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World Thorium Occurrences, Deposits and Resources

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WORLD THORIUM OCCURRENCES, DEPOSITS AND RESOURCES

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WORLD THORIUM OCCURRENCES, DEPOSITS AND RESOURCES

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FOREWORD

With increased demand for carbon-free energy and accelerated growth of global nuclear power, it is possible that thorium will be used as a nuclear fuel in the foreseeable future. The thorium fuel cycle offers several potential advantages, including superior physical and nuclear properties of fuel, enhanced proliferation resistance, and reduced plutonium and actinide production. Thorium use in light water reactors, high temperature reactors and liquid fluoride thorium reactors has been successfully demonstrated. Recently, many Member States have announced new initiatives involving the use of thorium.

During the peak years of nuclear development in the 1960s and 1970s, thorium was regarded as an alternative to uranium for fuelling nuclear reactors, and a number of thorium fuelled reactors were developed and put into operation. Thorium fuelled reactors have demonstrated advantages such as a higher yield of neutrons and the absence of plutonium produced in the uranium fuel cycle. Among the disadvantages are the intermediate production of protactinium-233, which diminishes the yield of neutrons, and problems related to radiation, the inert nature of thorium oxide and the reprocessing of spent thorium fuel.

The crustal abundance of thorium is three to five times greater than that of uranium. Thorium occurs as oxides, silicates and phosphates, often with rare earth elements and other critical materials such as niobium, tantalum and zirconium. The total world thorium resources are estimated to be around 6 million tonnes. However, thorium resources cannot be compared with uranium resources, the total identified and predicted resources of which were approximately 9.3 million tonnes as of 2014. These thorium estimates are based on historic data and recent estimates from a few countries. Thorium geology and mineralogy, though not widely studied in the past, is currently receiving increasing attention owing to its close association with rare earth elements and other critical materials. The possibility of thorium as a by-product of rare earth element production is becoming increasingly relevant today.

This publication attempts to combine existing knowledge of thorium geology and mineralization into a brief account of the worldwide occurrence of thorium resources. Recent advances in estimating thorium resources are also presented.

The IAEA officers responsible for this publication were M. Fairclough and H. Tulsidas of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION 1
   - 1.1. BACKGROUND 1
   - 1.2. OBJECTIVE 1
   - 1.3. SCOPE 2
   - 1.4. STRUCTURE 2
2. PRINCIPAL PHYSICAL AND CHEMICAL PROPERTIES 2
3. THORIUM MINERALS 3
4. CLASSIFICATION OF THORIUM DEPOSITS 4
   - 4.1. DESCRIPTION OF THORIUM DEPOSIT TYPES AND EXAMPLES 8
     - 4.1.1. Carbonatite 8
     - 4.1.2. Alkaline/peralkaline rocks 9
     - 4.1.3. Vein type 9
     - 4.1.4. Placers 9
     - 4.1.5. Metamorphic type 9
5. GEOLOGICAL CHARACTERISTICS OF THORIUM DEPOSITS 10
   - 5.1. RESOURCE CLASSIFICATION TERMINOLOGY 10
   - 5.2. NEA/IAEA RESOURCE TERMINOLOGY 11
   - 5.3. UNFC RESOURCE TERMINOLOGY 12
   - 5.4. SUMMARY 13
6. DESCRIPTION OF INDIVIDUAL THORIUM DEPOSITS 13
   - 6.1. EUROPE 14
     - 6.1.1. Austria 14
     - 6.1.2. Finland 14
     - 6.1.3. France 15
     - 6.1.4. Greenland/Denmark 15
     - 6.1.5. Italy 18
     - 6.1.6 Macedonia 18
     - 6.1.7. Norway 18
     - 6.1.8. Poland 21
     - 6.1.9. Portugal 21
     - 6.1.10. Russian Federation (European Part) 21
     - 6.1.11. Serbia 23
     - 6.1.12. Slovenia 23
     - 6.1.13. Spain 23
     - 6.1.14. Sweden 23
     - 6.1.15. Turkey 24
     - 6.1.16. Ukraine 26
     - 6.1.17. Summary for Europe 26
   - 6.2. NORTH AMERICA 26
     - 6.2.1. Canada 26
     - 6.2.2. Mexico 29
     - 6.2.3. United States of America 29
   - 6.3. CENTRAL AMERICA AND CARIBBEAN ISLANDS 36
   - 6.4. SOUTH AMERICA 36
     - 6.4.1. Argentina 37
     - 6.4.2. Bolivia, Plurinational State of 38
     - 6.4.3. Brazil 38

6.4.4. Chile 46
6.4.5. Colombia 47
6.4.6. Peru 47
6.4.7. Suriname 47
6.4.8. Uruguay 47
6.4.9. Venezuela, Bolivarian Republic of 47
6.4.10. Summary for South America 49
6.5. AFRICA 49
6.5.1. Angola 49
6.5.2. Burundi, 50
6.5.3. Central African Republic 50
6.5.4. Democratic Republic of Congo 50
6.5.5. Cote d'Ivoire 50
6.5.6. Egypt 50
6.5.7. Ghana 51
6.5.8. Kenya 51
6.5.9. Liberia 51
6.5.10. Madagascar 51
6.5.11. Malawi 54
6.5.12. Mauritania 54
6.5.13. Morocco 54
6.5.14. Mozambique 55
6.5.15. Namibia 55
6.5.16. Nigeria 55
6.5.17. Sierra Leone 55
6.5.18. Somalia 55
6.5.19. South Africa 55
6.5.20. Tanzania, United Republic of 58
6.5.21. Togo 58
6.5.22. Uganda 59
6.5.23. Zambia 60
6.5.24. Summary for Africa 60
6.6. ASIA 60
6.6.1. Bangladesh 60
6.6.2. China 61
6.6.3. India 65
6.6.4. Indonesia 73
6.6.5. Iran, Islamic Republic of 76
6.6.6. Kazakhstan 76
6.6.7. Korea, Republic of 77
6.6.8. Kyrgyzstan 78
6.6.9. Malaysia 79
6.6.10. Mongolia 80
6.6.11. Myanmar 81
6.6.12. Pakistan 81
6.6.13. Philippines 81
6.6.14. Russian Federation, Asian part 83
6.6.15. Saudi Arabia 84
6.6.16. Sri Lanka 84
6.6.17. Thailand 86
6.6.18. Uzbekistan 87
6.6.19. Vietnam 87
6.6.20. Summary for Asia 89
6.7. AUSTRALIA AND NEW ZEALAND 89
6.7.1. Australia 89

6.7.2. New Zealand 100
6.8. PACIFIC OCEAN ISLANDS AND ANTARCTICA 102

7. SUMMARY OF WORLD THORIUM RESOURCES AND SUPPLY 102

7.1. HISTORICAL DEVELOPMENT OF THORIUM RESOURCES 102
7.2. GEOGRAPHIC DISTRIBUTION.. 107
7.3. GEOLOGIC-METALLOGENIC DISTRIBUTION OF RESOURCES 108
7.4. THORIUM SUPPLY 109
7.5. PRINCIPAL PRODUCING COUNTRIES 110
7.6. PRICES 111
7.7. APPLICATIONS 111
7.7.1. Non-nuclear applications 111
7.7.2. Nuclear application 111

8. CONCLUSIONS 113

REFERENCES 115

ABBREVIATIONS…………………………………………………………………….....121

CONTRIBUTORS TO DRAFTING AND REVIEW 122

1. INTRODUCTION

Thorium was discovered in an unknown black mineral found by Hans M.T. Esmark on the island of Lövö, Norway. He sent it to his father, Jens Esmark, a geologist, for identification. Unable to identify the mineral, Esmark sent it to the Swedish chemist Jöns Jakob Berzelius, who identified in 1828 a new element which he called Thorium after the Nordic God Thor of Thunder/War. The mineral was described as the thorium-silicate thorite.

The isolation of the element thorium was made by D. Lely Jr. and L. Hamburger in 1914 [1–2]. Thorium has the atomic number 90 and the atomic weight 232. Its chemical symbol is Th. The element thorium is a metal, which in its metallic state is silvery white. However, in nature, thorium occurs in compounds, mainly as an oxide or silicate and very often as a substituted minor element in a number of minerals.

The main industrial application of thorium is as thorium nitrate in gas mantles to produce bright light. Thorium can be used as nuclear fuel instead of or in addition to uranium in nuclear reactors.

1.1. BACKGROUND

The first nuclear power plants using thorium or thorium-uranium as fuel for producing energy were mainly experimental and prototype plants. They were developed in the 1960s and brought into operation in the United States of America, the United Kingdom of Great Britain and Northern Ireland, in the Former Soviet Union, and Germany. The initial enthusiasm was not sustained due to sufficient supply of uranium, which originally was expected not to last for extended time spans and to satisfy industrialised and developing countries. Nuclear technologies applying both natural and enriched uranium matured over the time and, thus the ‘uranium fuel cycle’ became the leading nuclear technology.

Realising that uranium availability may have various limits, being either declining availability due to costs developments or declining amounts of secondary sources expected for coming decades, the introduction of the thorium fuel cycle is potentially a complementary source for nuclear energy. In addition, growth of nuclear energy is foreseen in different countries in the context of accelerating a carbon-free energy. Thus, the sustainable use of nuclear fuel such as uranium and thorium is important. Consequently, since the end of the 20th century and the beginning of the 21st century, awareness of national and international organisations related to securing energy demand renewed interest in thorium. Among them, the IAEA intensified its efforts to increase knowledge on thorium.

The thorium fuel cycle offers several potential advantages over the uranium fuel cycle. Among others, thorium is geochemically more abundant, it has superior physical and nuclear properties, a better proliferation resistance (see non-proliferation treaty), and produces lower amount of plutonium and actinide elements.

1.2. OBJECTIVE

This document on world distribution of thorium occurrences/deposits and thorium resources aims to collect published and unpublished information on the availability of the radioactive element thorium. A great number of papers have been published decades ago and may be outdated. Interest for thorium has been very limited over past decades. Especially estimates on economic aspects of thorium availability may be no longer realistic due to changes of economic circumstances. Thus, this document reviews available data on thorium occurrences/deposits and thorium resources and presents a classification of deposits according to geological and economic criteria.

The number of countries reporting thorium deposits or occurrences is limited. However, due to the presence of thorium in the lattice of the mineral monazite, it seems appropriate at least to include information on monazite deposits and occurrences for those countries.

1.3. SCOPE

The International Atomic Energy Agency undertakes efforts to integrate all nuclear fuel cycle-related databases and to make them readily accessible to Member States. In this context, a database including all relevant information on uranium deposits and resources was established and a comprehensive document named “World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification” was issued in 2009. An updated and extended document has been published in 2018.

As mentioned above, owing to the recently renewed interest in the thorium fuel cycle, the IAEA started to prepare a database for thorium, comparable to the UDEPO database. A consultants meeting was held in 2010 to establish guidelines for the structure of the database called “World Thorium Deposits and Resources” (ThDEPO). It was agreed by the consultants to prepare a document collecting available information on thorium resources and deposits. A number of meetings were held by the IAEA on this subject and are listed at the end of the document.

1.4. STRUCTURE

This document is structured as outlined in the table of contents. A short description of the principal physical and chemical properties of thorium is followed by an overview of thorium minerals. The consultants in their meetings in 2010–2013 felt the need to develop a classification of thorium deposits to understand the availability of thorium. The main part of this document covers a description of individual thorium deposits and major occurrences country by country, followed by an overview of their geographic distribution and geological-metallogenic characteristics. The final chapters cover thorium availability, principal producers, prices and applications.

Figures are taken, if not otherwise noted, from the publication by F. Barthel and F. Dahlkamp, on Thorium Deposits [3], and from presentations held at the IAEA Technical Meeting “World Thorium Resources”, in Thiruvananthapuram, India (Oct. 2011).

2. PRINCIPAL PHYSICAL AND CHEMICAL PROPERTIES

Thorium is a radioactive element of the actinide group of elements of the Periodic System. Thorium oxidises in air after several days resulting in a thin layer of black oxide that covers the metal.

The radioactivity of thorium was discovered independently in 1898 by the physicist Marie Sklodowska-Curie and the chemist Gerhard C. Schmidt. After the discovery of radioactivity in 1900, Ernest Rutherford and Frederick Soddy found that thorium decays with a certain constant (half-life time) of 1.405×10^{10} years. Further discoveries led to the identification of several isotopes of thorium, of which ^{232}Th is the most common and displays the mentioned half-life. Other isotopes are ^{234}Th, ^{231}Th, ^{230}Th, ^{229}Th, ^{228}Th, and ^{227}Th occurring in trace amounts only. They represent radionuclides produced by the radioactive decay of ^{238}U, ^{235}U and ^{232}Th and are characterised by comparatively short half-life times of several hours (^{231}Th: 25.5 hours) to over 80 000 years (^{230}Th).

Chemically thorium is characterised by its stable +4 oxidation state, both in minerals and when dissolved in fluids. A common compound is the thorium dioxide **ThO_2.** Thorium dioxide has a melting point of 3 300 ºC, the highest of all oxides, which explains some of its uses. At low temperatures ThO_2 has a very low solubility which explains why thorium tends to be enriched in the oxidised zones of many thorium deposits. The solubility of thorium increases strongly as pH decreases weakly. At pH 3, the solubility of thorium reaches 100 ppm as a sulphate complex (e.g. in Italy thorium was deposited in acid hot spring concretions in Quaternary thorium-rich alkali basalts).

Thorium has a large ionic radius and a high charge which prevents it from being incorporated in most rock-forming minerals. In magmas, during partial melting and fractional crystallisation in the mantle, thorium has a strongly incompatible behaviour, similar to elements such as U, REEs, Zr, Nb and others.

In the primitive mantle, thorium concentration is estimated to vary from 29.8 ppb (in chondritic meteorites) to 83.4 ppb [4]. Thorium is nearly half as dense as uranium (d=11.7 g/cm^3).

The behaviour of thorium in the geochemical cycle is extreme in peralkaline magmas because of its high-temperature genesis and excess in alkali elements with respect to alumina, required to form feldspars [5]. Excess alkalis appear as feldspathoids, Na-amphiboles and Na- pyroxenes and other alkali-rich phases. In peralkaline silicate melts, the elements thorium, U, REEs, Zr, Nb are enriched simultaneously and the initial Th/U chondritic ratios of 3–4 tend to be preserved.

In ore deposits formed during fractional crystallisation of peralkaline magmas, thorium tends to be 3–4 times more abundant than U and crystallises together with REEs, Zr and/or Nb/Ta-bearing minerals [5]. Owing to these properties, most thorium deposits are linked to peralkaline magmatism directly or indirectly:

- Carbonatites generally representing the last phase of peralkaline complexes;
- Magmatic fluids chiefly arising from carbonatites result in th mineralisation in veins (with or without associated u, ree, zr and nb) or in metasomatised rocks (fenites);
- Undersaturated or quartz-saturated acidic pegmatitic, peralkaline plutonic or volcanic rocks [6].

The geochemistry of thorium shows its preference for acidic rocks, such as granite where it can reach concentrations of several tens of ppm because of its strong incompatible behaviour. In the earth´s crust, the mean thorium content is ~5.6 ppm, with 10.5 ppm in the upper crust and 1.2 ppm in the lower crust. Hence, thorium is enriched 15–40 times in the lower crust compared to the primitive mantle and up to 350 times in the upper crust [7–8].

3. THORIUM MINERALS

Thorium does not occur in its metallic form in nature because it is markedly oxyphile and, thus, occurs as oxides (thorianite), silicates (thorite) and phosphates (frequently with REEs). A common rare earth-thorium mineral is phosphate monazite, in which the thorium content can reach up to 26%. However, the most frequent concentrations of thorium in monazite do not exceed 10%. Other common minerals, however lower in thorium content, are xenotime and zircon. A tentative classification of thorium minerals by chemical composition and mineralogical characteristics is as follows:

- Silicates with thorium as a major element;
- Silicates with thorium as a minor constituent;
- Oxides, hydroxides, phosphates, carbonate (rare), with thorium as either a major or minor element.

The variety of minerals that contain thorium is great and the following Table 1 may be not complete, but does contain a number of minerals, some of which are very rare and described from only one or a few localities. Except for thorium minerals of comparatively simple composition, other minerals are complex in their mineralogical formula and are not repeated here. The reader is referred to corresponding textbooks. In addition to the minerals listed in Table 1 in the corresponding specific literature unnamed thorium-bearing silicates and phosphates are mentioned.

As it will be shown later, thorium minerals can occur in a variety of rocks. Under certain geological circumstances, thorium is not incorporated in common rock-forming minerals (i.e. it is a non-compatible element) and may be enriched in specific minerals to such concentrations that it can be extracted, either as a by-product or as major product.

Under prevailing economic conditions thorium recovery as by-product of other elements, such as REEs, may be the preferred option. At present, with few exceptions, recovery of thorium from such sources is not pursued. However, conditions may change in the future if thorium is deemed essential and becomes economical as a primary commodity.

TABLE 1. MINERALS WITH THORIUM AS A MAJOR OR MINOR COMPONENT

Th-bearing oxides, -hydroxides	Th-bearing silicates	Th-bearing phosphates	Th-bearing carbonates
thorianite	thorite	monazite	thorobastnaesite
absite	zircon	xenotime	kukharenkoite
thorutite	huttonite	Th-crandalite	
broeggerite	thorogummite	brockite	
thucholite	steacyite	brabantite	
aeschynite	ekanite	cheralite	
zirkelite	umbozerite	eylettersite	
betafite	thorobritholite	kivuite	
brannerite	thorosteenstrupine	karnasurtite	
polymignite	melanocerite	fenghuangite	
euxenite	tritonite	saryarkite	
polycrase	yttrialite (yttrianite)	althupite	
thorotungstite	chevkinite	grayite	
priorite	perrierite	kamsurtite	
cerianite	dissakisite		
yttrocrasite	enalite		
pyrochlore	abenakirite		
	arapovite		
	ciprianite		
	coutinhoite		
	hellandite		
	iraqite		
	pierggorite		
	thomasite		
	tritomite		
	vicanite		

4. CLASSIFICATION OF THORIUM DEPOSITS

Thorium resources are generally 3–4 times greater than uranium resources because the Clarke concentrations of thorium are 3–4 times greater than uranium. Thorium often occurs in nature associated with uranium. However, under specific circumstances, thorium may form deposits that do not contain uranium or only in very small amounts.

Uranium has two valence states, U (IV) and U (VI), and is highly soluble as UO_2^{2+} in oxidising conditions. Thorium has only one valence state, Th (IV), and has low solubility at low to intermediate temperature. These properties have several major consequences:

- Thorium minerals can be concentrated mechanically as resistates in placer type deposits;
- Most other thorium deposit types are developed in magmatic and high-temperature hydrothermal environments;
- Metallurgical extraction of thorium from ores needs methods that are costlier than for U.

Despite its abundance, scientific interest in thorium deposits has been low, compared to uranium, because of its limited demand. Thus, attempts to classify thorium deposits are fewer. When commercial interest for thorium started in the 1960s and 1970s, several scientific papers were published and some attempts to classify thorium deposits were made. The attempt to classify deposits of thorium was renewed in 1991 when a tentative classification scheme of thorium mineralisations/deposits independent of their economic significance was proposed, using mainly their geologic settings and the host rocks (Table 2).

TABLE 2. TENTATIVE CLASSIFICATION OF THORIUM MINERALISATION/DEPOSITS AS OF 1991

Igneous	Syngenetic	Igneous epigenetic	Metasomatic	Metamorphic	Sedimentary
Intrusive	effusive				
Carbonatites	acidic volcanics	pegmatites	sodium metasomatites/albitites	migmatites	coastal placers
Syenites	alkaline volcanics	veins associated with alkaline batholiths		thoriferous charnockite	fluvial placers
Alkaline rocks	diatremes			thoriferous pyroxenite	residual placers
Peralkaline rocks		carbonatites		Contact metamorphic	paleo-placers
Granitic rocks		alkaline volcanics			dolomites
		unknown			black shales

Note: according to personal communication, Na-metasomatism does not carry thorium (M. Cuney, 2011).

The same classification was presented at the IAEA Technical Committee Meeting "New Developments in Uranium Resources, Production and Demand", Vienna, 26–29 August 1991, published in IAEA-TECDOC-650 [9]. T. Chung [10] gives a brief subdivision into three major types of deposits focussing however mainly on the situation in the United States of America:

- Vein deposits;
- Beach or stream placer deposits;
- Carbonatites.

A simplified version of the thorium deposits classification was provided at the IAEA Technical Meeting "Fissile Material Management Strategies for Sustainable Nuclear Energy" in September 2005, published by IAEA 2007 [11]. The table was reproduced in the paper "Unconventional Resources of Nuclear Fuel", presented at the IAEA Technical Meeting "Small Scale and Special Mining and Processing Technologies", in June 2007 [12]. This was further revised in OECD-NEA/IAEA Uranium 2014 (Table 3) [13]. No estimates of recovery costs are included. In order to understand their economic significance, corresponding resources and percentages are included.

TABLE 3. MAJOR THORIUM DEPOSIT TYPES AND THEIR RESOURCES AS OF 2013. MODIFIED AFTER [13]

Major deposit type	Resources (1 000 t Th)	Percentage
Placer	2 182	35.1
Carbonatite	1 783	28.7
Vein type	1 528	24.6
Alkaline rocks	584	9.4
Others/Unknown	135	2.2
Total	6 212	100.0

The classification shown here appears in simplified form and can be used for a rapid overview. The character is geologic-descriptive and to some extent reflects the economic significance of thorium deposits. The NEA and the IAEA in their joint publications “Uranium Resources, Production and Demand” [14] report subdivisions on thorium deposit types similar to Table 3. In 2011, a classification by M. Cuney focused on genetic conditions that prevailed during the formation of thorium deposits and is shown in the list of contents of his paper “Uranium and Thorium: The extreme diversity of the Resources of the World Energy Minerals” [6]. The list is reproduced in Table 4.

TABLE 4. CLASSIFICATION OF THORIUM DEPOSITS

Type 1 Related to crystal fractionation systems	Type 2 Related to partial melting systems	Type 3 Metasomatite	Type 4 High temperature hydrothermal systems	Type 5 Syn-sedimentary systems
a) Syenitic peralkaline; b) Granitic-trachytic peralkaline; c) Carbonatite.			a) Uranothorite; b) Th-bastnaesite veins; c) Monazite veins.	a) Coastal placers; b) Dunes; c) Offshore placers; d) Stream placers; e) Fossil placers; f) Metamorphosed placers; g) Coal, lignite.

A classification used in the countries of the former USSR has four major subdivisions, given in Table 5 below.

TABLE 5. CLASSIFICATION OF THORIUM ORE FORMATIONS IN THE FORMER USSR [15]

Type 1	Type 2	Type 3	Type 4
Magmatic alkaline formations of abyssal origin (Th-REE in agpaitic nepheline-syenite and in metasomatites. Th-REE-Rare metal in carbonatites and other metasomatites).	Metasomatic alkaline incrustal formations (Th-REE-U in pegmatites. Th-Rare Metal in sodium quartz-feldspar metasomatites).	Acid hydrothermalites bound within crustal alkaline rocks (Th-P-U in eusites. Th-REE in acid hydrothermalite).	Terrigeno-clastogenic transferred or residual ancient and modern formations (Th-Rare Metal in carbonatite weathering crust). Th-REE-Rare Metal (sometimes Au, U) in ancient and modern placers.

In 2010, in view of thorium´s future relevance as nuclear fuel, the IAEA initiated an activity on developing a new resource information system for thorium, ThDEPO–World distribution of thorium deposits and resources. A revised classification for the deposits of thorium was proposed by a group of experts associated with this activity. Further discussions and consultations with experts have shown that two approaches were preferred:

– geologic-descriptive scheme;
– classification related to genetic aspects.

A need was identified to relate the new scheme to existing classification schemes, so that a broad continuity could be maintained. A geological-descriptive scheme was preferred for its easier applicability to different environments. A classification related to genetic aspects alone could prove difficult if aspects of its genesis are not well studied. The revised classification is thus proposed here is based on geological description, with some elements of genesis added to it (Table 6).

TABLE 6. REVISED CLASSIFICATION OF THORIUM DEPOSITS AND RESOURCES

Type 1 Igneous	Type 2 Metasomatic	Type 3 Metamorphic	Type 4 Sedimentary	Type 5 Residual	Type 6 Others
a) Syngenetic: i) Granite/alaskite; ii) Syenite/peralkaline rocks; iii) Carbonatite; iv) Volcanic. b) Epigenetic: i) Pegmatite; ii) Vein related.			a) Beach/dune placers: i) Paleo placers; ii) Recent placers. b) Off-shore placers; c) River/stream placers: i) Paleo placers; ii) Recent placers. d) Coal/lignite; e) Phosphate.		

4.1. DESCRIPTION OF THORIUM DEPOSIT TYPES AND EXAMPLES

Thorium deposits of major importance are found in specific geological environments. For practical purposes, it seems useful to have a classification into:

- Carbonatite;
- Alkaline/peralkaline rocks;
- Vein-type;
- Placers;
- Metamorphic type.

Examples of each type of deposit listed above are provided below.

4.1.1. Carbonatite

There is a geologic association of peralkaline rocks and carbonatites. Carbonatites often occur as plugs within zoned alkali/peralkalic intrusive complexes. Carbonatites are classified into coarse calcitic söviet, and fine grained calcitic alvikite (Ca predominance). The dolomitic variety is called rauhaugite (Ca-Mg), and the ankeritic variety (iron rich carbonatite) is called beforsite.

The carbonatitic melt is of unusual composition as carbonates predominate silica minerals (>50% carbonate) and enriched in incompatible elements. Economic minerals can be apatite, barite, vermiculite, Th, Nb, Ta, Cu, Fe, Zr, Ti, U and others.

Examples: Araxa in Brazil, Bayan Obo in China, Fen in Norway, Sokli in Finland, Oka in Canada, Palabora in South Africa.

4.1.2. Alkaline/peralkaline rocks

As stated above, alkaline/peralkaline intrusions are often carrying a carbonatitic core or plug. Geochemically these rocks are characterised by an oversaturation of alkali elements and undersaturation of aluminium, which can be expressed asAl_2O_3 < (Na_2O +K_2O).

