, IAEA, Vienna (2022).

[5.27] ABZALOV, M.Z., Quality control of assay data: A review of procedures for measuring and monitoring precision and accuracy, Exploration and Mining Geology **17** 3–4 (2008) 131–144, https://doi.org/10.2113/gsemg.17.3-4.131

[5.28] PROSPECTORS & DEVELOPERS ASSOCIATION OF CANADA (PDAC), Excellence in Health and Safety e-toolkit (EHS), Version-01, An Initiative of the Prospectors & Developers Association of Canada (2009).

[5.29] PIRSA (The Department of Primary Industries and Resources of South Australia), Radioactive Core Storage and Handling – Standard Operating Procedure, Version 2.0 (2007).

[5.30] PACKAGING AND TRANSPORT OF NUCLEAR SUBSTANCES REGULATIONS, SOR/2015–145 (2015).

[5.31] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standard Series No. SSR-6 (Rev. 1), IAEA, Vienna (2018), https://doi.org/10.61092/iaea.ur52-my9o

[5.32] INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR OFFICE, Occupational Radiation Protection, IAEA Safety Standards Series No. GSG-7, IAEA, Vienna (2018).

[5.33] INTERNATIONAL ATOMIC ENERGY AGENCY, Stakeholder Engagement in Nuclear Programmes, IAEA Nuclear Energy Series No. NG-G-5.1, IAEA, Vienna (2021).

[5.34] HALDAR, S., Mineral Exploration – Principles and Applications, Second Edition, Amsterdam (2018), https://doi.org/10.1016/B978-0-12-814022-2.00001-0

[5.35] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidelines for Radioelement Mapping Using Gamma Ray Spectrometry Data, IAEA-TECDOC-1363, IAEA, Vienna (2003).

[5.36] INTERNATIONAL ATOMIC ENERGY AGENCY, Airborne Gamma Ray Spectrometer Surveying, Technical Reports Series No. 323, IAEA, Vienna (1991).

[5.37] INTERNATIONAL ATOMIC ENERGY AGENCY, Descriptive Uranium Deposit and Mineral System Models, IAEA, Vienna (2020).

[5.38] INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium exploration planning and practice, IAEA-TECDOC-583, IAEA, Vienna (1991).

[5.39] INTERNATIONAL ATOMIC ENERGY AGENCY, Best Practice in Environmental Management of Uranium Mining, IAEA-NF-T-1.2, IAEA, Vienna (2009).

[5.40] INTERNATIONAL ATOMIC ENERGY AGENCY, Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development, IAEA-NF-T-1.1, IAEA, Vienna (2009).

LIST OF ABBREVIATIONS

cm	centimeter
CRIRSCO	Committee For Mineral Reserves International Reporting Standards
CRMs	certified reference materials
DMP	data management plan
eTh	equivalent thorium
eU	equivalent uranium
f_{O2}	oxygen fugacity
GIS	Geographical Information Systems
GPS	global positioning system
ISR	in-situ recovery
JORC	Joint Ore Reserves Committee
kgU	kilograms of uranium metal
km^2	square kilometres
lb	pound
m	metre
Mlb	million pound
NI 43–101	National Instrument 43–101
ppm	parts per million
PEA	Preliminary Economic Assessment
QAQC	quality assurance and quality control
QC	quality control
RAR	reasonably assured resources
RC	reverse circulation
RPEEE	reasonable prospects for eventual economic extraction
RQD	rock-quality designation
SD	standard deviation
SOP	standard operating procedures
Sv	sievert
tU	tons of uranium metal
UDEPO	Uranium Deposits Database

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