Examples: Illimaussaq in Greenland/Denmark, Lovozero in Russian Federation, Poços de Caldas in Brazil.

4.1.3. Vein type

Vein-type mineralisation is described as a discordant mineralisation mostly inclined in various country rocks (mostly magmatic and metamorphic) occupying faults, joints or fissures. They can be monometallic or polymetallic. Beside economic concentrations of base metals, rare metals, uranium and thorium, REEs, the common gangue minerals are quartz, barite, carbonate, fluorspar, etc.

Examples: Lemhi Pass, uranothorianite, in the United States of America, Kizilcaören, polymetallic vein, in Turkey, Steenkampskraal monazite vein, in South Africa.

4.1.4. Placers

Deposits in placers can be divided into several subtypes according to the location of the material.

Examples:

- Coastal placers–Kerala, India, Brazil;
- Dune placers–Queensland, Australia;
- Offshore placers–Neendakarai, Kerala, India;
- Alluvial placers–Western Australia, Australia;
- Fossil placers–New South Wales, Australia;
- Metamorphic placer–quartz pebble conglomerates, Ontario, Canada.

4.1.5. Metamorphic type

A deposit type of lesser importance and, thus, not well described in the literature is that occurring in a metamorphic environment. Little information is available on thorium deposits of metamorphic origin. In principle, this type consists of thorium concentrations in metamorphosed or metasomatised rocks. Thorium-bearing minerals are mostly in fine dispersed form, on joints, schistosity planes, etc. Host rocks of this type can be anatexites, migmatites, pyroxenites, gneisses and schists, as well as contact-metamorphic rocks such as skarn, hornfels and marbles. Examples: Southern Kerala in India; Sri Lanka; Sierra Leone; Madagascar; Mary Kathleen, in Australia.

As mentioned earlier, the behavior of thorium in the geochemical cycle is extreme in peralkaline magmas because of its high-temperature genesis and excess in alkali elements compared to alumina, required to form feldspars. Alkali excess is due to feldspathoids, Na-amphiboles and Na- pyroxenes and other alkali-rich phases. In peralkaline silicate melts, the elements thorium, uranium, REEs, zirconium, niobium, are enriched simultaneously and the initial Th/U chondritic ratios of 3–4 tend to be preserved. In ore deposits generated by the fractional crystallisation of peralkaline magmas, thorium tends to be 3-4 times more abundant than uranium and crystallises together with REEs, zirconium and/or Nb/Ta-bearing minerals. Because of these properties, most thorium deposits are directly or indirectly linked to peralkaline magmatism:

1) Carbonatites generally representing the last phase of peralkaline complexes;
2) Magmatic fluids chiefly arising from carbonatites result in Th deposition in veins (with or without associated uranium, REEs, zirconium and niobium) or in metasomatised rocks (fenites);

3) Undersaturated or quartz-saturated pegmatitic, acidic peralkaline plutonic or volcanic rocks.

For further information, see Chapter 5 and sections 7.2 Geographic Distribution and 7.3 Geologic–Metallogenic Distribution.

5. GEOLOGICAL CHARACTERISTICS OF THORIUM DEPOSITS

Thorium is often associated with uranium in some of the deposit types and in certain uraniferous minerals. In addition, some thorium deposits are found independently from uranium deposits. Many rocks, mostly of igneous origin, have elevated thorium content, although too low to be considered as mineable deposits under present economic conditions. The IAEA [16] and the OECD/NEA have classified thorium resources into four major types of deposits (Table 3). Apparently, thorium resources around the world are concentrated moderately in carbonatite-type deposits, which account for ~30% of the world totals. The rest of Th resources are distributed more equally among the other three deposit types, which, in increasing order of abundance, are alkaline rocks, vein-type deposits and placers. In Australia, deposits of some heavy mineral sands (placers) comprise ~70% of known thorium resources. In India, almost all of estimated thorium resources are accounted for in placer deposits with monazite, occurring at coastal areas. In Brazil, placers are well known at the coast and in carbonatite present in the state of Minas Gerais among others (see section on Brazil).

5.1. RESOURCE CLASSIFICATION TERMINOLOGY

Mineral resources classification schemes have been developed in several mining countries over the last several decades. These usually included divergent formal definitions of 'resource' and 'reserve', and diverse treatment of economic and other factors in various national reporting schemes. This has led to often extreme difficulty in comparison of mineral endowments across the world.

Established in 1994 through the sponsorships of the Council of Mining and Metallurgical Institutes (CMMI), the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) [17] is an assembly of delegates of associations that are tasked with creating mineral reporting codes and guidelines in United States of America (SME), South Africa (SAMREC), Russian Federation (NAEN), Europe (National Committee PERC), Chile (National Committee), Canada (CIM), and Australasia (JORC).

The integrated worth of mining companies included in the stock exchanges of the above-mentioned countries sums to >80% of the recorded mining industry capital. The CRIRSCO Template is the international standard for the public reporting by companies of exploration results, mineral resources and reserves of deposits inclusive of thorium and uranium deposits. A Public Report in the CRIRSCO Template "refers to any report on Exploration Results, Mineral Resources or Mineral Reserves, prepared for the purpose of informing investors or potential investors and their advisers, or to satisfy regulatory requirements". Figure 1 shows the framework upon which the CRIRSCO Template and the standards affiliated to it are based.

For reporting individual, regional, national and international estimates of thorium and uranium resources, an NEA/IAEA scheme was developed whereby uranium/thorium resources are categorised in terms of geological certainty and costs of production. The scheme is applied to integrate estimates of resources from several different countries into harmonised global figures. Currently, harmonisation of nationally or internationally applied mineral resources classifications is made possible by the United Nations Framework Classification for Fossil Energy and Mineral Resources (UNFC–2009) [18]. This was established by the Expert Group on Resource Classification and managed by the United Nations Economic Commission for Europe on behalf of the United Nations.

The UNFC–2009 is a standardised system for inventorising naturally-occurring solid minerals and petroleum resources and reserves on or within the Earth's crust. A crucial feature of this system is that, for broad application, it needs to line up with traditional and widely-used classifications (e.g. as a high-level umbrella system). It was developed to sustain, as much as possible, the requirements of applications pertinent to mineral and energy studies, corporate business process, financial reporting standards and resource management functions. Accordingly, assessments of worldwide thorium resources may be also classified using currently discussed systems of the UNFC–2009. The comparison between the resource data published by the NEA/IAEA using resource terminology (e.g. in the Red Books) and the categories applied by the UNFC–2009 may be the basis for a correlation/harmonisation.

Several countries have submitted recent assessments of their thorium resources that are detailed enough to meet the requirements for the UNFC–2009 described below or are close to these requirements. In order to provide a basis for comparison, the resource terminology used by the NEA/IAEA and the UNFC–2009 is briefly put forward in the paragraphs below.

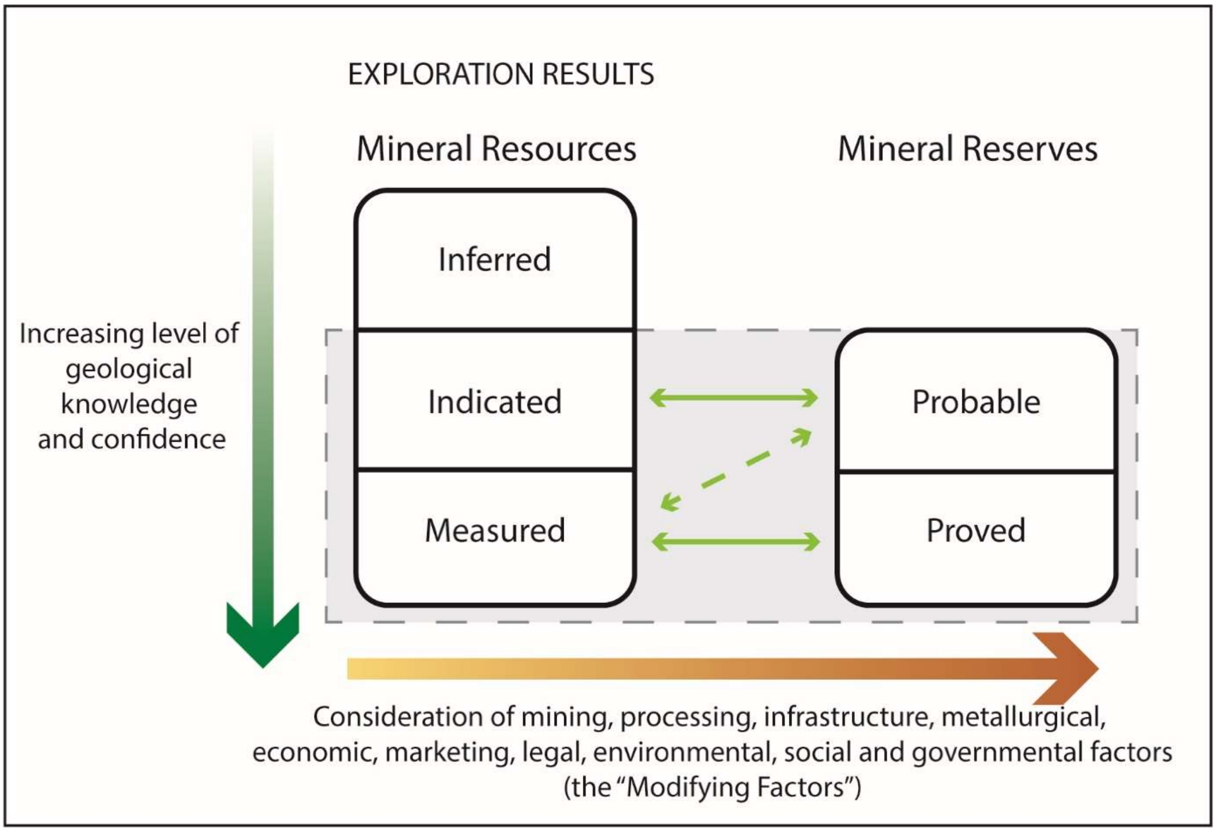

FIG. 1. The CRIRSCO classification system (modified from CRIRSCO template) [17].

5.2. NEA/IAEA RESOURCE TERMINOLOGY

Reasonably Assured Resources (RAR): Detailed explored deposit or part of it; high assurance of existence. Size, grade configuration are known, resources are recoverable.

Inferred Resources (IR): Resources in addition to RAR, based on geological evidence, Extension of well-explored deposits. Detailed knowledge of deposit characteristics is less than for RAR. Resources are recoverable.

Prognosticated Resources (PR): In addition to IR, expected to occur, mainly indirect evidence, less reliance on estimates of quantities, resources in situ.

Speculative Resources (SR): In addition to PR, thought to exist based on indirect evidence. Existence expected in a geological region or trend. Resources in situ.

For details of the above terminology please refer to [13, 14].

5.3. UNFC RESOURCE TERMINOLOGY

UNFC–2009 uses three major classes for its resource classification, which are subdivided according to the status of the project assessed. The three classes are E, F, and G (Fig. 2):

- E describes the socio-economic stage of development, in which E1 resources are economically viable under current market conditions, E2 stands for anticipated economic sale in foreseeable future, and E3 for resources not anticipated to be economically viable in the foreseeable future or whose stage of development or evaluation is too early to establish economic viability;
- F determines the degree of feasibility for a development project or mining operation. F1 stands for confirmed feasibility, F2, F3 and F4 have gradually lower degrees of feasibility, in which F4 indicates that no development or mining operation has been identified;
- G characterises the geological knowledge of resources. G1 stands for quantities in known deposits estimated with a high level of confidence, G2 for quantities estimated with a moderate level of confidence, and G3 for quantities estimated with a low level of confidence.

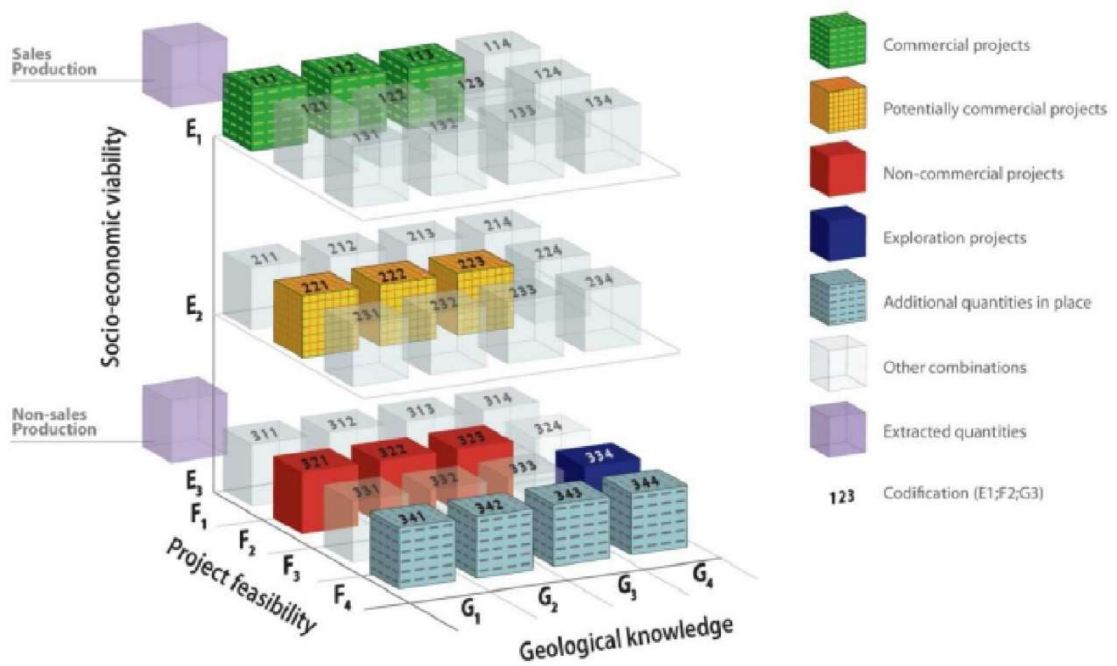

FIG. 2. UNFC–2009 categories and examples of classes (Reproduced with permission of UNECE) [18].

The UNFC–2009 has set forth principles that describe how to classify resources. Detailed description of the different classes and their subdivision into subclasses is given in [18]. The CRIRSCO Template sets the rules for application of the UNFC–2009 for solid minerals [17]. The UNFC–2009 is bridged to the NEA/IAEA classification for uranium and thorium. Recently, a set of guidelines were also released for the application of the UNFC–2009 to thorium and uranium projects, which includes a mapping with the CRIRSCO Template. Selected cases studies concerning the application of the UNFC–2009 to thorium and uranium resources are also available.

Currently, thorium has minimal commercial applications. It is a potential fuel for generation of nuclear reactors. It is at present being produced as a by-product of mining and processing of certain mineral commodities (e.g. REEs), and some projects stockpile thorium minerals for future use. As long as thorium is stored such that it remains open for commercial sale in the future, it can be ascribed to E3.2 or E3.3 (and subsequently assigned to E2 and E1 when there arises a large scale commercial market for thorium as a nuclear reactor fuel).

In the assessment of thorium resources using the UNFC–2009, as shown in the table below, available recent data are included, e.g. country submissions for the Red Book 2014 edition and submissions at recent IAEA technical meetings. Due to limitations for the UNFC, at present only a small number of countries meet the requirements. Recent resource assessments using NEA/IAEA classifications are given in Table 7.

At the Consultancy in March 2010, India reported a total of more than 846 000 t Th, without further breakdown of resource categories and cost of recovery. The new assessment is higher than previously reported (319 000 t Th of RAR < US$ 80/kg Th).

TABLE 7. RECENT UPDATES ON THORIUM RESOURCES (1000 t Th)

Country	RAR by-product	Inferred by-product	Identified	Prognosticated	Total	Date of assessment
Australia	N/A	N/A	595	N/A	595	RB 2014
Brazil	172	130	302	330	632	RB 2014
India			846		846	Consultancy3/2010
United States of America	N/A		595		595	RB 2014

RB 2014 — The 'Red Book' 2014 edition.

5.4. SUMMARY

Under the assumption that thorium is recovered as by-product, a comparison of categories used in the terminology of the Red Book with UNFC may be seen as follows:

- RAR recovered as by-product (Existing, Committed or Planned) would be comparable to UNFC classes E1 or 2, F1 or 2, G1, 2, 3 (Commercial Projects and Potentially Commercial Projects. This is mapped to CRIRSCO Mineral Reserves and Mineral Resources;
- RAR (with status unclarified or not-viable) = ~UNFC E3, F2, G1,2,3 (Non-Commercial Projects);
- Undiscovered Resources (prognosticated + speculative.) = ~UNFC E3, F3, G4 (Exploration Projects).

India is the only country today extracting thorium from monazite for which information was announced.

6. DESCRIPTION OF INDIVIDUAL THORIUM DEPOSITS

This chapter describes individual deposits by region.

6.1. EUROPE

Deposits of thorium in Europe are found in Finland, Greenland, Norway, and Turkey. Occurrences are described in the literature and other professional papers from Austria, Italy, Spain and Sweden. Recently, resource figures assigned to categories and cost classes which for instance have been previously published for Norway and Turkey, have not officially been confirmed and may not appear in tables. Except for low grade concentrations of Th in heavy mineral sands in some coastal areas in Europe no other occurrences were found. Presently, no mining for thorium is undertaken in Europe. Currently the following types of deposits are found[1]:

- Vein deposits;
- Peralkaline intrusions;
- Carbonatite;
- Volcanic rock of acidic to alkaline composition;
- Placers.

6.1.1. Austria

In southern Austria at Eisenkappel/Carinthia, a zone of Middle Permian Gröden Sandstone shows irregular parts enriched in Th (thorite, uranothorianite). The mineralisation is too small to be economically interesting.

6.1.2. Finland

The Sokli carbonatite, north of the Arctic Circle in eastern Lapland, was found to be of economic importance for its phosphate and pyrochlore content (Fig. 3). More than 50 Mt of phosphatic ore and ~1.5 Mt of pyrochlore ore were delineated by detailed exploration. The pyrochlore ore contains between 3 and 5% Th and resources were estimated in earlier publications (e.g. Red Books [14] to be ~60 000 t Th).

[1] In order to have the types comparable to what is described in the literature, the old classification is used.

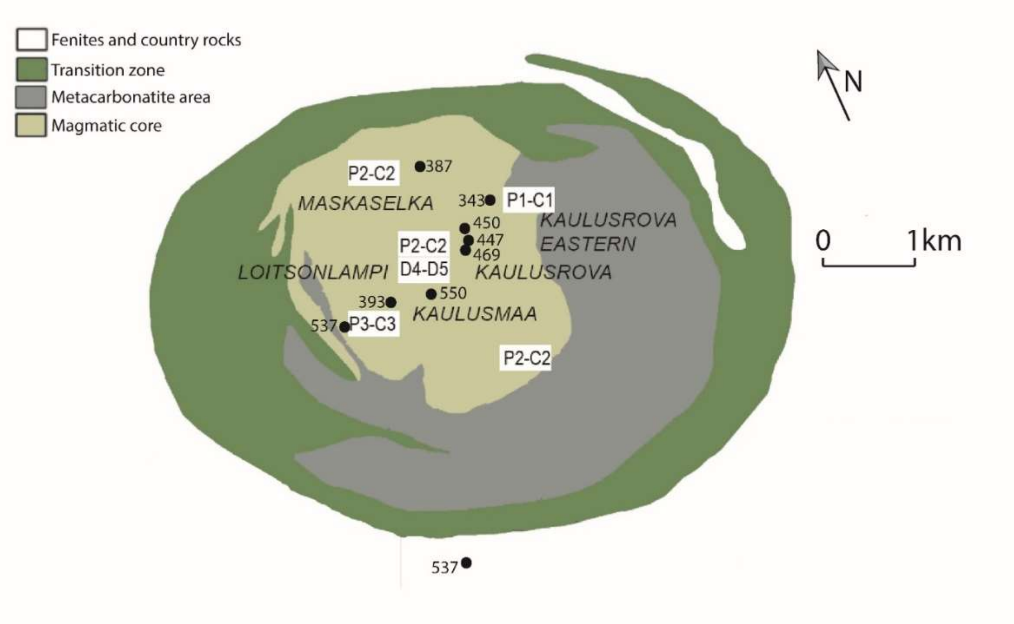

FIG. 3. Map of the Sokli alkaline-carbonatite massif, showing the location of sampling drill holes and distribution of five stage phoscorites and carbonatites (modified from Mi Jung Lee et al, 2006) [19].

The Sokli carbonatite is considered as a potential source of phosphate (apatite). Possible by-products are iron, niobium, REEs and thorium. However, at present no mining is undertaken or planned in the near future. Thus, thorium can be regarded as a future source with uncertain chances.

In southeastern Finland, paleo-placers were found in Lower Proterozoic quartzites containing occasionally up to 200 ppm Th. They are not of economic significance.

6.1.3. France

In the southern Vosges, monzonites belonging to the Ballons highly potassic calcalkaline plutonic complex have contents up to 250 ppm Th, mostly hosted by uranothorite. In northern Brittany, biotitites in the Ploumanach highly potassic calcalkaline granite may have concentrations of several 100s ppm Th over several meters. The highest measured content reaches 1120 ppm Th for a mean of 610 ppm Th (4 samples). Th is hosted dominantly by uranothorite and to a lesser extent by allanite. In southern Brittany, a series of small syenite intrusions have elevated Th contents. These occurrences have no economic interest. The total resources of France are estimated of several hundred tonnes of thorium, perhaps up to 1 000 t Th.

6.1.4. Greenland (Denmark)

The deposit of Kvanefjeld, exposed at surface, is located in southern Greenland, close to the port of Narsarsuaq. It contains uranium, thorium and elements of commercial interest such as REE, Zn and others. The deposit was discovered in 1955. Aerial and ground prospecting was followed by 10 000 m of drilling in 77 holes. A total of ~4 million US$ were spent during the phase ending in 1984 [14]. The intrusion of Ilimaussaq (Fig. 4), in which Kvanefjeld is located, covers an area of ~150 km² and is surrounded by a large area of fenitisation (sodium metasomatism by magmatic Na-solutions).

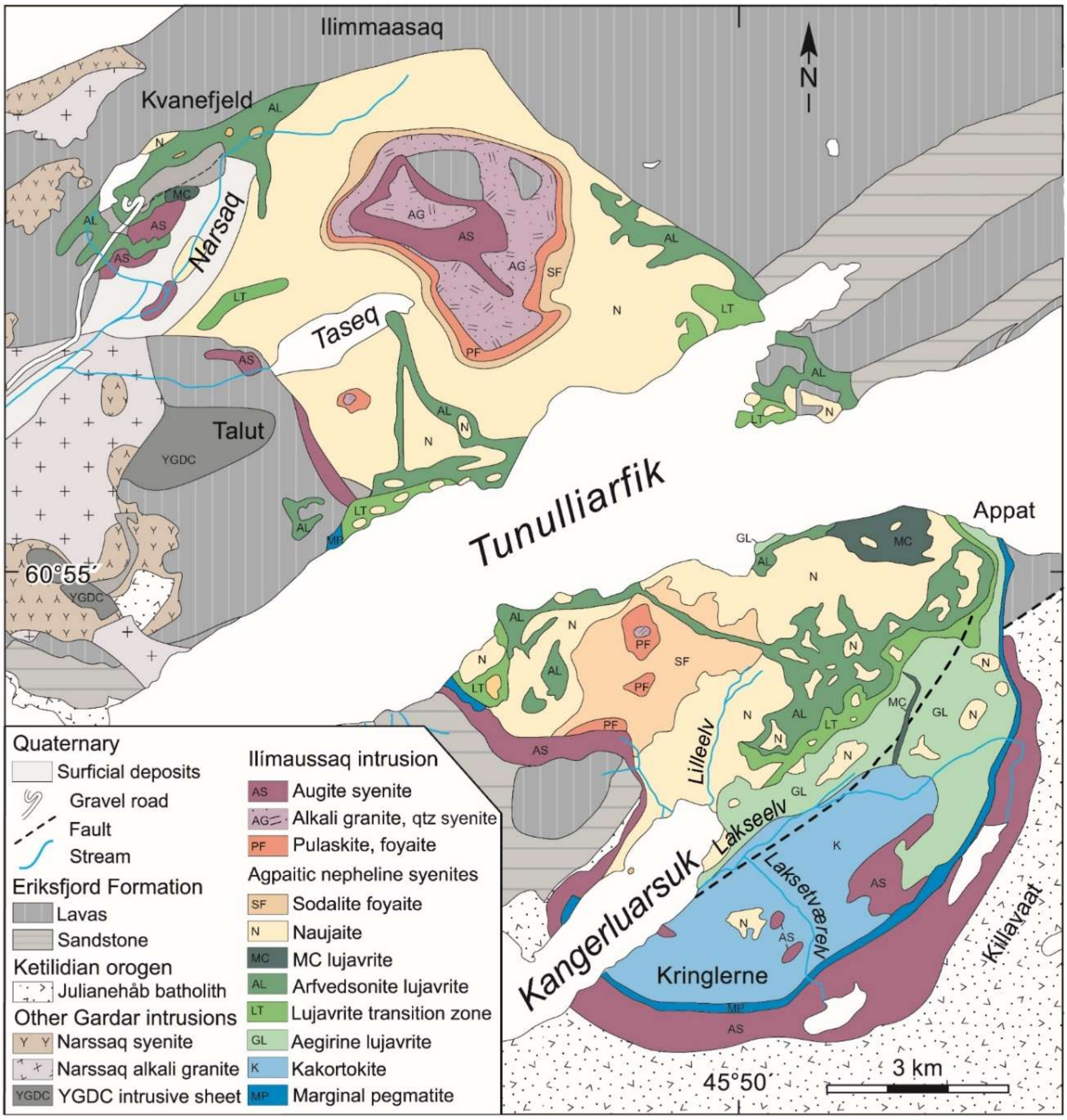

FIG. 4. Geological map of the Ilimaussaq Complex (Reproduced with the permission of GEUS, Geological Survey of Denmark and Greenland, from Upton (2013), after Ferguson (1964), Andersen et al (1988) and Sorensen (2001)) [20].

The area hosts unusual examples of magmatic differentiation representing several pulses of quartz-undersaturated intrusions, starting with augite-syenite followed by peralkaline agpaitic nepheline syenite, carrying Na-pyroxenes and Na-amphiboles. The differential crystallisation developed from pulaskite to foyaite, naujaite, kakortokite and lujavrite. The suite is the result of a continental rift setting, dated by U-Pb isotopes on baddeleyite at 1.160 +/- 5 billion years [21].

Increasing contents of uranium and thorium are observed, passing from 10 ppm U and 20 ppm Th in pulaskite to more than 60 ppm U and 60 ppm Th in lujavrite. In some lujavrite varieties concentrations may exceed 1 000 ppm U and 5 000 ppm Th. Uranium resources in the medium-coarse grained lujavrites (peralkaline nepheline syenite) amounted to 27 000 tU of RAR and 16 000 tU of estimated additional resources averaging 0.034% U at a cut-off grade of 0.025% U.

Additional SR were estimated to 50 000 tU. Studies on mining and milling concluded in the 1980s that uranium recovery is not economical. Thorium resources were reported in earlier publications of the Red

Book [14]. In its 2009 edition [16], Greenland's thorium RAR resources total 54 000 t Th at costs<US$ 80/kg Th, and PR totalled 32 000 t Th without cost categories assigned. Assuming that total uranium resources are ~100 000 t U and that the chondritic ratio is Th/U = 3, total resources of thorium may come to ~300 000 t Th.

6.1.4.1. Characteristics of the mineralisation

In the nepheline syenite, accessory silicate minerals of unusual composition occur, such as eudialyte and rinkite. The suite of rocks is characterised by the abundance of volatile phases (F and Cl) and incompatible elements, e.g. REE, Be, Li, Nb, Zn, Zr, Sn, U and Th [22]. The unusual element combination is explained as the result of magmatic differentiation of strong peralkaline high temperature magmas. The latest stages are represented by kakortokites and lujavrites which are the most significant economical types. In parts uranium may be enriched to more than 0.15% U and thorium to around 0.5% Th. Late stage veins which locally may intersect the country rocks are enriched in uranium and thorium in about the same concentrations as in the late stage intrusive rocks.

According to [21] the highest concentrations of radioactive elements are found in the minerals rinkite (fluoro-silicate with Ca, Na, Ce, Ti, Zr) ranging from 0.3–1.2% U and from 0.3–0.4% Th, and steenstrupine (phosphato-silicate with Na, Ce, Mn, Nb, Fe) ranging from 0.2–1.5% U and 0.2–7.4% Th. Other important minerals are britholite, eudialyte, monazite, pyrochlore and uranothorite [20]. For the composition of the minerals refer to Table 1. The mineral steenstrupine preferentially occurs in the late stage lujavrite.

In the early 1980s, evaluations were made for the content of non-radioactive elements, such as Li, Be and REEs [14, 22].

6.1.4.2. Recent developments

Exploration in Greenland was revitalised in 2007 by the Australia-based company Greenland Minerals and Energy and was mainly focused on non-radioactive minerals [23]. Exploration and exploitation of uranium and thorium is prohibited. Nearly 30 000 m of drilling was reported for the years 2007 and 2008. During this time, data for uranium were re-evaluated and reported by Danish authorities for the Red Book 2009 edition [16]. In more than 300 Mt of ore (cut-off grade of 0.0256% U), the equivalent of 85 614 t U was found (JORC compliant resources). The resources are classified in the high cost category (< US$ 260/kg U) due to the refractory nature of the minerals. A recovery of 65% is assumed. In addition, SR of 50 000 tU are reported.

Apart from uranium, Kvanefjeld has ~5 Mt of Rare Earth Oxides (REO), close to 1 Mt Zn and more than 3 Mt NaF. According to news report, a feasibility study has been complied and mining license is being sought for possible commencement of operations by 2016 [23]. No information is given on whether uranium or thorium may be extracted. The future of the deposit remains uncertain. Certainly, the present company aims to produce what is allowed according to the existing mining legislation. At present, no mining of radioactive material is allowed. Political movements in Greenland are seeking to change the present status of autonomy into full independence. If this becomes a reality the situation for mining may change. In any case it can be assumed that both uranium and thorium might be recoverable preferably as by-products due to their low concentrations [13]. In the Red Book 2011 edition, 619 Mt ore at a cut-off grade of 0.022% U have been reported [24]. Thorium grades are obviously not revised from older reports. Thus, the totals of in situ resources of 86 000 t thorium are reasonable.

The Kvanefjeld Feasibility Study and the social and environment impact assessments (SIA and EIA) were conducted in 2014–2015, forming the foundation of the exploitation license application. Conventional resource inventory for Kvanefjeld has identified a total of 102 820 tU. In the Zone 3 and Zone Sørensen, associated with the Kvanefjeld, additional IR of 338 Mt ore equivalent to 125 143 tU are present [25]. No thorium resources were reported, but assuming that the chondritic ratio is Th/U=3, total thorium resources may come to ~684 000 t Th.

On 24 October 2013, the Greenland Parliament lifted a decades-long moratorium on mining radioactive elements, which has opened the way for potential future exploitation of uranium and thorium (Red Book 2016).

6.1.5. Italy

Some of the acidic and alkaline volcanics, mainly in the Latium region, are known to have elevated contents of thorium which can reach to 100 ppm Th in alkaline volcanics and to 240 ppm Th in peralkaline basalts, the latter is present in the Roman Comagmatic U-Th-Ta district. Rhyolitic volcanics are assumed to be the source for elevated contents of thorium in the beach sands of the Tyrrhenian coast. The occurrences are not of economic relevance.

6.1.6. Macedonia

Monazite with ~4% Th was found in sands near Strumica. No estimates on resources are available. These occurrences are not economically exploitable.

6.1.7. Norway

A geological sketch map, showing locations of thorium occurrences in Norway is presented in Fig. 5. In the Fen district of Telemark a carbonatite body was discovered in the 17^{th} century to carry iron ore that was extracted between 1652 and 1927. The Fen carbonatite body (Fig. 6) is ~600 m.y. old. The carbonatite consists mainly of the varieties sövite (prevailing Ca-carbonate) and rauhaugite (prevailing Ca-Mg-carbonate). Around the middle of the 20^{th} century mining of niobium ore (pyrochlore) in the Söve mine was carried out extracting annually between 1 200 and 2 700 kg Nb_2O_5.

Apart from the above-mentioned mineralisation, carbonatite also carries thorium mineralisation which was explored in detail in the first half of the 20^{th} century. The concentrations reach 0.5–2.0% Th in the mineral pyrochlore. Thorium is found in other minerals too and, on average, the ore concentration is estimated to range between 0.04 and 0.4% Th. The mineralogy of thorium minerals in the Fen carbonatite is complex, showing several Th-bearing minerals, very fine grained and for which traditional methods could not be used to extract thorium. As a result, it may be assumed that the Fen carbonatite is only a potential resource for Th.

In the Red Book 1979 edition [26], official estimates of thorium in carbonatite were given reserves amount to 132 000 t Th at a mean grade of 0.13%Th and additional resources to 132 000 t Th at about the same grade. The costs of recovery were estimated at that time at US$ 75/kg Th. In previously published Red Books [14], 132 000 t Th were reported as IR at recoverable costs < US$ 80/kg Th and additional 132 000 t Th as PR without cost categories assigned. In the Red Book 2014 edition [13], the resources are revised to 60 000 t Th.

In early 2008, a report stated that Norway has 170 000 t Th of reserves and additional 150 000 t Th of resources (reserve base), of which the majority is located in the Fen carbonatite. The report was mainly based on earlier publications [24]. In view of the complexity of the thorium ore it might be too optimistic to classify the resources as reserves.

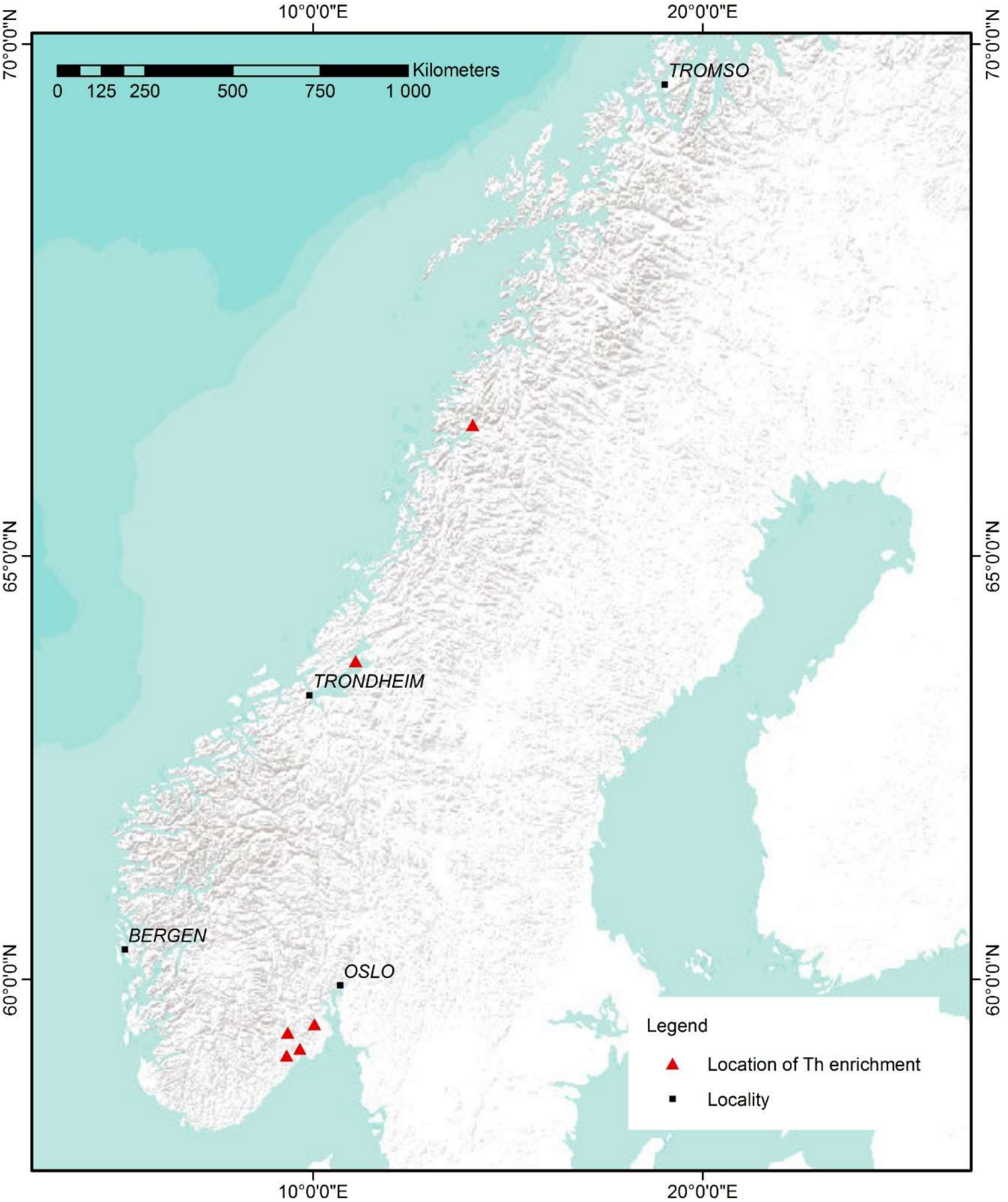

FIG. 5. Location of thorium rich sites in Norway (Reproduced with the permission of the Research Council of Norway and modified from a figure from the Norway Thorium Report Committee) [27].

According to [28], the Geological Survey of Norway reported estimates for the Fen carbonatite based on the content in surface samples and, to some extent, on data from drill core. Down to a depth of 100 m a conservative estimate gives ca. 80 000 t thorium in rocks with a mean grade of 0.047% Th. In the event of future exploitation thorium could be obtained as a by-product of the recovery of niobium and/or REEs.

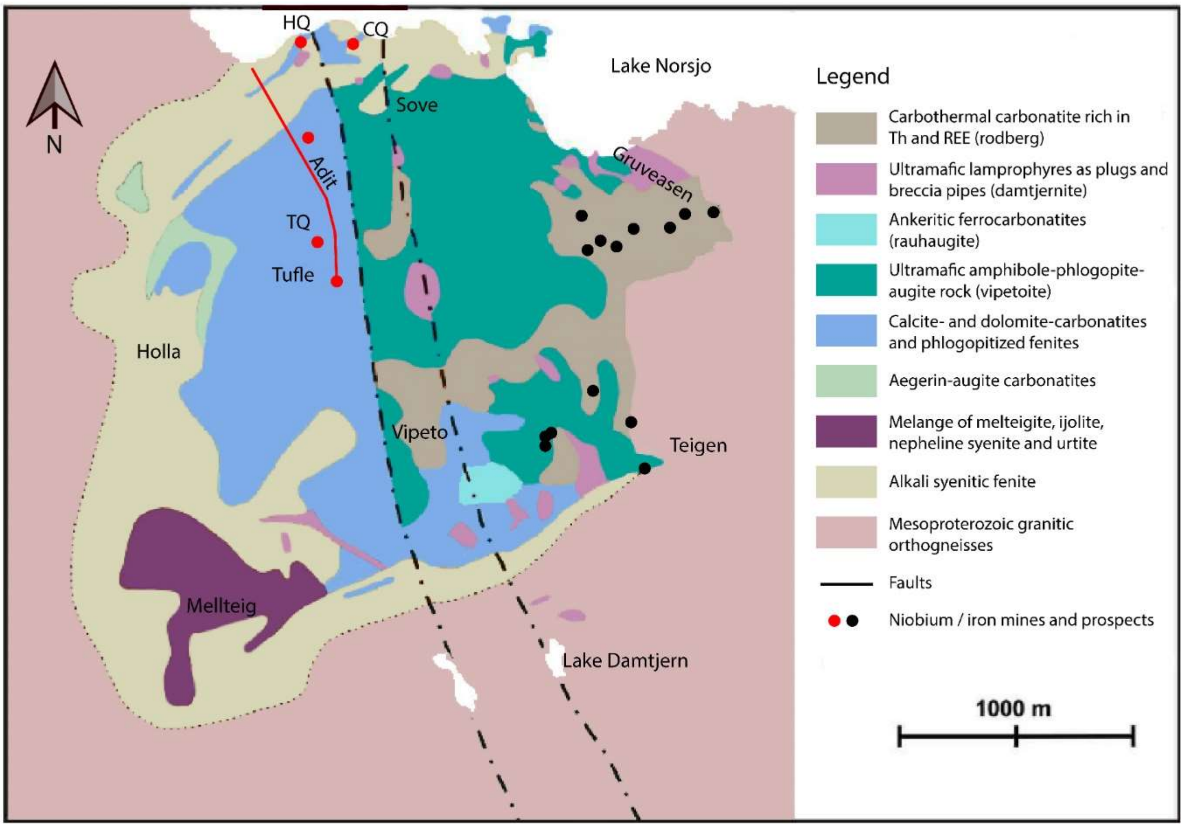

FIG. 6. Geological map of the Fen Carbonatite Complex (Reproduced with the permission of the Research Council of Norway and modified from a figure from the Norway Thorium Report Committee) [27].

6.1.7.1. *Other occurrences*

The Oslo Graben is known to have elevated values of thorium in the magmatic rock suite. In pegmatites, thorium can be enriched in coarse grained minerals. An occurrence with high concentrations of REEs, niobium, zirconium and thorium (400–00 ppm) was found in the Saeteräsen trachyte in the Oslo Graben. Due to the low thorium grade and refractory character of minerals the occurrence has presently no commercial interest (< 4000 t Th). According to [28], the Saeteräsen trachyte was estimated to contain ~8 Mt of rock containing niobium REEs and 0.049% Th. The total contained thorium was estimated at ca. 4000 t Th.

Occurrences in granitic orthogneisses in the Caledonides of Norway host low resources in thorium with low thorium concentration grades. Press releases expressed criticism of the economic relevance of Norway's thorium resources and discussed the accuracy of the data published, saying that current knowledge is not solid enough to draw economic conclusions. In addition, caution was expressed by Norwegian officials. In conclusion, thorium resources may exist in Norway and amount to ~320 000 t Th; however, it is too early to classify them as economically exploitable. Consequently, any resource figures for thorium in Norway were removed from the assessments of the USGS 2010 [29].

The latest comment by Norwegian authorities summarises total Norwegian thorium resources to 87 000 t without any categories [28]. It should be noted that, presently, exploration for REE and Th is occurring in Norway [30].

6.1.8. Poland

In some shale deposits enriched in copper (Kupferschiefer-type) elevated concentrations of thorium were reported in grains of the Th-U-hydrocarbon thucholite (up to 1.2% Th), which is however without economic relevance.

6.1.9. Portugal

Investigations, mainly for uranium deposits, recorded thorium mineralisations as a 'fall out' of the main purpose. An area of thorium potential could be delineated at Beira Baixa, North Alentejo, however only occurrences were discovered. According to updates made for the 2011 Technical Meeting in India three major types of thorium mineralisations can be identified:

- Granitic intrusions carrying monazite (<100 to >100 ppm Th);
- Ordovician quartzites with a range of ~ 100 ppm to >1000 ppm Th;
- Anomalous peralkaline rocks.

None of the occurrences are of economic relevance. Thorium extraction might be of interest only as a by-product of REE recovery [31].

6.1.10. Russian Federation (European Region)

The Russian Federation is geologically divided by the Ural Mountains into European Russia and Asian Russia, and no political implications are associated with this subdivision.Only deposits in the European region of the Russian Federation will be discussed here. For deposits located in the Asian region of the Russian Federation, see Asia.

In 1997, a publication [15] gave an overview of thorium deposits in the Commonwealth of Independent States (CIS). They have been grouped into eight 'ore formations' and, according to their relation to geological formations, into four groups (Table 5). The groups are described in the chapter on deposit classification.

On the Kola Peninsula, approximately 120–150 km south of Murmansk, two prominent alkaline intrusions are known, the alkaline massifs of Khibina and Lovozero (Lovozersk) (Fig. 7). The town of Apatity is located close to the Khibina massif. Details on the geology and formation of the alkaline province in northern Karelia (Kola Peninsula) are described in [32]. The intrusions belong to the Paleozoic magmatism starting around 400 m.y. ago. The magmatism is related to intense tectonic activity due to collision associated with the closure of the Iapetus Ocean. The *Khibina* massif is characterised by a peralkaline nepheline syenite intrusion, intercalated with ultrabasic and carbonatite series. The massif hosts deposits of apatite, nepheline and titanite. Pegmatite and lamprophyre dykes are widespread. The nepheline syenite can be enriched in thorium.

The *Lovozero* massif is characterised by agpaitic lujavrites (locality-type) in a layered intrusion which can be compared to Ilimaussaq in Greenland. Similar to Ilimaussaq, a sequence of rhythmic intrusions with lujavrite, foyaite and urtite rocks was mapped. Lovozero is well known for the mining of loparite (Nb, Ta) and eudialite (Zr, Hf) ores. Loparite mineralisation is concentrated in the second phase of the intrusive activity and prefers rock types like urtites, juvites and malignites. The loparite was found to contain ~0.1 to over 0.2% Th. The thorium grade in the ores varies in wide ranges and is reported to be between 0.01 and 0.1% Th. Official figures on thorium resources are not reported. From the descriptions of the deposit, the authors estimate resources to total several 10 000 t, perhaps 50 000 t Th including SR.

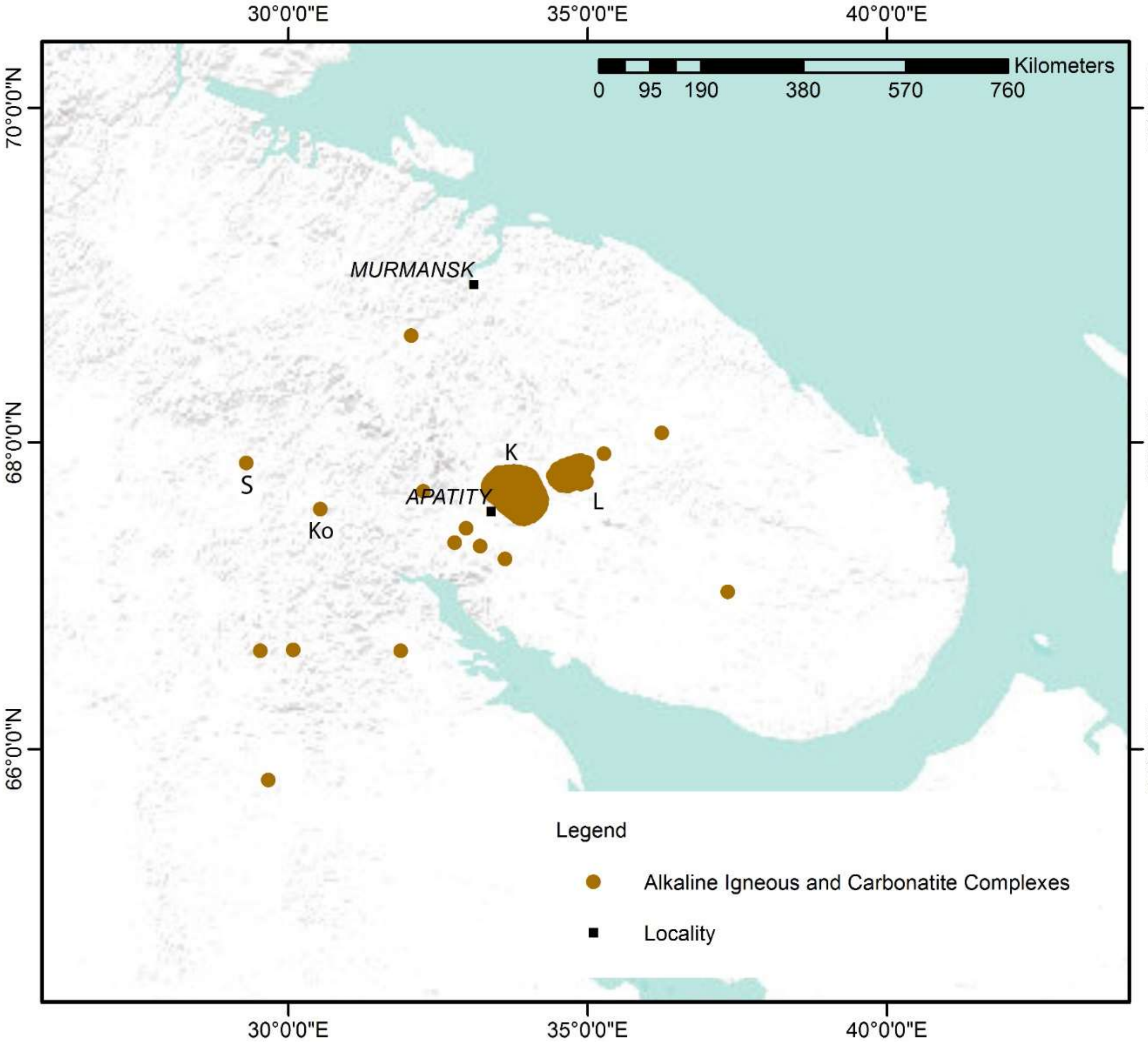

FIG. 7. Alkaline igneous and carbonatite complexes in the Kola Peninsula. K–Khibina, Ko–Kovdor, L-Lovozero, S–Sokli (Based on figure from M. Evans) [33].

Near Chelyabinsk the nepheline syenite of Vishnevogorsk carries pyrochlore, which is mined for niobium [34]. It can be assumed that the rocks are enriched in thorium, however concentrations are not reported. Numerous rare minerals such as silicates, phosphates and oxides with varying amounts of thorium were found in pegmatites and late magmatic veins. The total resources are not published. The grades are low and vary between 0.01 and 0.1% and occasionally locations in pegmatites may have up to 1% Th or more.

Monazite deposits have been found in placers in the 1940s by the Company 'Uralmonazit' near *Krasnoufimsk,* ~150 km west of Yekaterinburg (Sverdlovsk) and ~150 km SE of Perm. The resources were estimated at ~82 000 t monazite averaging about 6–7% Th which is about 5000–5 700 t Th. The deposit occurs obviously as placers on the river Ufa [35]. After the breakdown of the Soviet Union the company 'Minatom' took over the ownership of the deposit under the name 'Ural-Euro' and further work was planned to recover monazite concentrates [35].

Placer deposits (Beshpagirskoye, near Stavropol; Centralnaya, SE of Moscow; Lukoyanov, near Nishni-Novgorod), with titanium and zirconium, some of them mineable, are reported in the European part of the Russian Federation; however, data for thorium concentrations are not available. At present, the economic viability of the placer deposits is in question. In general, grades in the placers are too low for commercial operations and recovery can be only considered as by-product. According to a written communication [35], in the 1940s thorium extraction from monazite ore was envisaged to reach ~130 t Th per year.

Due to limited demand for thorium at present no recent research has been carried out; however, if technologies for thorium-fuelled reactors improve, research for thorium may be renewed.

6.1.11. Serbia

Alluvial deposits in the Cer and Iverak Mountains are reported to contain thorium-rich accessory minerals, however they are not of economic relevance.

6.1.12. Slovenia

Increased concentrations of Th have been reported for Permian clastic sediments in the area of the uranium deposit Zirovski Vrh. No estimates of resources were made. Not of economic relevance.

6.1.13. Spain

Beach sands on the coast of Galicia contain monazite with about 4–5% Th. Some small-scale mining in the past has exploited ~20 t of monazite annually. Thorium resources are not reported.

6.1.14. Sweden

The carbonatite of the Alnö complex, located on the Alnö Islands, is one example of fractional crystallisation in which the differentiation finally resulted in carbonate rocks called sövite (prevailing Ca-carbonate) (Fig. 8). The carbonatite body has an elliptical shape of about 4 × 3 km in extension. Exploration was carried out for phosphate in the sövite (1–13% apatite) and for barite. Phosphate resources were estimated at ~0.5 Mt from the surface to a depth of 50 m however due to low concentrations of P_2O_5 mining was not undertaken. During 1945–1951, ~6000 t of barite were mined.

The sövite contains the mineral perovskite with ~2.4% Th. Total resources are estimated by the authors at ~50 000 t Th. Extraction of any commodity of the carbonatite was considered as economically not feasible.

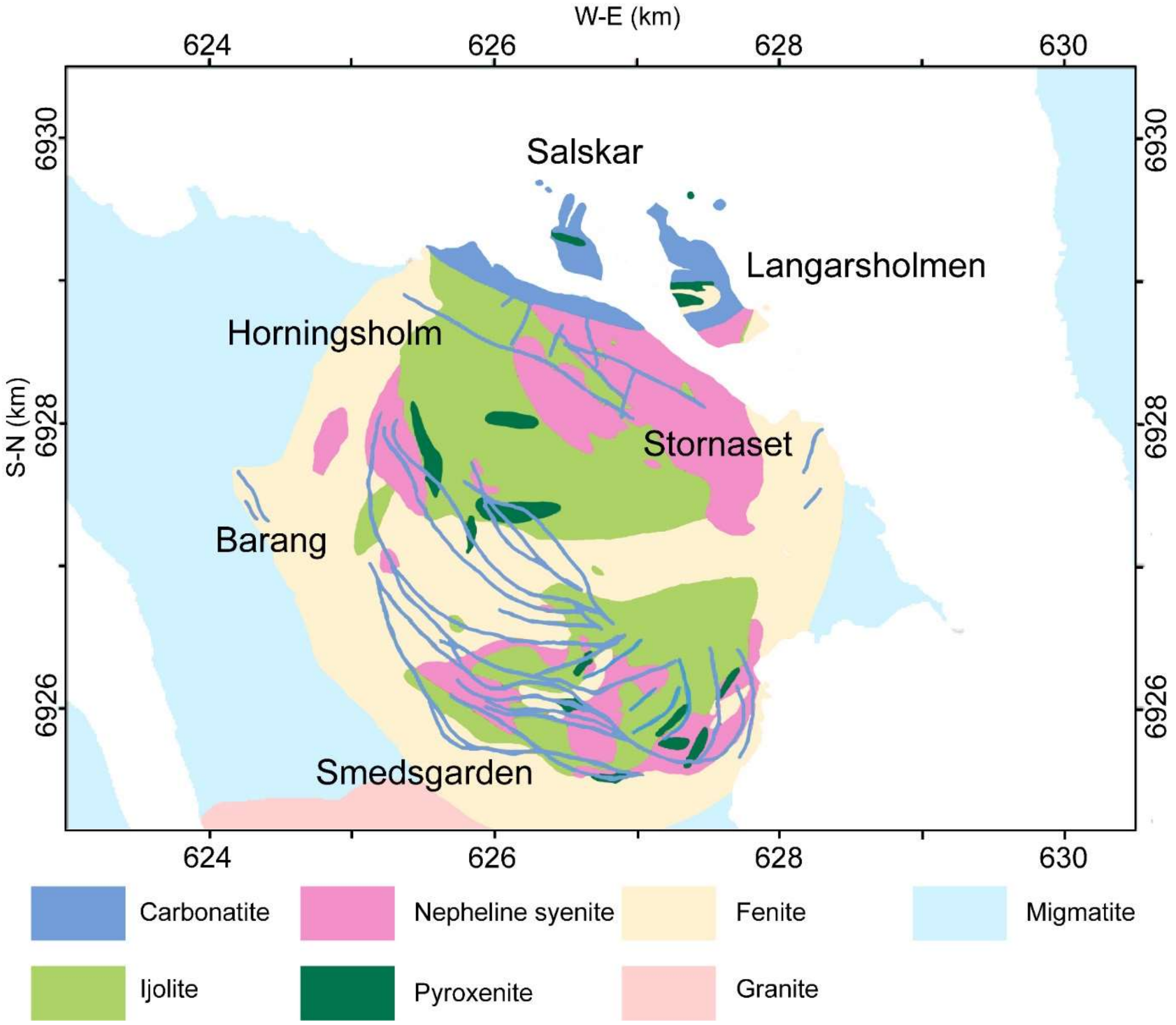

FIG. 8. Geologic map of the carbonatite Alnö complex (Reproduced with the permission of A. Malehmir and modified from A. Malehmir) [36].

6.1.15. Turkey

Thorium mineralisations have been reported from various parts of Turkey. The best investigated area is located near Sivrihisar, province of Eskisehir, ~150 km W of Ankara. The deposit of Kizilcaören was explored by drilling to a depth of ~400 m and a length of several km for REEs, thorium, barite and fluorite (Fig. 9). Horizontal striations–volcanic Hoyuklu formation; diagonal striations = limestones; s–serpentinites; spots–sand and gravel; while–alluvium. The richest F-Ba-Th-REE veins occur on the slopes of Devebagirtan Tepe (centre of the map).

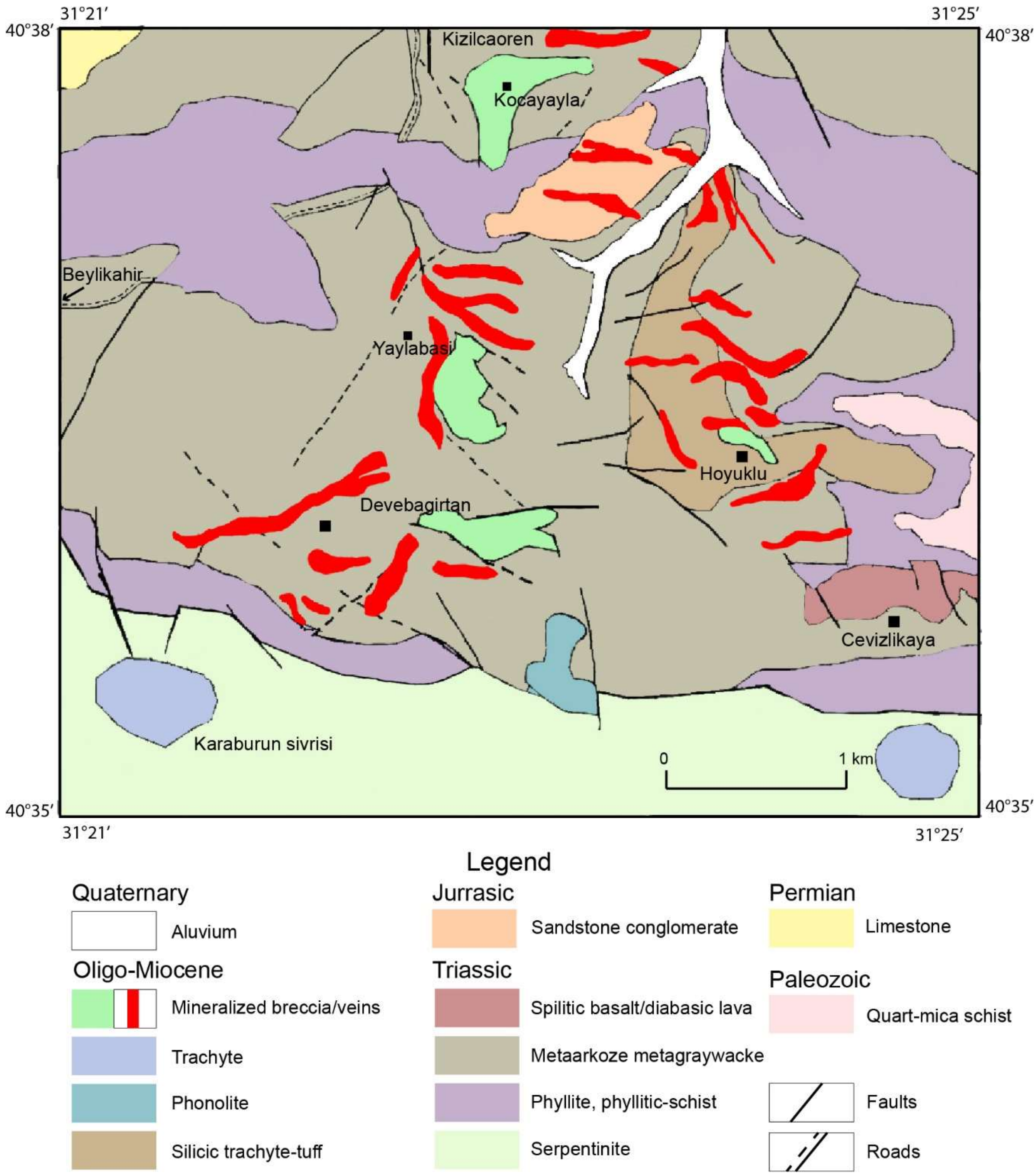

FIG. 9. Geological map of the Kizilcaören mineral district (Modified from A. Gultekir et al) [37].

The Kizilcaören F-Ba-Th-REE deposit, which occurs in weakly metamorphosed sediments and trachytic tuffs, has been considered to have been generated by the upwelling of carbonatitic magmatic fluids through by circular, radial and funnel shaped fractures. Fracturing, brecciation and mineralisation were linked to carbonatite intrusions. The mineralisation fills fractures and breccia pipes. Five breccia pipes formed next to alkaline porphyritic trachyte and phonolite.

In the late Oligocene epoch two phases of carbonatite intrusions have been distinguished:

1) As dykes up to 1.5 m in width;
2) As dykes of 1–10 cm widths cutting veins and breccia pipes.

In the first phase, prior to the brecciation event, fluorite (up to 37%) and barite (up to 31%) were formed. The second phase corresponded to thorium-rich bastnaesite (mean 3.35%Th) with minimal brockite, fluocerite, florencite and monazite formation after the brecciation. According to fluid inclusions, temperatures of 550–300°C and 300–190°C have been recorded for the first and second phases, respectively [38–39]. According to older reports, the deposit was estimated at several million t of barite and fluorite, ~4.7 Mt of REEs. Reasonably assured resources of thorium were reported to amount to 344 000 t Th and PR to an additional 400 000 t Th [14].

Reserves of 380 000 t at 0.2% ThO_2 and 3% REE were reported in 1985 [40]. Additional resources occur at Hekimhan, Kuluncak and Malatya, and are being explored according to news reports. The total resource may reach 880 000 t Th including PR. Exploration stopped in 1976 (however resources were reported in 1985). No reassessment was undertaken (personal communication of M. Alendar during a Technical Meeting in India in Oct. 2011). It is estimated that identified resources of 344 000 t thorium, as reported earlier may be realistic, however subject to verification.

6.1.15.1. Recent developments

Low grade Th mineralisation (60 ppm) in mineral sands were reported recently from the Aksu Diamas Project near Isparta, north of Antalya. Current explorations have provided estimations of rare earth minerals and titanium ore. Mineral sand extents along the river Aksu were recently drilled and indicated ~3.5 Mt TiO_2, 0.7 Mt of REO and ~21 Mt of iron ore. The resources of thorium are estimated at ~37 000 t Th.

The recovery of Th is planned, starting with an amount <10 t Th annually and gradually increasing to more than 100 t Th annually. Owing to the low grade of Th, its recovery may be justified as by-product only [41]. It might be justified to classify the resource figures for thorium in Turkey as resources without any category. Economic decisions may depend on the future uses of the commodities.

6.1.16. Ukraine

Prospecting for radioactive ore in Ukraine led to the discovery of monazite in titanium-zirconium-bearing alluvial deposits along the river Donez near Mariupol. Details are not reported [35]. The Red Book 2009 edition [16] reports the assessment of REE–Th–U mineralisation at Dibrovskoye in the Pryazov block (Ukrainian Shield). Further to drilling work at Dibrovskoye, estimation of prognosticated thorium resources in Ukraine continued. Results will be published once available.

6.1.17. Summary for Europe

Resource estimates for thorium have been made in Finland, Greenland, Norway and Turkey. Thorium occurs in carbonatite (Finland, Norway), peralkaline rocks (Greenland) and veins associated with carbonatite intrusions (Turkey). Preliminary assessments for Norway should be verified. No recent update on Turkey´s thorium resources was made, and previously published figures were deleted from respective tables in publications [16, 29]. Not considering resource categories or costs of recovery, the total resources in these countries were estimated to ~1 Mt thorium, including estimates by the authors for some deposits for which resource figures are not reported officially. However, only ~10% is estimated to be possibly economically available, assuming by-product recovery. Production of thorium under current market conditions is not expected in Europe. Placer occurrences are of very limited economic importance.

6.2. NORTH AMERICA

6.2.1. Canada

Resource figures for Canada vary in a wide range depending upon the source of estimates. In [16], IR were given as 44 000 t Th, and PR as 128 000 t Th. The resources mentioned in USGS report (2010) of

~100 000 t Th [29] which may be regarded as resources rather than reserves. Earlier estimates gave figures in the category RAR; however, revisions were made due to the closure of former uranium mines of the Blind River-Elliot Lake area where thorium was a by-product, hence the reclassification of resources is realistic.

In the former uranium mining district of Blind River-Elliot Lake (Fig. 10), the host rock for thorium is an oligomictic quartz-pebble conglomerate of Precambrian age, deposited ~2.45 billion years ago, in a geological environment which corresponds to a paleo-placer. The conglomerates are folded into broad synclines and anticlines. The components of the conglomerate, mostly quartz, are rounded pebbles in a matrix of finer grained quartz and feldspar and disseminated pyrite. Within the matrix uraninite, brannerite, monazite and locally uranothorite are present. Minor quantities of other minerals carrying U, Ti, and sulphides of base metals also occur. The main host for thorium is uraninite with 3–6% ThO_2, [14]. The formation of the U-Th-bearing ore is subject of conflicting ideas. Their origin as ancient placers without major additional changes as well as their epigenetic origin and participation of hydrothermal influx were discussed.

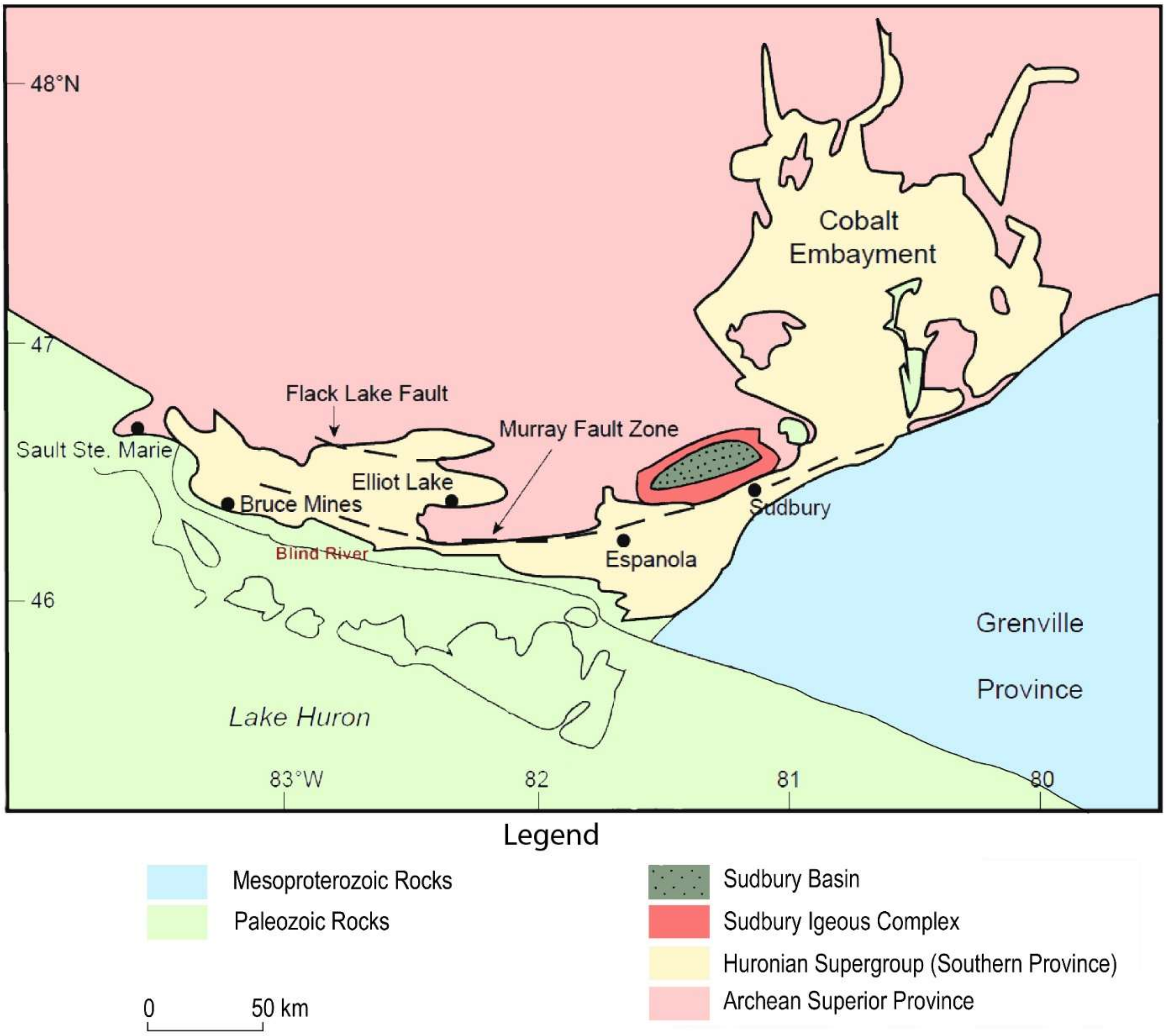

FIG. 10. Location map of Blind River-Elliot Lake area (Modified from C. M. Hill et al) [42].

When uranium mining in the said area was terminated for economic reasons in 1996 after producing several 10 000 tU, resource estimates for thorium had to be revised. Due to the closure of mine followed by decommissioning the ore is no longer accessible and its resources are no longer in the category of low cost reasonably assured [14]; instead they are classified now as IR. In addition, in the Red Book 1986 edition [43] some 85 000 t Th were reported to be associated with high cost uranium in the Elliot Lake area. In the same report ~6000 t Th were estimated to be associated with high cost prognosticated uranium resources, primarily in the Elliot Lake area.

In several pegmatites, preferentially in zoned pegmatites, mineralisations of Th and U occur, which in the case of the Haliburton-Bancroft area in Ontario, were subject to uranium mining. The mineralisation consists of uraninite, uranothorite and refractory Th-U-minerals. The origin of the Bancroft pegmatite is disputed. The presence of calcite, fluorite and apatite suggests hydrothermal influx or metasomatism; however, other features indicate its relation to magmatic-(migmatic) differentiation. The Bancroft pegmatite was mined for uranium from the 1960s to 1982, but according to available information thorium was not recovered. Remaining reserves are probably too low to allow future mining.

Other pegmatites in Ontario (Richardson, Peterborough, Mont Laurier) with reported Th-mineralisation are occurrences without economic interest for Th. The pegmatites in the Mont Laurier area of the Grenville Province may be classified as results of high grade metamorphic segregations. In Saskatchewan pegmatites occur in the Charlebois Lake area, which carry U-Th-mineralisations. Geological evidence exists that the pegmatites could have been formed either by magmatic or migmatic processes and metasomatism may be associated too. No estimates of thorium resources were reported.

The Oka carbonatite (Québec) (Fig. 11) is one of the best investigated carbonatites for its radioactive components and other ore mineralisation. It is a ring complex consisting mainly of sövite in which niobium, iron and apatite were found. Estimated reserves of 150 Mt of niobium ore grading 0.33% Nb_2O_5 have been reported. Thorium is associated with betafite. No economic use has been announced.

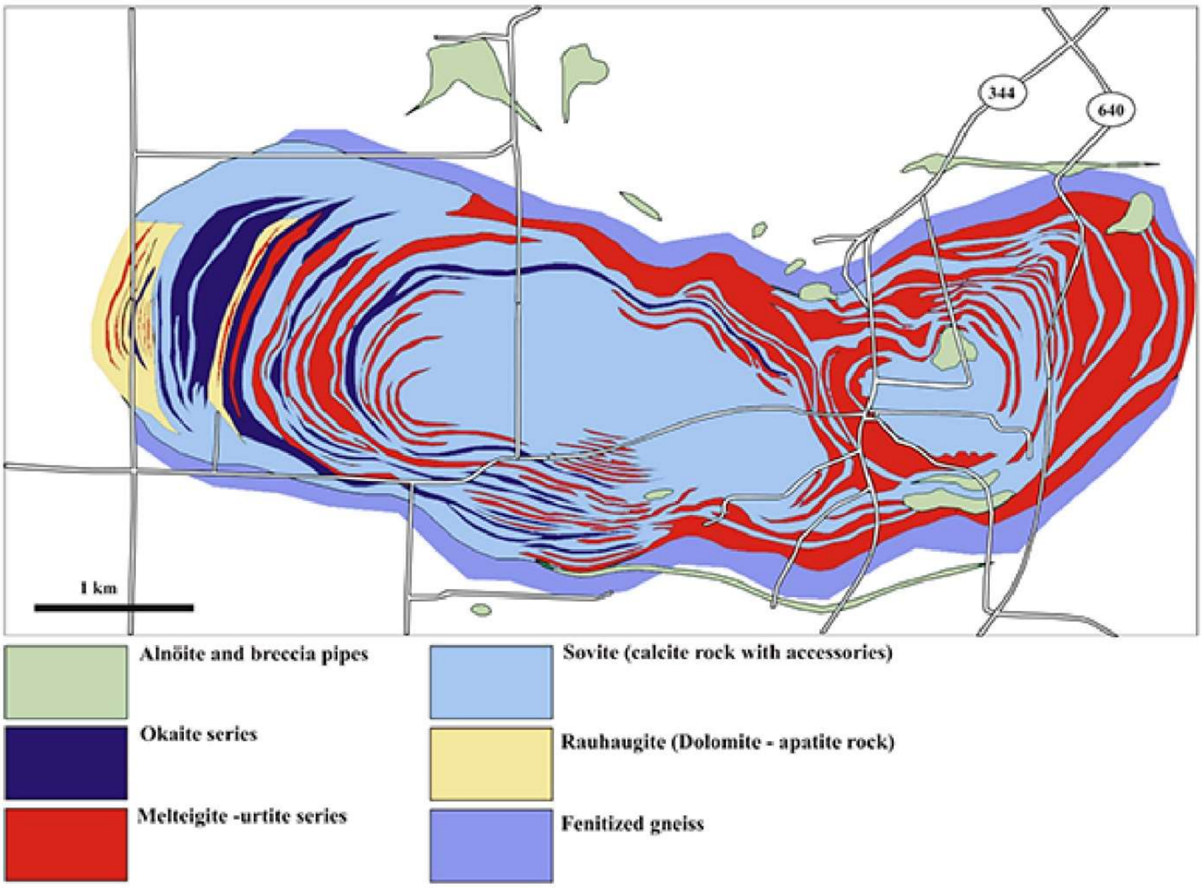

FIG. 11. Geological map of the Oka carbonatite complex (Modified from D. Lentz et al) [44].

6.2.1.1. Other occurrences

Uneconomic mineralisations with thorium are known from the Rexspar U-F-veins (British Columbia) in trachytic tuffs. The Yates property (Ontario) may be regarded as a contact-metamorphic occurrence in which thorium minerals occur in basic rocks of the Grenville structural province. Other thorium showings in the Grenville province may be related to gneisses. None of these and other occurrences are of economic interest.

The Thor Lake deposit in the Great Slave Lake area carries REEs, niobium, tantalum and some other minerals, including enrichments of thorium minerals. The deposit is related to the intrusion of the Thor Lake syenite. Recent company reports are describing low grade thorium resources (<200 ppm) of approximately 22 000 t Th.

6.2.1.2. Summary for Canada

In the Red Book 2009 edition [16], Canada reported IR of 44 000 t Th resources, recoverable at less than US$ 80/kg Th, and additional PR of 128 000 t Th. Resources in other cost classes were not reported. Different to these estimates, USGS [26] reported resources of 100 000 t Th, without giving specifics for resource categories or costs. The difference between the two estimates may be seen in the fact that approaches for reporting are not the same. Due to the fact that most of the thorium resources are associated with uranium either in the Blind River-Elliot Lake area or in pegmatite or carbonatites, no mining takes place in any of them; therefore, thorium resources listed may be regarded as future potential sources only.

6.2.2. Mexico

In the list of deposits of ThDEPO, several anomalies with Th are mentioned from occurrences in the province of Sonora. The Th anomalies San Miquel de Horcasitas, Santa Rosalia, San Jose de Pimas and Siera Lista Blanca occur in alkaline rocks, for which no further details are described. The anomaly La Colorada was found in an abandoned gold mine.

6.2.3. United States of America

The United States of America are one of the best investigated countries for thorium deposits (Fig. 12). The latest comprehensive report was published in 2009 as the US Geological Survey Circular 1336 [45]. The report groups the thorium deposits of the United States of America into three major types:

- Vein-, dike-, and breccia-hosted deposits associated with alkaline intrusive complexes;
- Massive carbonatites;
- Placer deposits.

Total resources, including 'probable potential resources' (which may correspond to IR), amount to 434 000 t Th, similar to the resource estimate published by the USGS in January 2010 [29] of 440 000 t Th. In [16] identified resources are reported as 400 000 t Th, recoverable at < US$ 80/kg Th, separated in 122 000 t Th RAR and 278 000 t Th IR. In addition, the Red Book 2009 edition reported estimates of PR as 274 000 t Th. The latter are not reported in [29 and 45].

The majority of Th resources occur in vein deposits, amounting to ~347 435 t Th which represents ~80% of the estimated U.S. total thorium resources. Around 113 140 t Th in vein deposits are classified in [45] as 'reserves', which may better be categorised as 'RAR' according to the scheme used in the Red Books, according to personal communication.

6.2.3.1. *Vein deposits*

According to detailed description in [45], vein-type deposits are associated both with alkaline intrusions and carbonatite stocks. In consideration of their settings, veins may be characterised as 'veins associated to alkaline rocks' and 'veins associated to carbonatite rocks'. Vein deposits and their resources occur in the following areas [45] (Table 8):

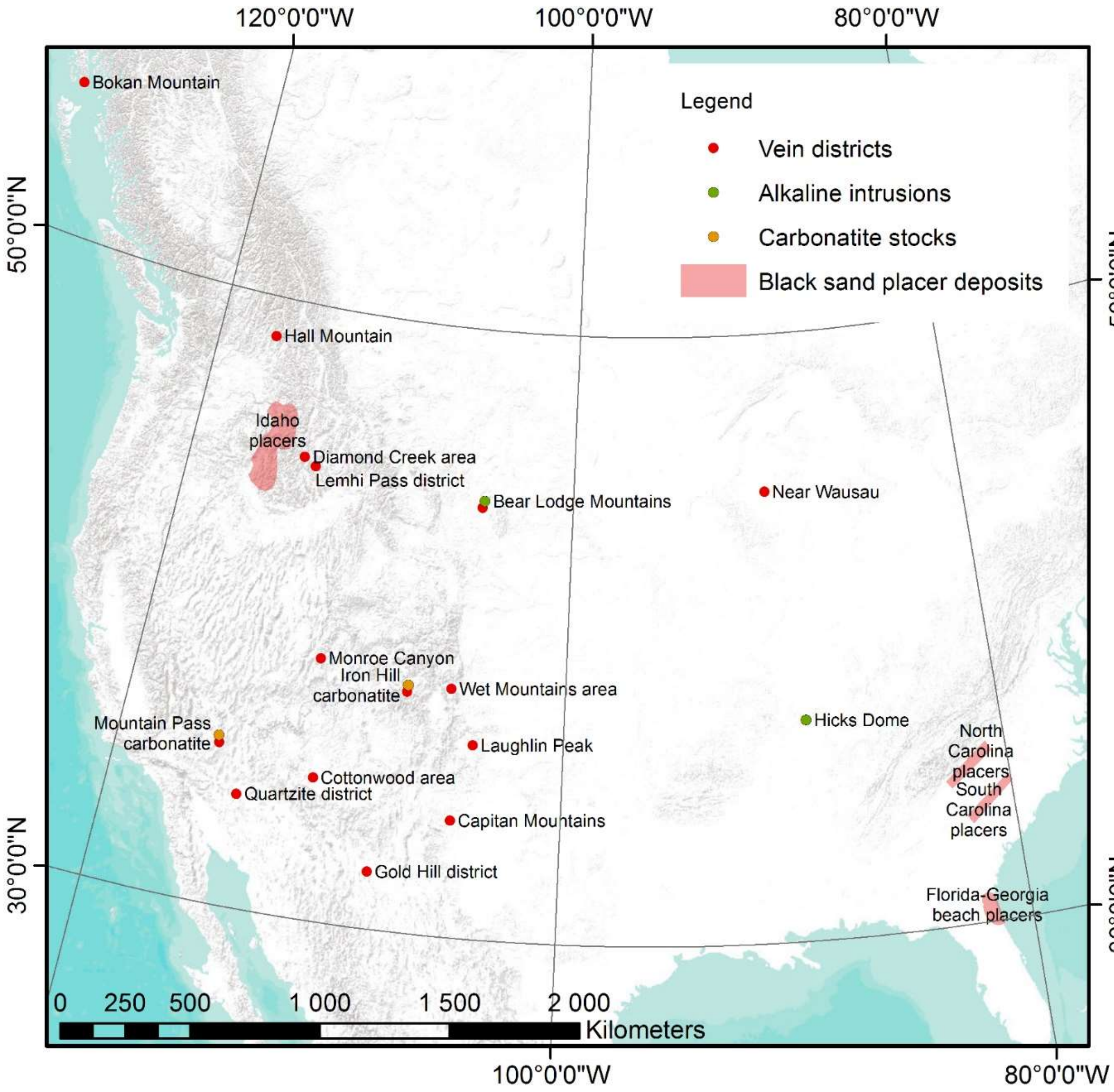

FIG. 12. Thorium districts in the United States of America (Reproduced with the permission of U.S. Geological Survey and based on USGS report) [45].

TABLE 8. VEIN DEPOSITS IN THE UNITED STATES OF AMERICA (T Th)

Region	Reasonably assured resources	Probable potential resources (inferred resources)	Total resources
Lemhi Pass district, Montana-Idaho	56 240	106 340	162 580
Wet Mountains area, Colorado	51 150	127 955	179 105
Hall Mountain, Idaho	3 650	NA	3 650
Iron Hill, Colorado, 'thorium veins'	1 490	NA	1 490
Iron Hill, Colorado, 'carbonatite dikes'	610	NA	610
Total	113 140	234 295	347 435

The Lemhi Pass district hosts probably the largest thorium concentration in the United States of America. Numerous veins have been mapped within an area of 140 km². The ten largest veins contain ~95% of the Th resources. The assessments of resources are mainly based on publications and reports prepared in the late 1970s and during the 1980s. Recently private companies have carried out reassessments of individual veins [45]. The veins may be classified into those with dominantly quartz-hematite-thorite and others with monazite-thorite-apatite; all occur in Proterozoic quartzite and siltite. Genetically strong evidence for the association of the veins with alkaline intrusions that lie at depth is favoured by local experts; however, their origin, as well as the age of the veins, remains uncertain. According to [45], total resources of the Lemhi Pass veins were estimated at ~160 000 t Th, of which ~56 000 t Th are better known resources.

The Wet Mountains area in south-central Colorado can be compared to the Lemhi Pass district. Thorium deposits and occurrences have been found across an area of more than 1000 km². Thorium mineralisation occurs in veins, dikes and fracture zones associated with alkaline complexes of Cambrian age (Fig. 13). Most of the veins can be linked to large syenitic alkaline intrusions and carbonatite dikes. The veins and fracture zones, which are related to three alkaline intrusions, are of the highest economic potential. As shown by regional association, a separation can be made into replacement carbonatite and primary magmatic carbonatite. According to analytical results the concentrations of Th are higher (0.15–1.8% Th) in the primary magmatic carbonatite than in the replacement type (<0.1% Th). Estimates for the resource in the Wet Mountains area total ~179 000 t Th, of which ~51 000 t Th are better known resources [45].

6.2.3.2. Other veins

Areas containing thorium occurrences and deposits of vein type are listed in [45]. They are grouped into nine different geographic regions. The richest veins, some with more than 20% Th, were found at Hall Mountain, northernmost Idaho. The total of the Hall Mountain district was estimated at ~3 650 t Th [45]. In the area of Iron Hill, Colorado, veins containing an estimated 2 100 t Th were found.

6.2.3.3. Carbonatite

Unusual concentrations of REEs, rare metals and some light elements (grouped as "non-compatible") are known to be present in carbonatites worldwide. Usually carbonatites contain low grade concentrations of uranium and thorium.

A large carbonatite mass is found in the United States of America in Colorado at Iron Hill. This massive carbonatite stock contains low-grade concentrations of around 30–40 ppm Th. Veins in the country rocks surrounding the carbonatite stock have higher thorium concentrations (estimated total resources of ~2100 t Th, see 6.2.1.1. The low grade, non-economic Th mineralisation in the carbonatite stock was estimated at ~24 800 t Th, which occurs with REEs and niobium [45].

The carbonatite at Mountain Pass, California is an example of economic grade of REEs in the mineral bastnaesite. In its Sulphide Queen ore body, the carbonatite is mined, processed, and the REEs are recovered. The thorium is moved with other residues into the tailings impoundment. In 2015, thorium resources were estimated to amount 4 200 t Th, at a mean grade of 0.025 % Th [45].

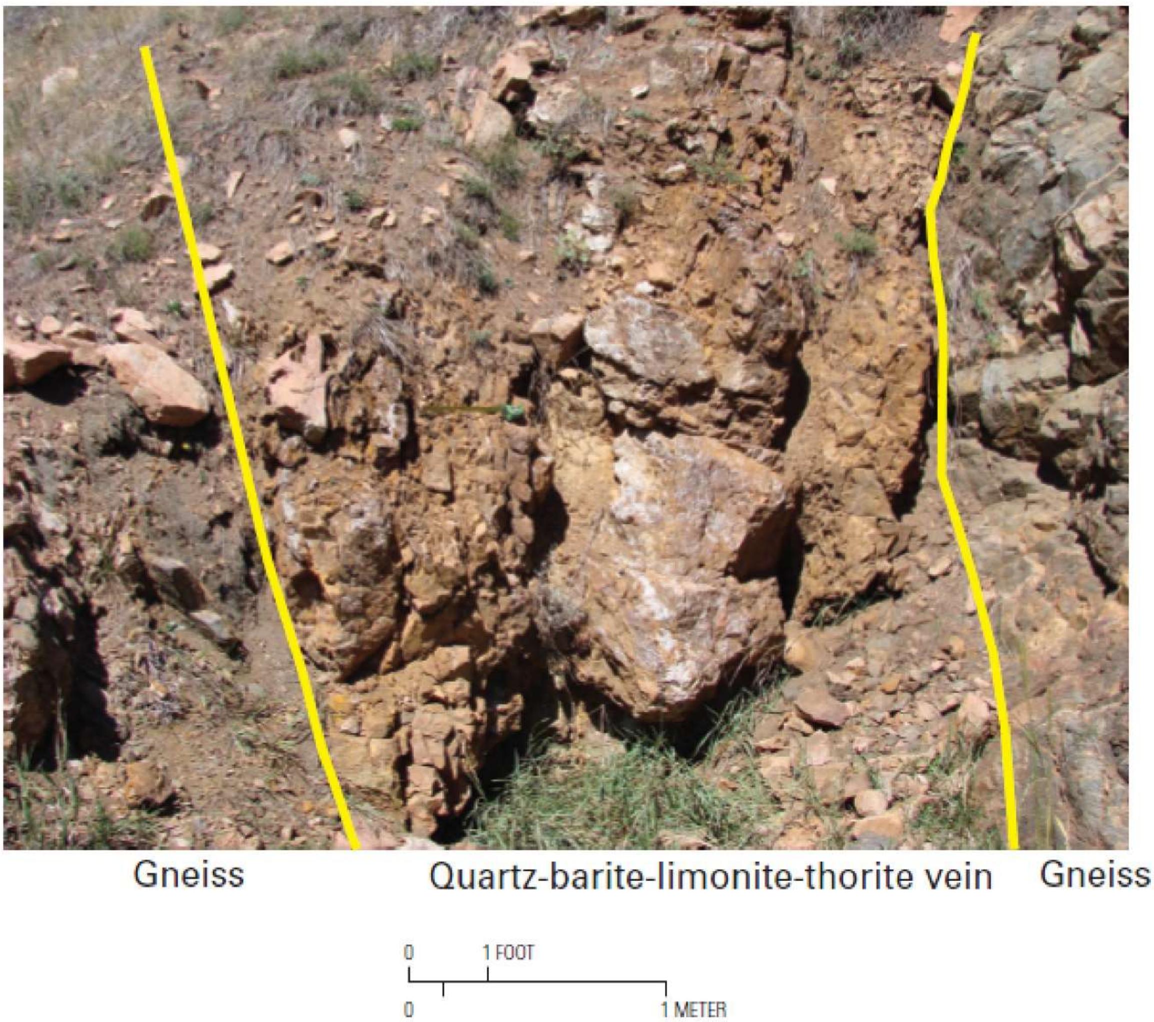

FIG. 13. Sewell Ranch thorium vein (between yellow lines), Wet Mountains area, Colorado (Reproduced with the permission of the U.S. Geological Survey) [46].

6.2.3.4. Alkaline intrusions

Many alkaline intrusions are linked with carbonatitic rock massifs and vice versa. In some instances, a distinct separation is very difficult. Apart from low grade thorium concentrations in carbonatite, low grade thorium concentrations were found in peralkaline intrusions [45]. Examples are the alkaline Conway granite in New Hampshire and the Darby granite in Alaska, in which 65 ppm Th were measured. These examples are not of economic interest. Examples of higher grade Th concentrations are Hicks Dome in Illinois and deposits in the Bear Lodge Mountains of Wyoming. At Hicks Dome, formed by an explosive intrusion, core drill samples in brecciated rocks at various depths have been analysed, finding between 60 and 1600 ppm Th [45].

Deposits in the Bear Lodge Mountains occur in a subvolcanic intrusion of trachyte and phonolite. Mineralised parts are mostly in veinlets and as fracture coatings**,** which have as much as 0.1% Th [45]. At the Ross Adams mine, located on Prince of Wales Island in southernmost Alaska, uranium was extracted from a breccia pipe complex within an albitised peralkaline granite (Bokan Mountain granite); this ore contained ~1000 t U, associated with an estimated 3 500 t Th. The primary ore mineral was uranothorite.

6.2.3.5. Placer deposits

In the Piedmont region of North and South Carolina, placer occurrences are known to contain workable monazite concentrations. The first operations producing monazite date back to 1887. Until 1917, ~5000 t of monazite were produced [45]. The major deposits shown in Fig. 14 are; South Muddy Creek; Silver Creek; First Broad River and its tributaries–Hinton Creek, Duncans Creek, and Wards Creek; Knob Creek; Sandy Run Creek; Buffalo Creek; Broad River at its junction with Buffalo Creek; Thicketty Creek; North Tyger River at its junction with Middle Tyger River; North and South Rabon Creeks; Big Generostee Creek; Horse Creek; and Hollow Creek.

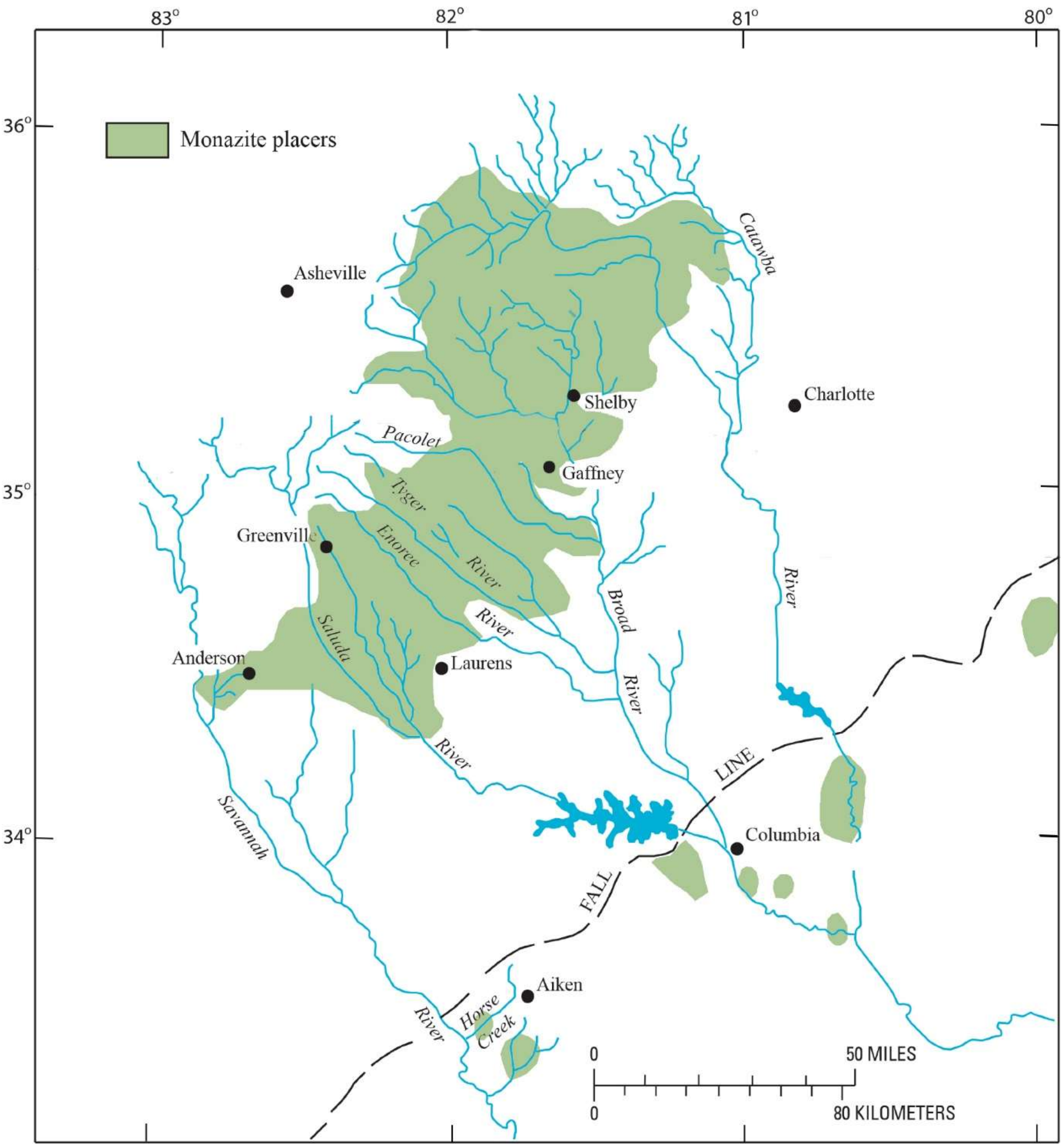

FIG. 14. Monazite-bearing placer deposits in the Piedmont region of North and South Carolina (Reproduced with the permission of the U.S. Geological Survey and based on M. H. Staatz et al., U.S. Geol. Surv. Circ. 805 1–42) [46].

The placers are inland placers of the upper course of the Catawba and Savannah Rivers and intervening streams. The alluvium is believed to be derived from the surrounding high-grade metamorphic rocks. The sands contain 0.15–2.0% heavy minerals, of which about 3.5–13% is monazite. The mean thorium content in the monazite was established at ~5% Th [45]. Thorium resources for North and South Carolina have been estimated at ~4 200 t Th and [45] additional potential at ~29 500 t Th [45].

Another area of inland placer deposits occurs in Idaho in the Bear Valley, Burgdorf-Warren area, Boise Basin, Elk City-Newsome area and Long Valley (Fig. 15). Historical dredging is reported from several places, earlier for gold and later for monazite. About 6 430 t of monazite were recovered containing ~240 t Th for the government stockpile, [45]. The monazite of the area contains between 2 and 5.6% Th. The total of the area was estimated at 8000 t Th.

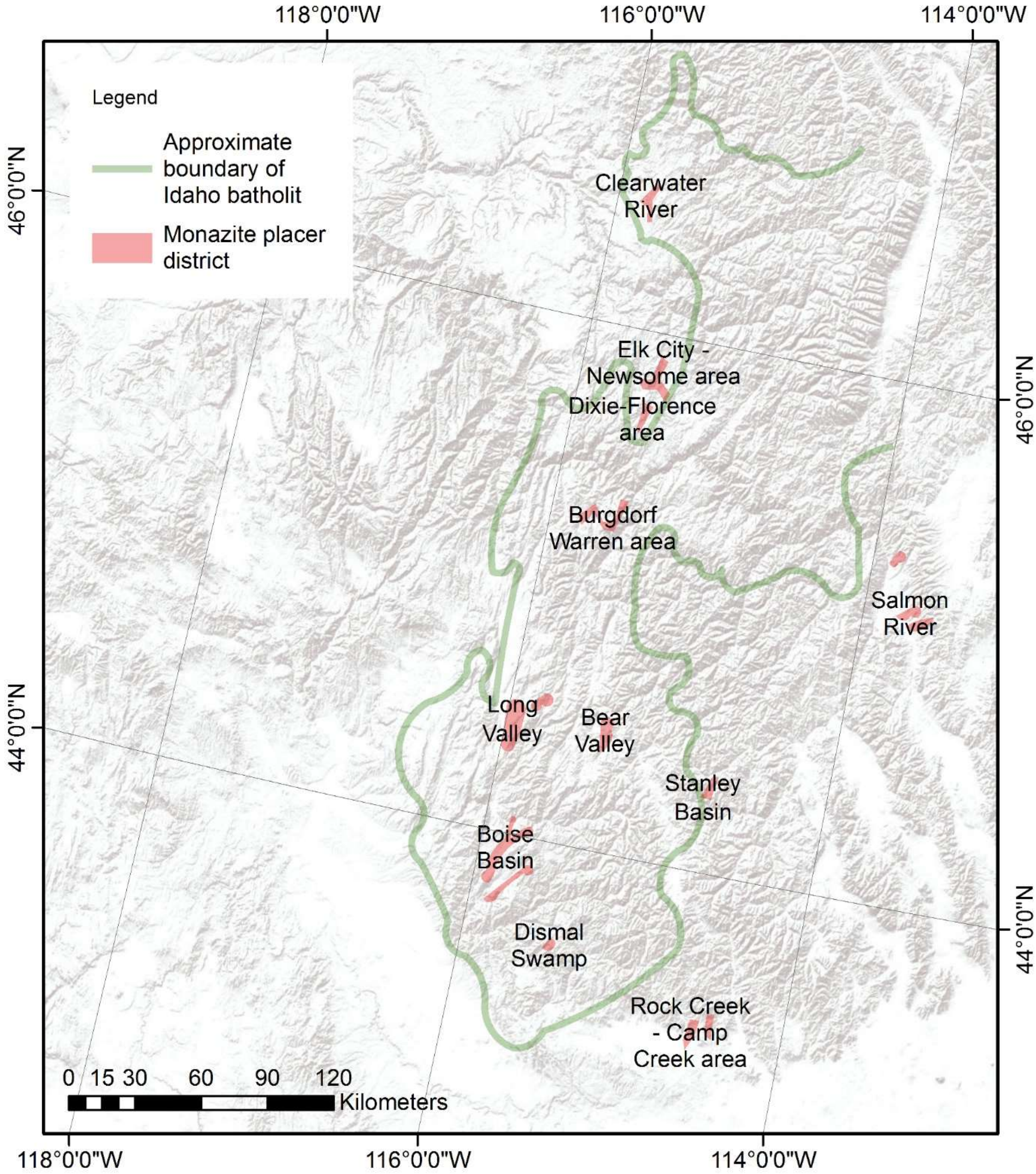

FIG. 15. Monazite placer districts in Idaho (Reproduced with the permission of U.S. Geological Survey and based on M. H. Staatz et al. Geol. Surv. Circ. 824, 1980, Thorium Resources of Selected Regions in the United States of America [46].

The beaches of northeastern Florida and southeastern Georgia are known to contain heavy mineral sands in which monazite is the main thorium-mineral. In the late 1970s, the beach placers were suppliers of monazite as a by-product of ilmenite, rutile and other valuable heavy minerals. The beach placers were estimated to contain ~12 900 t Th [45].

6.2.3.6. Summary for United States of America

In the United States of America, majority of identified thorium resources occur in veins, with estimated resources of 113 000 t Th and additional potential of ~234 000 t Th. In some of the veins other useful ores occur, such as REEs, and if mined, thorium eventually could be recovered as a by-product [45]. However, it is estimated that only limited amounts of thorium could be made available annually. The additional potential is estimated from inferred extensions of measured and sampled vein deposits.

Thorium resources estimated in carbonatites and alkaline intrusions are not in the range of economic consideration unless they are extracted as a by-product of mining another mineral commodity. For example, the carbonatite of Mountain Pass contains an estimated 29 Mt of carbonatite ore grading ~9% of total REO and about 0.02–0.04% Th. The Mountain Pass mine reopened in early 2011 to once again produce REEs [45]. The ore mineral is bastnaesite.

Some economic potential can be assigned to the placers, as examples of past mining show. If demand arises, then Th-minerals (monazite) can be recovered relatively easily from the placer deposits. Resources are sufficient for expected initial demands for supply.

In the Red Book 2009 edition, estimates of RAR of 122 000 t Th, recoverable at less than US$ 80/kg Th, were reported plus IR at the same cost class of 278 000 t Th. The sum is close to the assessment made in the USGS Circular 1336 [45], however no breakdown by deposit type is given in the Red Book. At present, there is no reported production of thorium in the United States of America.

6.3. CENTRAL AMERICA AND CARIBBEAN ISLANDS

No information on thorium resources.

6.4. SOUTH AMERICA

According to sources, thorium deposits and occurrences are found in Argentina, Brazil, Chile, Colombia, Peru, Suriname, Uruguay and the Bolivarian Republic of Venezuela. The most significant resources are in Brazil and in the Bolivarian Republic of Venezuela. In both cases they are related to the South American Platform.

Up to 2009, the mining of coastal beach sand deposits was carried out in the Buena region of Brazil and ~20 000 t of monazite were stockpiled, containing ~4.4% Th. The stockpile is ready to sell through Industrias Nucleares do Brasil (INB).

Similar to other areas of the world, resource categories and cost classes published previously in various documents are subject to controversy. Many assessments are based on figures obtained in the past under conditions which may be different from those existing today. Thus, the differences may be explained by the different dates of estimates and resource categories applied.

Differences in estimates may be demonstrated in the case of Brazil. Estimates of 172 000 t Th RAR recoverable at costs < US$ 80/kg Th, additional IR of 130 000 t Th recoverable at costs < US$ 80/kg Th, and PR to 330 000 t Th were reported in [16]. The USGS [29] report 16 000 t Th for Brazil. In previous editions, the USGS estimated the reserve base for Brazil at 18 000 t Th. In [14], total resources are estimated at ~606 000 t Th in deposits grading between 0.13 and 5%Th. For Brazil, total unspecified resources of Th have been estimated at 1.3 Mt [11] [13]. However, all resources are in situ and in deposits where they can be only made available as by-product.

In South America thorium is currently found in the following geological environments:

1) Igneous deposits:
    a) Carbonatite;

b) Alkali igneous;
c) Other igneous associated (including pegmatites and veins);
2) Weathered deposits:
a) Carbonatite derivated laterite deposit (Cerro Impacto, Bolivarian Republic of Venezuela);
b) Placer (alluvial, ancient);
c) Deposits in weathering crust due to adsorption.

6.4.1. Argentina

Thorium resources of 1 270 t were reported in the Red Book 1986 edition as PR (at that time: estimated additional, cat. II) in six different occurrences; however, without details (Fig. 16).

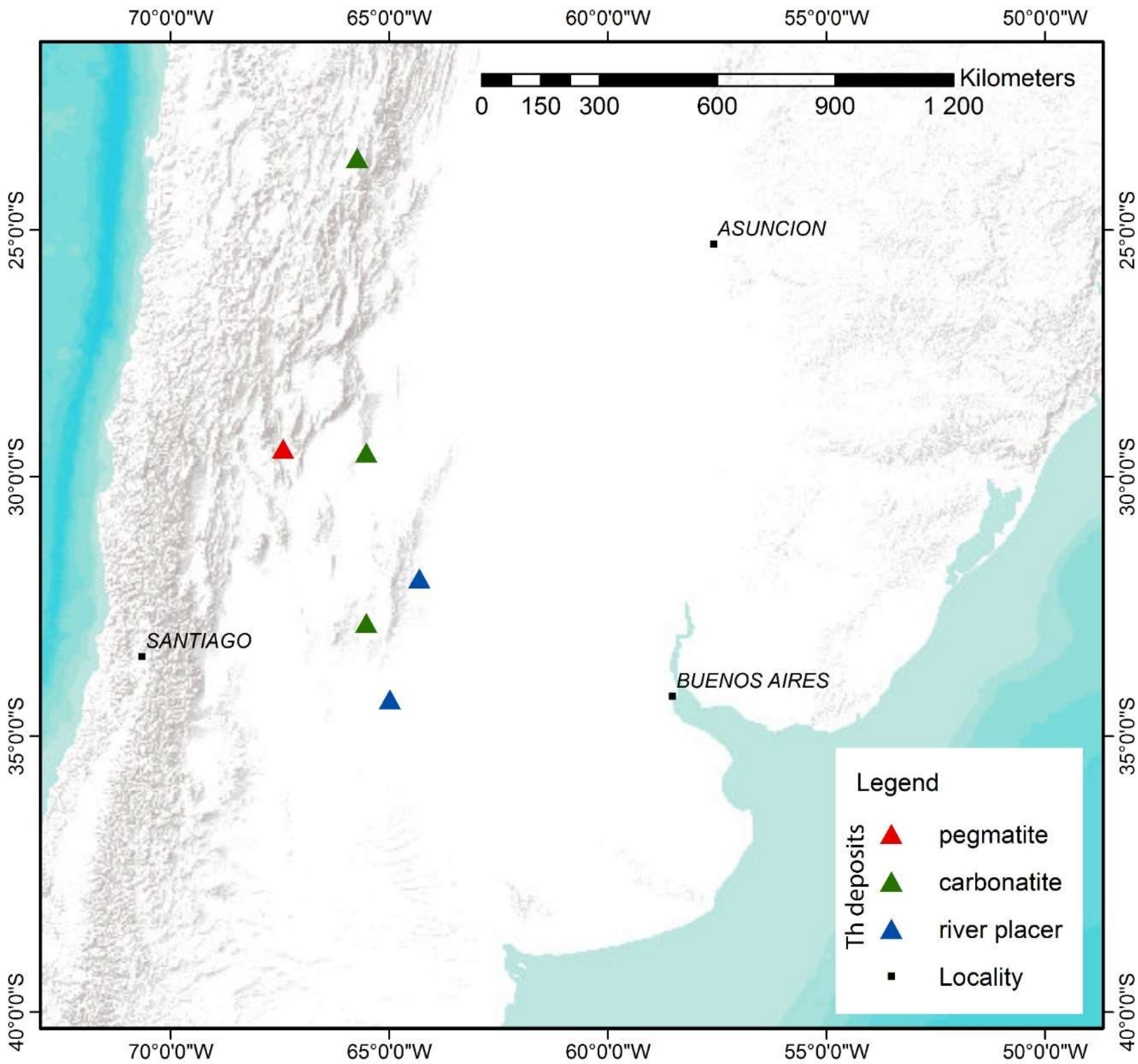

FIG. 16. Thorium deposits/occurrences of Argentina (Reproduced with the permission of L. Lopez and based on L. Lopez) [47].

Alluvial placers of the Rio Tercero, Province of Cordoba, ~135 km along the river from Rio Tercero City to Villa Maria, contain garnet, magnetite, ilmenite and monazite and date back to Upper Tertiary and Quaternary age. The material was derived from plutonic and metamorphic rocks of the Cordoba Mts. According to recent evaluations, this area accounts for ~25 500 t of monazite with ~3.45% Th, with a total SR of 880 t Th. The placers of Rio Tercero contain garnet, magnetite, ilmenite and monazite and date back to Upper Tertiary and Quaternary age. The material was derived from plutonic and metamorphic rocks of the Cordoba Mountains. Overall resources are low.

Additional resources were reported from Rio Quito and Rio La Carpa, San Luis and from La Aurelita, La Pampa, [16]. The resources are low (270 t Th) according to recent information [48]. In Rio Orosmayo, Province of Jujuy, monazite with 5–6%Th was reported in placers.

A carbonatite in the Jasimampa area of Sierra de Sumampa, Santiago del Estero, in the Sierra Norte de Cordoba, is known to contain light REEs, niobium and thorium [49]. The intrusion is interpreted to be derived from the fractionation of oceanic island basalt during Devonian age. Monazite is obviously the main ore mineral (4 390 ppm Th). Alteration and mineralisation can be compared to the deposit of Bayan Obo in China [49].

At the IAEA Technical Meeting on World Thorium Resources held in October 2011 in India, three major types of mineralisation of thorium were reported; carbonatites with associated veins containing REE and Th; river placers; and pegmatites. In carbonatites and associated veins from the northwestern region grades range between 0.005 and 0.45% Th, and potential resources are estimated at ~25 000 t averaging 0.4% Th. Prognosticated resources of REE +Y were estimated at ~35 000 t.

The mineralisation at Rodeo de los Molles is known for its REE-U-Th and is compared to the Mountain Pass Mine in the United States of America. Speculative resources of 117 600 t REO and 950 t U are estimated. Thorium resources from pegmatites (content 18–2 220 ppm) seem to be unimportant. However, the Teodesia pegmatite deposit (San Juan) is the only known case for recovery of monazite during 1954 and 1956 with a total production of 1 010 Kg.

A 2017 study on the application of the United Nations Framework Classification to Rare Earth Elements and Thorium resources in Argentina [50] reports thorium deposits and occurrences in carbonatites (Rodeo de los Molles, Puna, Cordilla Oriental, Jasimampa, Susques, Cueva del Chacho), in pegmatites (Cachi, Valle fertile Range, Teodesia line) and in placers (III River, V River). About 900 t Th have been estimated at Rodeo de los Molles, associated to 965 t U and 117 600 t REO. Additional 10 000 tTh could exist on the project. At Puna and Cordillera Oriental, Identified Resources of 23 900 t Th at a grade of 0.37 % Th, and 35 300 tREO+Y are associated to 9 mineral deposits. The III River and V River projects could contain ~1 110 t of thorium and 15 500 tREO.

6.4.2. Bolivia, Plurinational State of

No detailed investigation seems to have been carried out for occurrences of Th in lead and zinc mines in the Departments of Potosi and Chuquisaca. The carbonatite of Cerro Manomo in the province of Santa Cruz contains elevated concentrations of Th. The main minerals are reported to be bastnasite, monazite and cerianite. Phosphate with La and Nd are present as well however not described in as much details as the mineralisations with Th, U, Sc, Nb [49].

6.4.3. Brazil

Several individual occurrences, showings and deposits have been described and published in various papers, the interested reader is referred to [3, 51–52]. In a 2011 written communication, Villas Boas [49] mentions the following important geological environments for the formation of thorium deposits and occurrences:

- Pegmatites with monazite and/or complex Ta-Nb-minerals,
- Residual monazite in eluvial and alluvial deposits (mainly placers),
- Carbonatites and nepheline-syenites.

In [49], a total of 44 deposits/occurrences and showings containing thorium in varying concentrations are listed (Fig. 17).

As mentioned above the evaluation of thorium resources depends upon the date of assessment and the resource categories applied. Most assessments have been made in the past in expectation of increasing demand for thorium, and estimates on resources may have been optimistic and may have included resource estimates otherwise not relevant. This is not only the case in Brazil but for other countries too. Resource figures vary in various publications. Total thorium resource figures of in situ for this publication are 632 000 t thorium as reported in [16]. During 1886–1950, ~95 000 t of monazite were exported.

All thorium resources known so far in Brazil are extractable as by-product of other minerals and availability depends on the needs for the main product. In the past thorium has been extracted from heavy mineral sands (monazite) from placer deposits at the coast of Sao Paulo. However recent information is not available.

Geologically thorium deposits can be grouped into:

1) Granitic intrusions;
2) Carbonatites;
3) Peralkaline intrusions;
4) Placers [51].

6.4.3.1. Granitic intrusions

Investigations at the Pitinga Mine, explored for tin, niobium and tantalum, have shown important quantities of thorium resources totalling ~251 000 t thorium of which ~40% are in the category of measured resources, which amount to ~100 000 t thorium (Fig. 18). The grades vary between 0.07% (measured resources) and 0.05% (indicated resources). Extraction of thorium is presently not undertaken and would only be possible as by-product. In [51], measured thorium resources of ~251 000 t were reported in hard rocks to a depth of 100 m.

6.4.3.2. Carbonatites

One of the largest carbonatite deposits on the world scale is the carbonatite complex of Araxa**,** in the state of Minas Gerais, which is one of the largest niobium deposit in the world (Fig. 19). The carbonatite was intruded into Precambrian metasediments during Cretaceous time. The intrusion is located on a deep reaching major structural lineament. The ore mineral mined is pandaite, a Ba-containing variety of pyrochlore containing up to 2% Th and some U. The mean grade in the mined ore in the weathered zone (canga) reaches up to 0.13% Th, which results in total Th resources to ~400 000 t Th.

Thorium is not recovered at Araxa. During the production of ferroniobium, impurities enter into the slag, and annually ~ 1000 t Th and ~ 100 t U are disposed in the slag [52]. If an economic process is developed to recover Th and U from the slag, Araxa could become a by-product producer both for Th and U.

Several other carbonatites, most of them with niobium ore, e.g. Morro dos Seis Lagos/Amazonas, Salitre/Minas Gerais, Serra Negra/Minas Gerais, Tapira/Minas Gerais are known to contain elevated contents of Th.

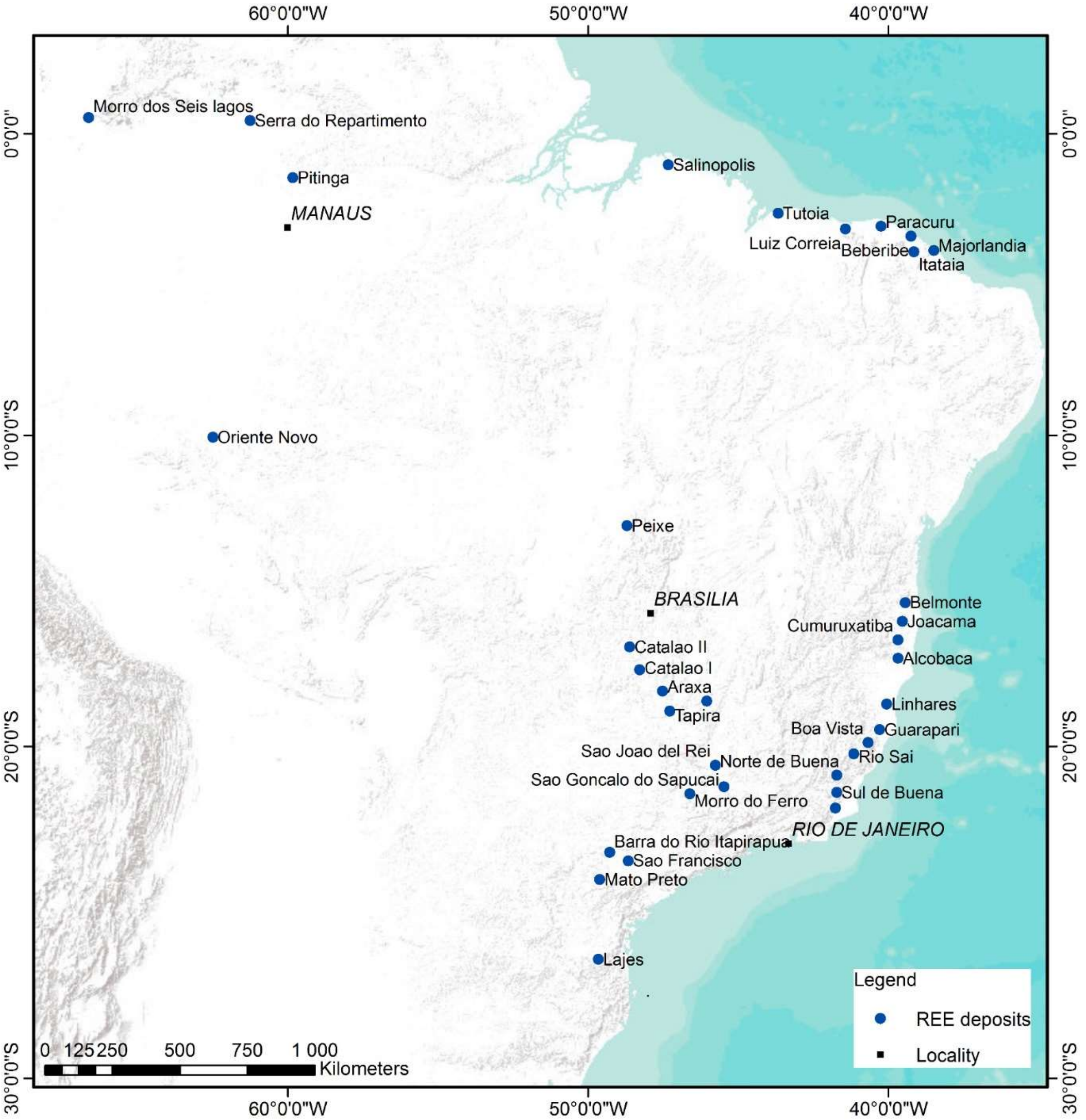

FIG. 17. Rare earth deposits of Brazil (Based on Lapido & Santos, CETEM, 2011) [53].

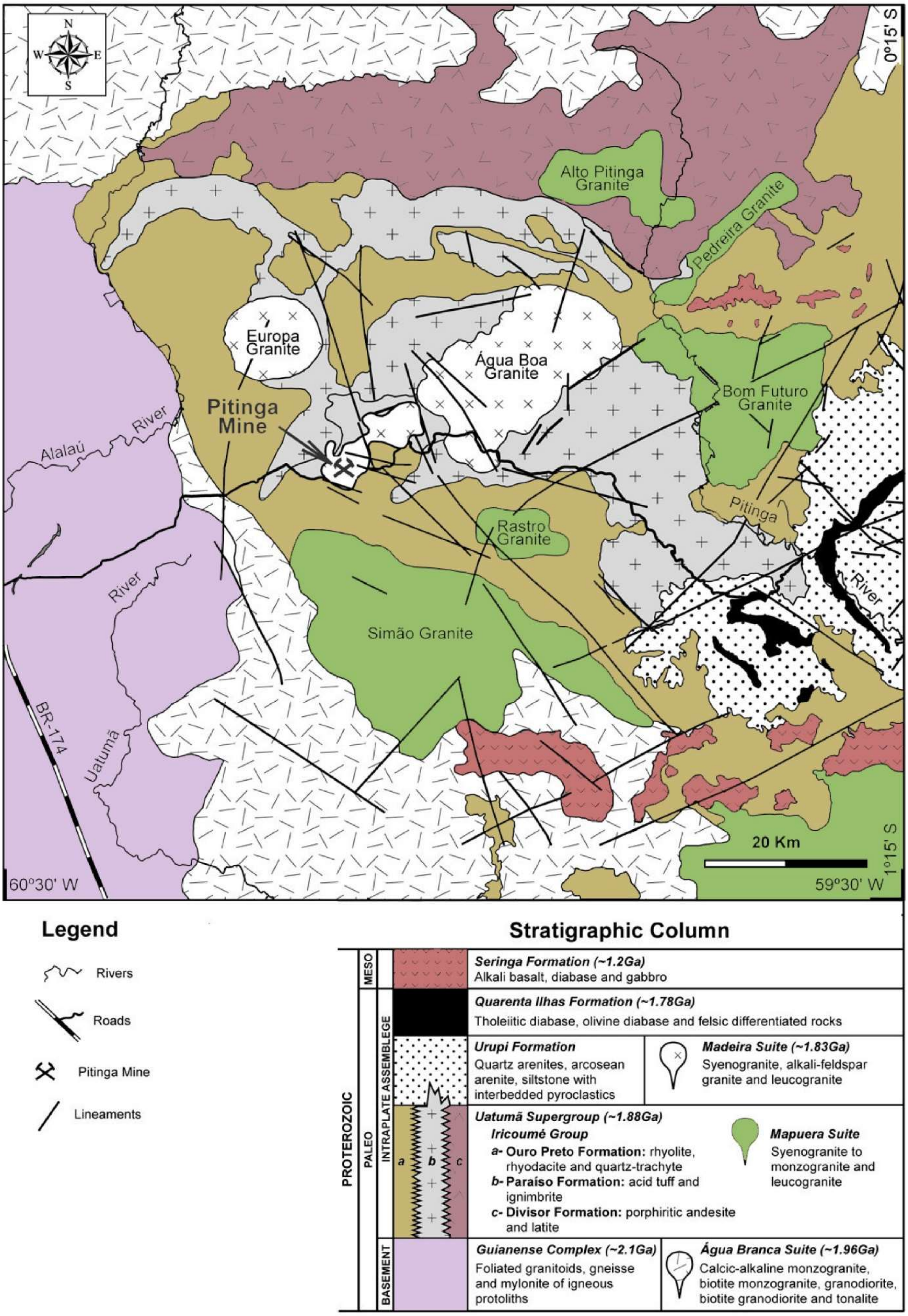

FIG. 18. Geology of the Pitinga Mine area (Reproduced with the permission of the Anais da Academia Brasileira de Ciencias, modified from Hartmann and Delgado (2001) and Ferron et al (2007) [54].

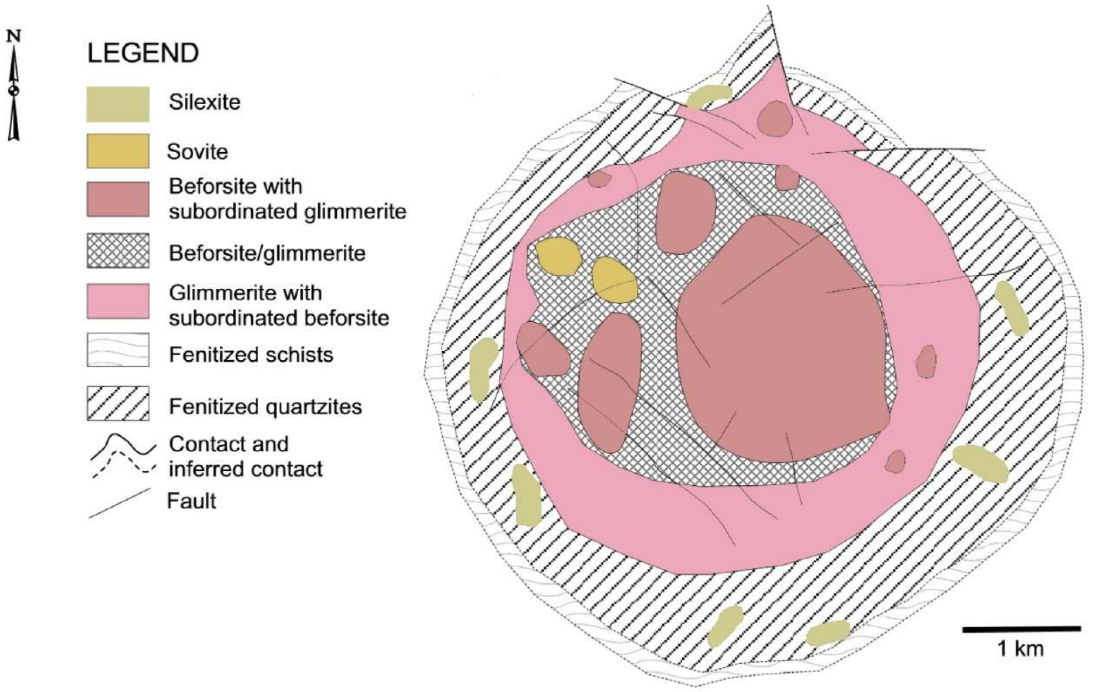

FIG. 19. Geology of the Araxa carbonatite complex (Reproduced with the permission of the Anais da Academia Brasileira de Ciencias, modified from Issa Filho et al (1984) and Grossi-Sad & Torres (1976)) [55].

6.4.3.3. Peralkaline intrusions

Other thorium resources are located in the Morro de Ferro deposit in the Pocos de Caldas peralkaline complex [56] (Fig. 20). Morro de Ferro contains ~17 500 t Th with mean grade of 1.2% Th. At Pocos de Caldas total resources of ~59 000 t thorium at a grade of 0.44% Th were estimated and published in earlier reports. According to [51] recent estimates indicate 30 000 t thorium. Apart from thorium, the deposit contains uranium, which was subject to mining (~1 000 t U [17]) until 1997. During the restoration phase monazite was extracted for the recovery of rare earth metals. The resulting 4 000 t of thorium cake were stored in 20 000 drums. The stockpile may be available for sale through INB, the owner of the mine.

This alkaline volcanic crater, 5 km diameter, holds a very complex suite of minerals. For 10 years INB has mined uranium. In this site there are some 4 000 t of "torta II" (pie II) thorium stored in 20 000 drums as the result of the opening of monazite to produce REE. Measuring ~28 km in diameter, the Late Cretaceous Poços de Caldas massif is among the largest peralkaline complexes of the world. It was emplaced between 78 and 76 m.y. ago. Like Illimaussaq, it is composed of a highly potassic silica-undersaturated igneous complex forming an almost perfect circular ring structure of caldera type. Estimates of ~30 000 t thorium were reported as totals for the entire Pocos de Caldas complex [51].

In the alkaline intrusion of Catalao (Fig. 21), thorium was found. However, it still has to be estimated. Recently, ~65 Mt of ore were reported [51] together with large resources of niobium. Thorium resources were estimated at ~12 000 t without categories.

Locations of all the major alkaline complexes are shown in Fig. 22.

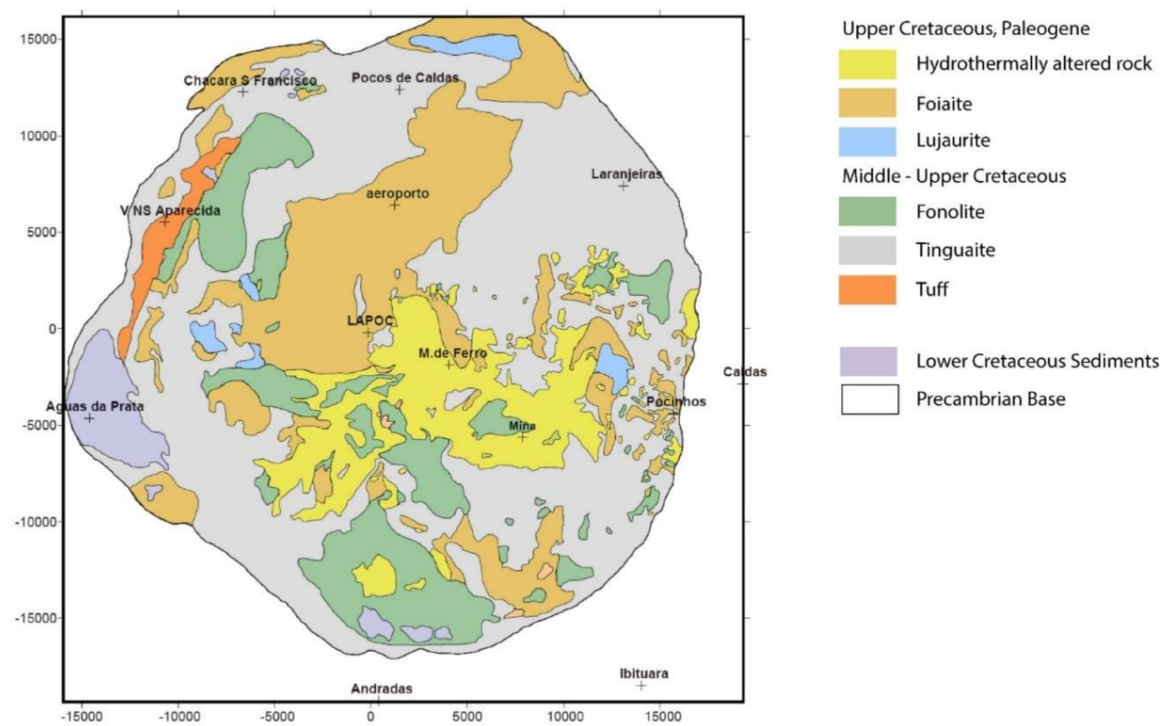

FIG. 20. Location of the Morro do Ferro deposit within the alkaline complex of Poços de Caldas (adapted from Bossew et al 2015) [57].

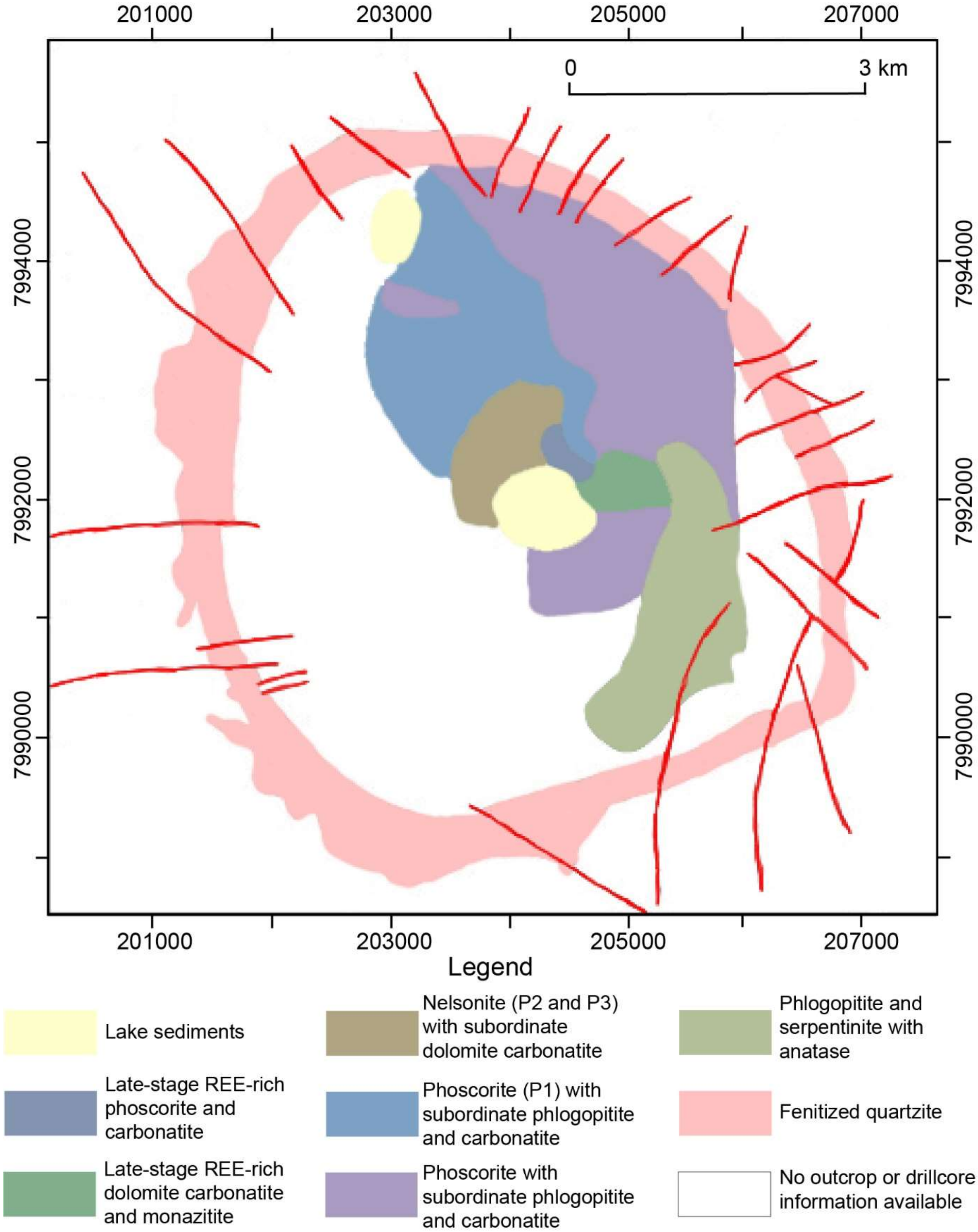

FIG. 21. Geological map of the Catalao alkaline intrusion (modified from Brod et al 2002) [58].

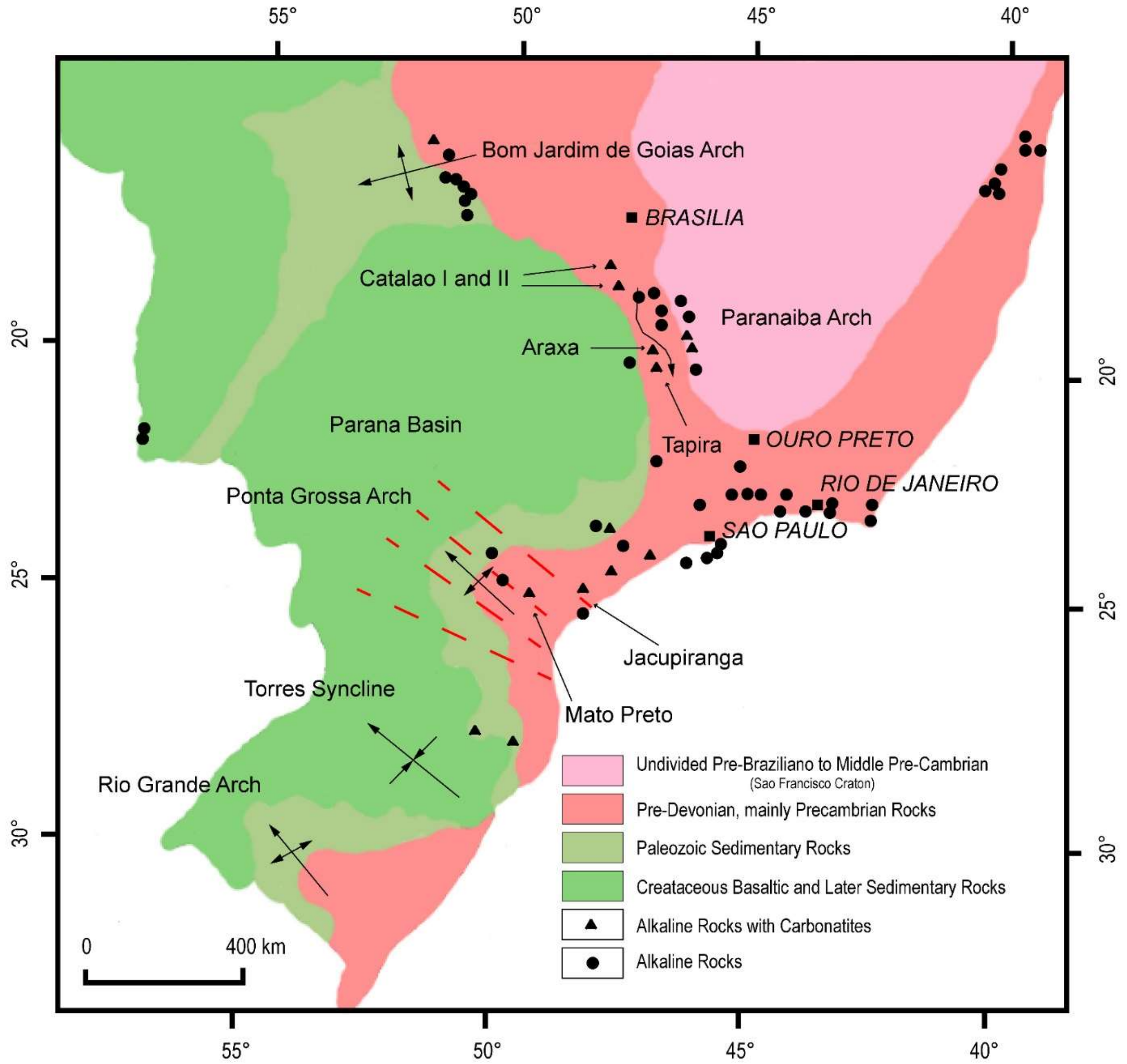

FIG. 22. Location of alkaline complexes in Brazil (Based on R. V. Santos et al. [59]).

6.4.3.4. *Placers*

Resources of thorium in the beach sands/placers along the coastal areas from Rio de Janeiro, Espirito Santo and Bahia are estimated at ~4000 t Th in heavy minerals, mainly monazite (Fig. 23). Monazite was discovered in the beach sands in 1880 to be a component of the heavy mineral sands used as ballast for trade ships returning to Europe. For example, in Germany, the Auer Company extracted Th from monazite for the production of gas mantles. The monazite and other heavy minerals (ilmenite, rutile, zircon etc.) in the placers are derived from Precambrian rocks in the hinterland. During episodes of uplifting and erosion material was ready for transportation by rivers to the shore where at specific places by wave action heavy minerals were accumulated to workable concentrations. The heavy mineral content in beach sands ranges from 20–40%, and monazite has a fraction of 2–5%, locally up to 20%. The thorium content of the monazite ranges from 4–5%. Known places for monazite extraction are Itabapoana/Rio de Janeiro, Cumuruxatiba/Bahia and Guarapary/Espirito Santo. Further processing is done in Sao Paulo. The Buena mine, the only REE producing mine in Brazil, is located in northeast Rio de Janeiro. The orebody is a beach placer monazite sand. In 2010, proven and probable monazite and ThO_2 resources amounted to 608 690 t of monazite sands at 0.103% monazite, and 31.35 t ThO_2 at 5% ThO_2 in monazite [60].

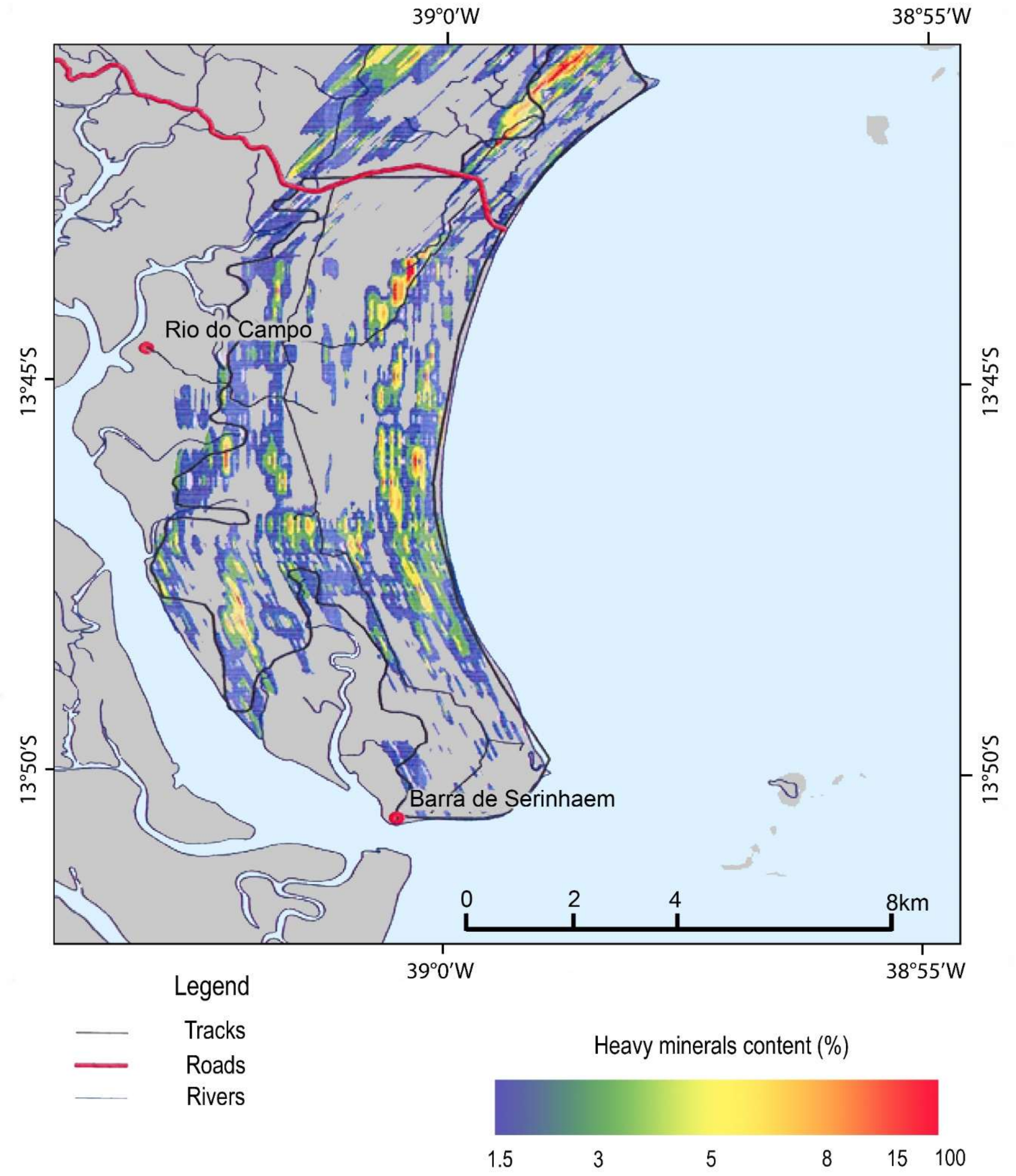

FIG. 23. Map of placer deposits in the Pratigi area of Brazil (Reproduced with the permission of R. Avena Neto, Technical Director of CBPM) [61].

6.4.4. Chile

No systematic estimates on thorium resources were done on the scattered occurrences found during initial exploration. Placers are found at the coast line with elevated thorium contents, such as Playa de Cahull and Santo Domingo, however the main minerals are titanium and iron ores. No details are available for the indications of thorium occurrences in the northern part of Chile.

6.4.5. Colombia

Anomalies with elevated contents of thorium are reported from several parts of the country, e.g. Macizo de Garzon, Mocoa, Fredonia/Antioquia, Galemzabara; however, no details are available.

6.4.6. Peru

The REEs deposit Mina Cerro Iman was investigated for its thorium content, which averages ~10 ppm. A total, very low grade, tonnage was estimated at ~20 000 t Th [14].

6.4.7. Suriname

The red mud from bauxite mining at Moengo was found to contain ~0.8% Th; however, no resource estimates are given [14].

6.4.8. Uruguay

Beach sands were found to contain thorium and estimates indicate ~3000 t Th.

6.4.9. Venezuela, Bolivarian Republic of

During airborne radiometrical surveys in the Bolivar state a carbonatite at Cerro Impacto was discovered carrying thorium, REEs and niobium (Fig. 24, 25). Mineralisation occurs in the tropical rain forest in elevation at 1260–1550 m high. A drilling programme has investigated the extent of the mineralisation in a lateritic layer over an area of 10 km by 1 km. The laterite contains the typical mineral assemblage for carbonatite, however no tantalum. It was found that the central part of the body has up to 1.5% Th whereas the outer areas carry ~0.2% Th. A mean of 0.3% Th was estimated for a part covering ~25% of the total. Estimates reported ~300 000 t Th of PR in 1986. According to Greaves [62], a conservative estimate was made for the explored area amounting to 324 000 t Th, averaging 0.43% Th. Apart from thorium, the element association (REE, niobium, iron, manganese) found gave rise to believe that the underlying body is a carbonatite. The majority of thorium is associated with the iron minerals goethite and hematite [62]. Extraction of thorium by sulphuric acid at elevated temperature and organic solvents was carried out on a lab scale only.

Another occurrence was found in the alkaline intrusion of Churuata, Amazonas state.

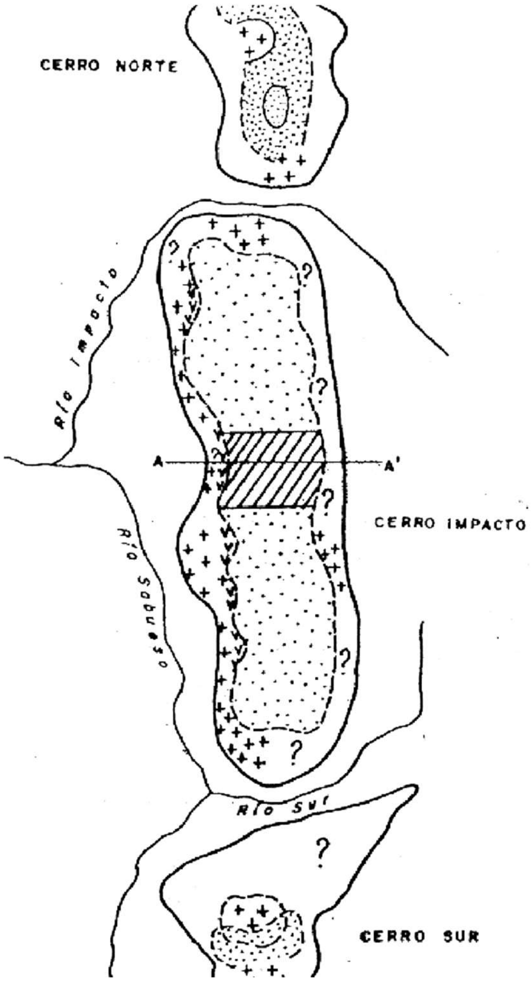

FIG. 24. Geology of the Cerro Impacto deposit [62].

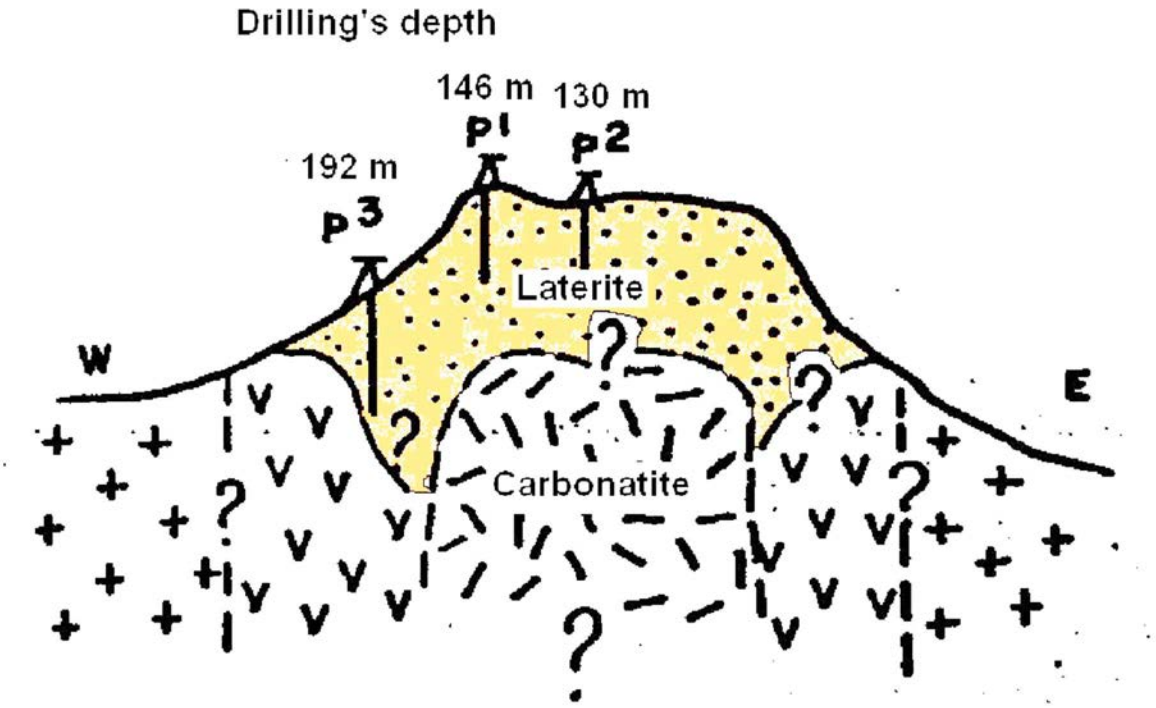

FIG. 25. Section A–A, Cerro Impacto deposit [62].

6.4.10. Summary for South America

With the exception of Brazil, no thorium has been extracted so far in South America. However, the total amount of extracted thorium is limited. Total resources of ~1 Mt of thorium seem to be high, however extraction is possible only as by-product. In the case of Araxa, where niobium ore is mined and ferroniobium is produced, thorium enters during the process into the slag and is disposed in the amount of ~1000 t Th annually. At present no economic process for extraction of Th exists. If greater needs for thorium as a nuclear fuel would arise, its extraction from the slag would be an option.

6.5. AFRICA

With few exceptions, knowledge on thorium deposits in Africa is restricted to previous and active mining projects, mainly for uranium and for placers (South Africa) or to occurrences in other placers of probably very limited to nil economic relevance. Only few countries, mainly South Africa, have resources in deposits readily available for extraction in the case demand would develop.

For completeness countries for which indications in the literature were found will be mentioned.

6.5.1. Angola

On the plateau of Huambo, between Ganda and Andulo, 11 alkaline and carbonatite complexes were found, of which seven were reported to have thorium mineralisations. The ring complex of Logonjo hosts a carbonatite with iron ore, columbite, pyrochlore, rare- earth minerals, apatite, barite and fluorite. In the primary rock, ~0.73% Th has been found, which can be enriched to 0.9% Th in the weathered part. During the 20th century, the carbonatite of Logonjo was the best investigated of the country. Other carbonatites with thorium mineralisations are Chianga, Coola, Capuia, Bailundo, Canata and Andulo. Their thorium contents are not of economic interest. With respect to various carbonatites with enriched contents of thorium, the total resources of the country are estimated to10 000 t Th without any categorisation.

6.5.2. Burundi

Poor thorium mineralisation of the Karonge mine, mined for bastnaesite after the late 1940s, is reported. The occurrence is not economic at present.

6.5.3. Central African Republic

Alluvial placers, some with reported diamond concentrates, contain monazite with ~5% Th. Not economic.

6.5.4. Democratic Republic of the Congo

A theoretical resource estimate for the pyrochlore of the carbonatite of Bingo results in approximately 2 500 t Th.

6.5.5. Cote d'Ivoire

In heavy mineral sands at the coast some monazite was found, however uneconomic.

6.5.6. Egypt

Since 1973 (Red Book), thorium mineralisations are reported from heavy mineral sands in the Nile delta (between Rosetta and Damietta) (Fig. 26). Investigations, mainly by the Egyptian Nuclear Materials Authority (NMA), were carried out to estimate thorium resources in monazite, contained to ~1% in the heavy minerals, sometimes referred as "black sands". According to [63], monazite content in the black sands varies between 0.4 and 0.6%. The monazite itself contains around 5.8% ThO_2. The resource figures were collected ~45 years ago. In addition, thorium occurrences are reported in fluvial placers in the Southeastern Desert and in albitised rocks in the Eastern Desert. None of them seems to be of any economic significance.

The Red Book 2009 edition [16] identified thorium resources of 100 000 t Th recoverable at costs up to US$ 80/kg, and additional PR of 280 000 t Th. The 2010 USGS [29] did not report any thorium reserves in Egypt (see Table 12). Considering the date of estimation of resource data, it might be justified to question whether their categorisation as in [16] is still relevant. It is not clear whether PR of 280 000 t Th include any SR.
For the heavy mineral sands of the Nile Delta, Nuclear Materials Authority (NMA) reports its role being restricted to assess radiation hazards and mitigation for mining operations on Ti and Zr. It is not reported whether any thorium is presently recovered as by-product. Laboratory tests were made to produce ThO_2, treating monazite with sulphuric acid [63].

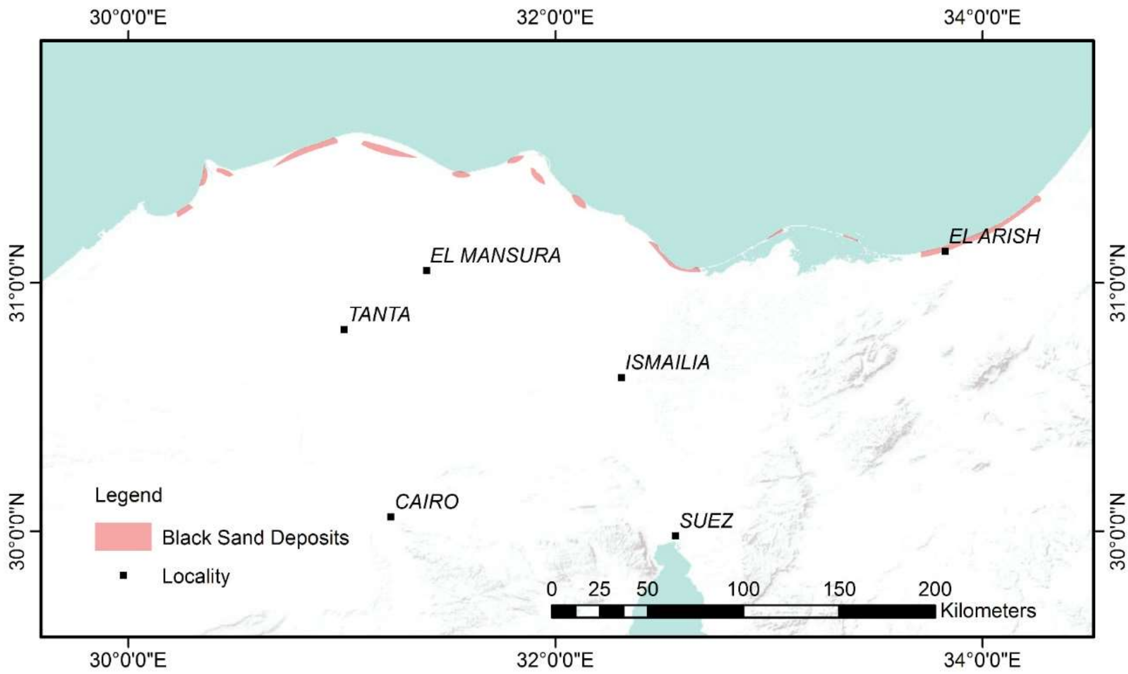

FIG. 26. Black sand deposits along the Mediterranean Sea coast and Sinai, Egypt (Based on document by E.A. Zaghloul (2013) [64].

6.5.7. Ghana

Coastal placers with monazite were found to contain ~6% Th. They are not of economic significance.

6.5.8. Kenya

A carbonatite at Mrima Hill, ~70 km SW Mombasa has been explored for pyrochlore and rare earth minerals. Low grade thorium values (0.1–0.2% Th) occur in the ore, which can be slightly enriched by thorium in the residual soil. Elevated thorium content was found in the Ruri Group of the Rangwa Complex. Limited monazite concentrations were found in some coastal placers. Total resources of Kenya were estimated at 8000 t Th, without giving any category.

6.5.9. Liberia

The coastal area was explored for heavy mineral sands and more than 800 000 t of heavy minerals with varying grades of monazite and zircon were found. The coastal placers were estimated to contain approximately 600 t Th. Commercial operations are not envisaged.

6.5.10. Madagascar

At Tranomaro, South-East Madagascar, uranothorianite-bearing pyroxenites are located in skarns. A metasomatic zonation is believed to occur between marbles and granite injections, controlled by metasomatic exchange of Si and Ca between the two lithologies. The main mineralisation is related to skarns, which are composed of two varieties – endoskarns and exo-skarns. The chief ore mineral is uranothorianite. It is proposed that the fluids implicated in the metasomatism and Th–U-REE-Zr mineralisation were generated from devolatisation reactions that occur at depth during granulitic metamorphism and from over-saturation of the granitic melts injected into the Tranomaro metamorphic series. Fluid circulation linked to metasomatism and U-Th mineralisation was synchronous with granulitic metamorphism at 850–800°C and 5–3 kbar. Most Th/U ratios of the mineralised rocks vary from 2 to 3, nearly the mean crustal ratio, indicating coeval enrichment in Th and U. Fluor-phlogopite - fluor-pargasite–uranothorianite - REE-rich veins represent a later episode of mineralisation.

In 1955–1968, 1 030 t of U and 3 218 t of Th have produced by private companies and the French Atomic Energy Commission, indicating ore with mean Th/U ratio of ~3 [6, 8]. Over 100 occurrences and deposits of uranothorianite are known in the Fort Dauphin area in southern Madagascar (Fig. 27). Mineralisation is associated with zones enriched in wermerites and pyroxenites [65]. Additionally, the fossil dunes (reworked placers) are unusually rich in heavy minerals (30–40%) of which between 1 and 2% are monazite (6–8% Th). In the past, a total of ~22 000 t Th have been estimated of which ~2000 t were estimated in the category of RAR.

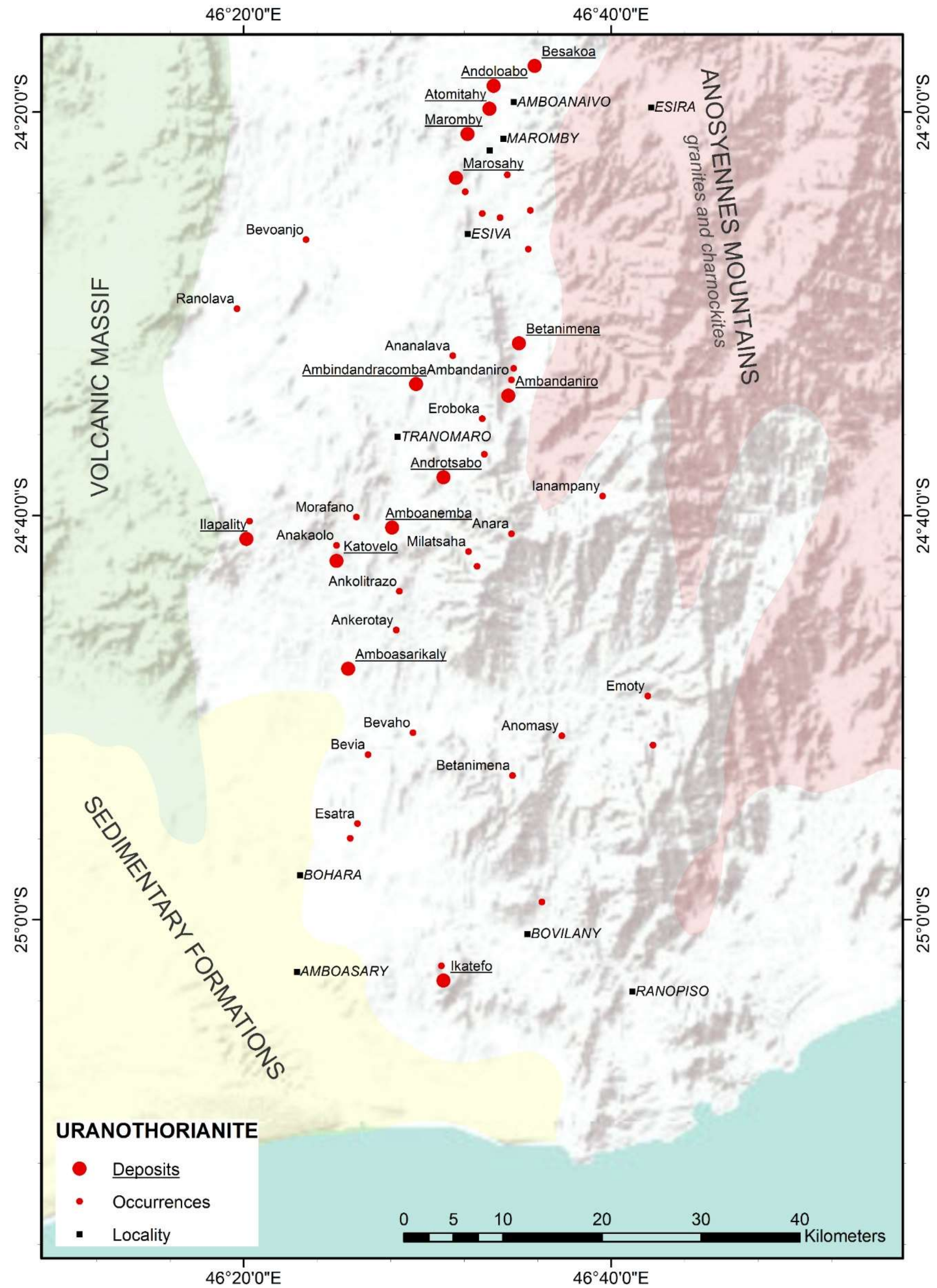

FIG. 27. Location of uranothorianite deposits and occurrences in the Fort Dauphin area (Based on Besairie, 1966) [65].

6.5.11. Malawi

Carbonatite and alkaline complexes in the Chilwa Lake area contain pyrochlore, monazite and other rare earth minerals with Th in the range of 0.8–0.9% (Fig. 28). At Kanyika, the total Th resources are estimated at ~9000 t Th, according to older estimates in the category of IR.

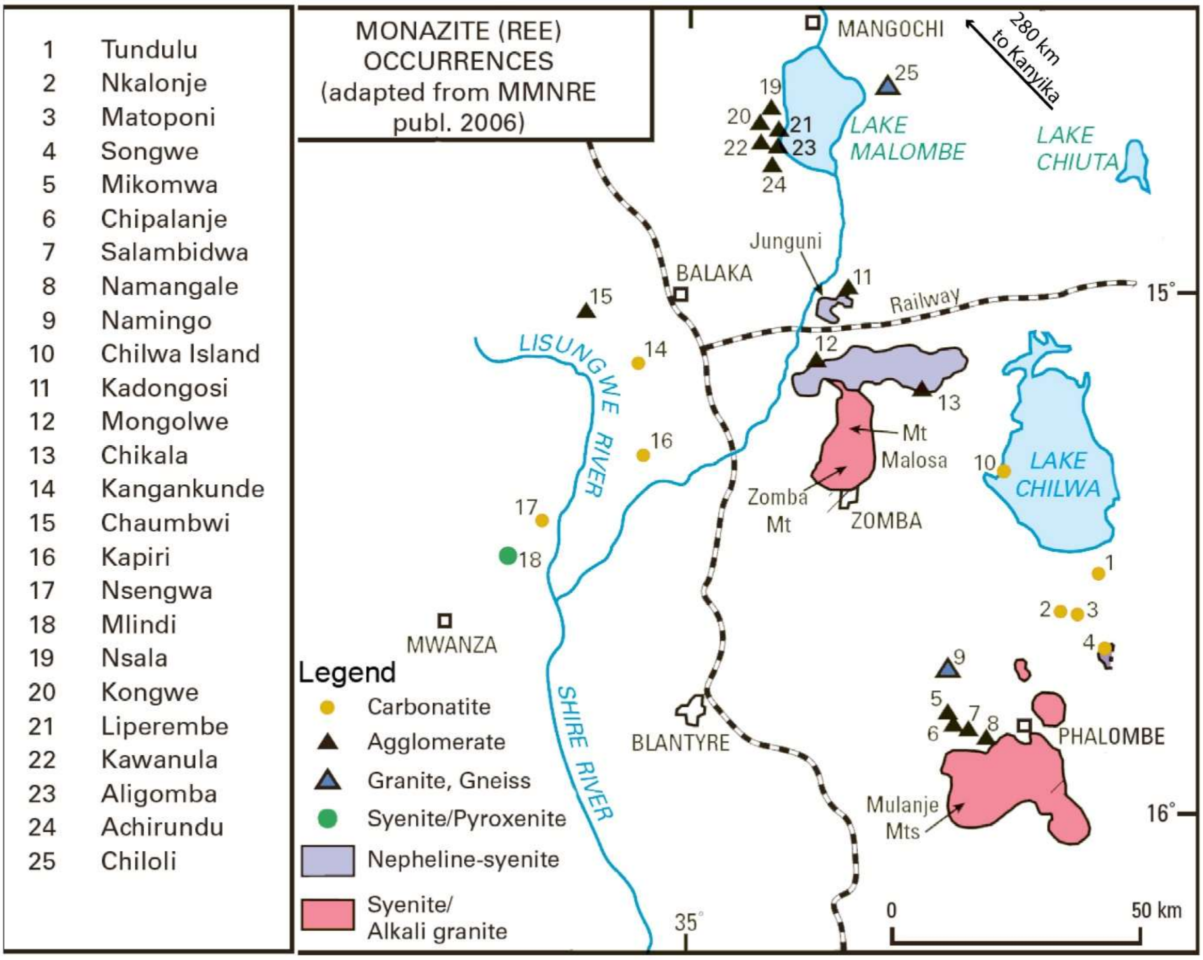

FIG. 28. Monazite occurrences in the Chilwa Province, Malawi (Modified after Ministry of Energy and Mines of Malawi) [66].

6.5.12. Mauritania

A small vein deposit near Bou Naga was mined for rare earth minerals in the 1960s. No indication on the thorium content was reported. Coastal placers are reported to contain some monazite.

6.5.13. Morocco

Nepheline syenite and carbonatite intrusions near Midelt in the High Atlas were investigated for rare metals and rare earth minerals which apparently were low grade. The total potential was estimated at 30 000 t Th, at a grade of 0.03% Th. South of the location higher Th grades are found in pegmatitic dykes of the nepheline syenite. The occurrence was rated as uneconomic. In the Anti-Atlas, paleo-placers of Cambrian age have been reported in older publications to carry ~0.17% Th.

6.5.14. Mozambique

Several pegmatites are reported to contain Th. In the mine of Mavuzi, near Tete, high-temperature hydrothermal veins have been mined for uranium from davidite (U-Th-complex oxide). Content and recovery of thorium are not reported. Coastal placers are known for their rich monazite concentrations. They are the possible extension of the heavy mineral sands of South Africa, where they are subject of mining. Presently, no exploitation takes place. Thorium resources are estimated by the authors to be ~10 000 t.

6.5.15. Namibia

The alaskite of Rössing, which is mined for uranium, contains thorium in non-economic quantities (50–100 ppm). Several other alaskites are found to contain low grade thorium and uranium. High grade metamorphic rocks, common in the Namib Desert, have also shown enrichments of thorium; however, the processes did not result in economic concentrations.

6.5.16. Nigeria

The alkali granite of the Jos-Complex is known for the enrichment of tin and columbite which are mined. As a by-product thorite was recovered in the past during tin-recovery process. About 60–70 t Th were estimated in the 1950s to be associated with tin ore concentrates. About 1000-2000 t of thorium were considered as reserves in the past. According to older estimates, the total resources (not considering resource categories nor cost of extraction) were estimated at 29 000 t Th.

6.5.17. Sierra Leone

Some indications of monazite are reported in metamorphic rocks, without further details.

6.5.18. Somalia

No details on thorium have been reported from rocks of the Bur region which underwent metasomatic alteration. Coastal placers are low grade.

6.5.19. South Africa

The country is the richest and best investigated country for thorium in Africa. Thorium resources are known from coastal placers, vein deposits and carbonatites. Under present market conditions, however, the only viable source of thorium are the coastal placers where monazite is a by-product of the recovery of ilmenite (Ti) and the vein-type deposit of Steenkampskraal. Approximately 17 000–18 000 t Th are estimated in the coastal placers. Coastal placers are subject to mining for contained heavy minerals mainly the Ti-ore ilmenite. If required, monazite will be extracted for its REEs and Th obtained in a separate extraction.

The vein-type deposit of Steenkampskraal, presently owned by the Great Western Minerals Group Ltd. [67], occurs in Namaqualand metamorphic complex, in the Cape Province (Fig. 29). In 1963, mine operation was discontinued (Fig. 30). The vein is hosted in granulite facies rocks (charnockite), ~1 billion years old (Fig. 31). It contains monazite, apatite, magnetite and small amounts of zircon and base-metal sulphides [68]. The mean grade was recently published by Great Western at 17% total REO, which is probably the highest grade rare earth deposit of the world. Copper and gold are additional economic commodities. According to [67] the current rare earth resources are sufficient to supply an operation of more than 10 years. According to independent project review resources of 30 000 t total REO were estimated.

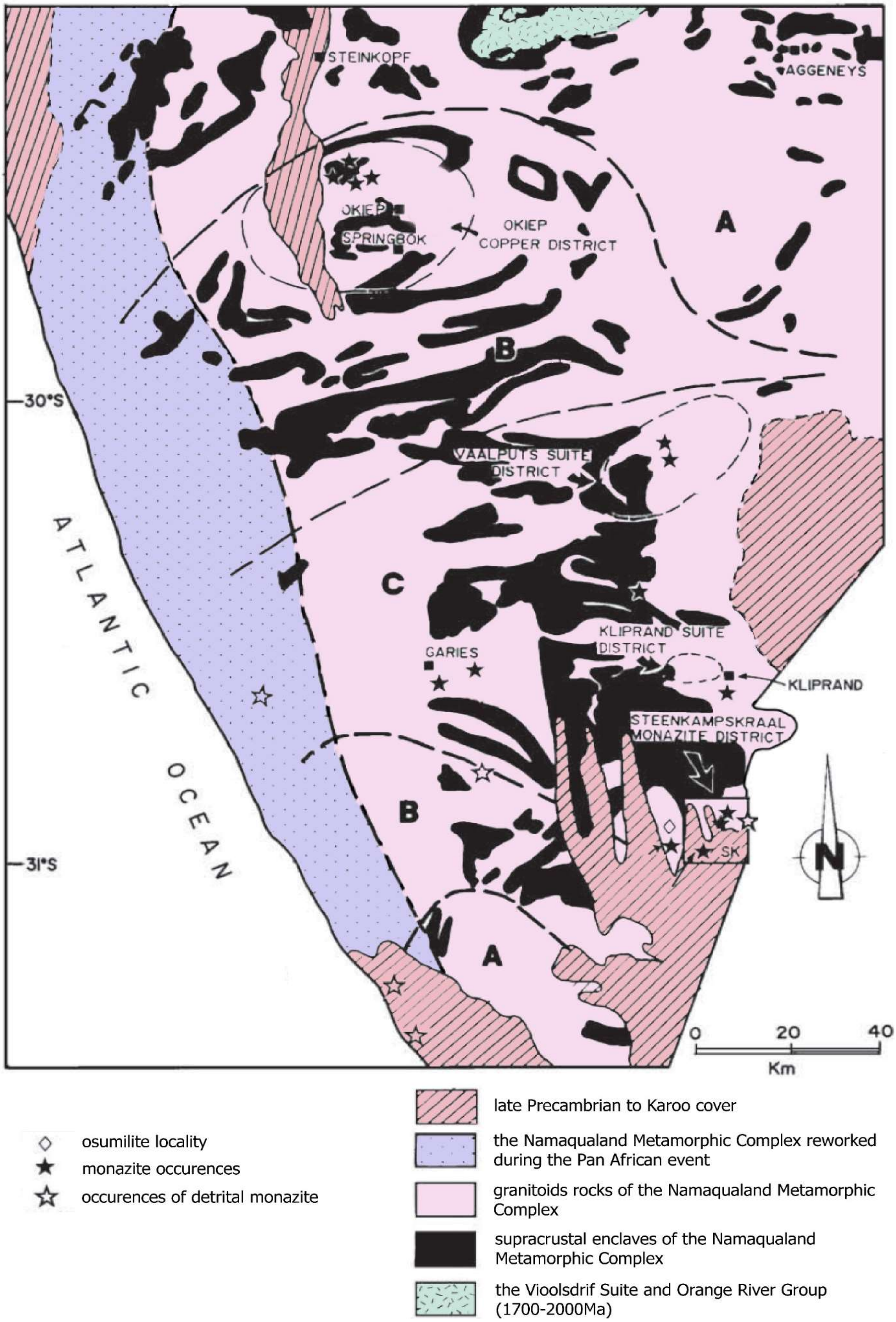

FIG. 29. Geologic map of the Namaqua metamorphic Complex, South Africa (Reproduced with the permission of Economic Geology/Society of Economic Geologists) [68].

During the 1950s to 1960s, ~50 000 t of monazite concentrates with 3.3–7.6% Th have been extracted. About 2000 t ThO_2 have been produced and exported, mainly to India [69]. The mined ore has an in-situ grade of 2.5% Th [67], which is considered as an attractive by-product. Plans are to extract thorium from the mixed rare earth chloride concentrate, mix it with concrete and store it in specified areas. By acid digestion, thorium is recoverable and made available for customers. Total reserves have been estimated in the past at 15 000 t Th [67]. Production of REO is slated for 2013 [69]. Thorium hydroxide will be stockpiled at a rate of ~360 t/year.

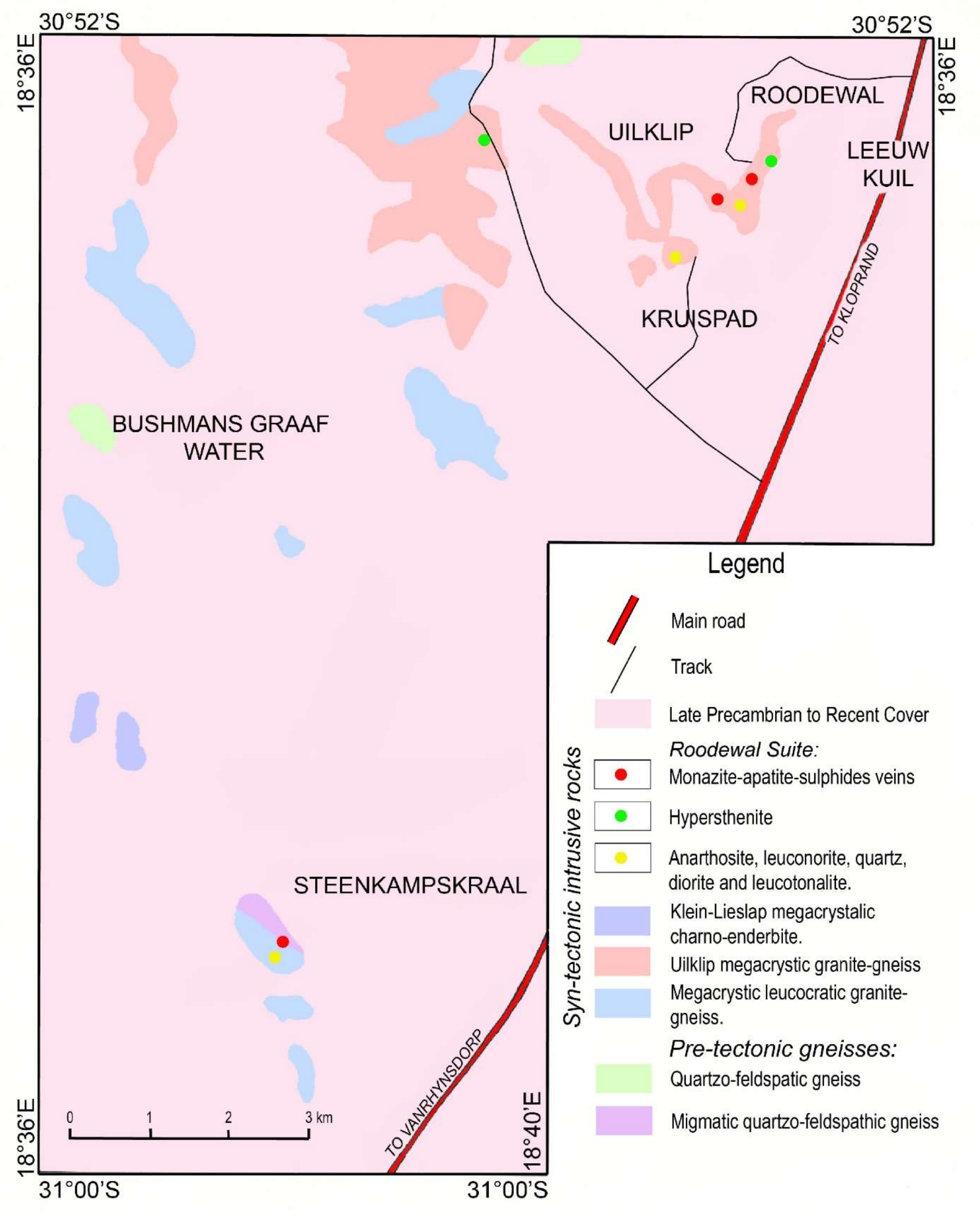

FIG. 30. Regional geology and monazite occurrences in Steenkampskraal area, South Africa (Reproduced with the permission of Economic Geology/Society of Economic Geologists) [70].

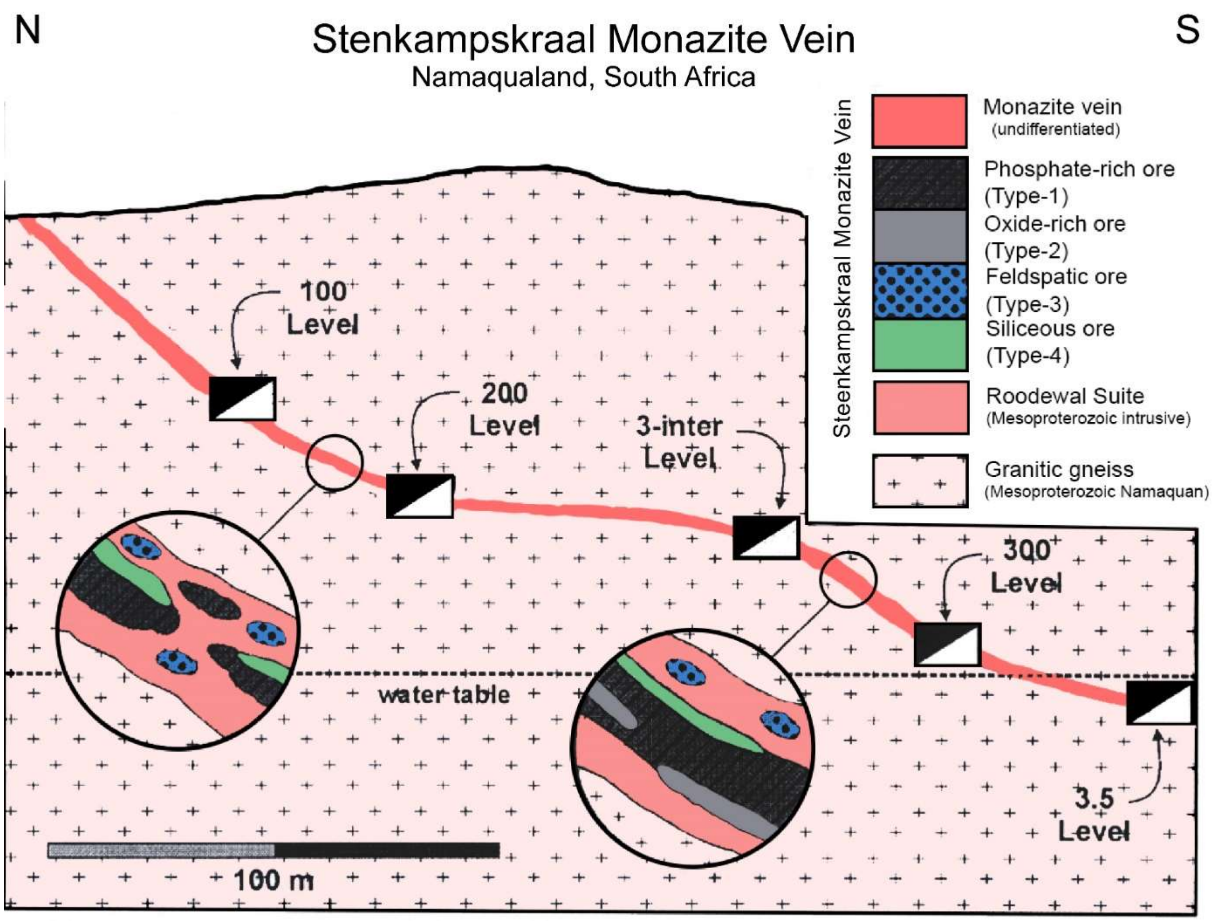

FIG. 31. Section showing the monazite vein, Steenkampskraal, South Africa (Reproduced with the permission of the European Journal of Mineralogy (www.schweizerbart.de/journals/ejm) [71].

The third major resource of thorium is the carbonatite of Palabora (Phalaborwa) in NE Transvaal. The peralkaline intrusive complex was emplaced at ~2 030 ± 18 m.y. in northeastern Transvaal, South Africa. In the central part, carbonatite and phoscorite form the Loolekop pipe (0.8 km by 1.4 km), which is intruded by a dike-like carbonatite. The intrusive complex carries apart from calcite (main mineral), magnetite, apatite and copper sulphides. Uranothorianite is the main Th- and U-bearing mineral. It is contemporaneous to magnetite, and, together with baddeleyite, was retrieved as heavy mineral and processed for uranium by-production, totalling 540 t U during 1994–2002, [14]. The uranothorianite contains more Th than U. With mean grade of 0.01% Th, the carbonatite likely contains ~10 500 t Th per 100 m of depth. Thorium was not recovered.

The alkaline syenite of Pilanesberg is known for its increased concentration of thorium. Total thorium resources of South Africa have been estimated in 2010 [16] at 148 000 t, of which 130 000 t are PR and 18 000 t Th RAR.

6.5.20. United Republic of Tanzania

Carbonatite bodies at Wigu Hill, Morogoro district and at Panda Hill are known for pyrochlore with Th; however, no economic studies are known. No specific information is available on the Songwe Scarp carbonatite. Placers with monazite occur in limited quantities.

6.5.21. Togo

Some indications for Th have been found in metamorphosed rocks of Proterozoic age.

6.5.22. Uganda

The carbonatite of Sukulu carries Th-minerals in residual soil, however not of economic interest (Fig. 32). The enrichment of thorium in the weathered part over carbonatite bodies seems to be similar to what has been observed in Araxa, Brazil and Impacto, Venezuela. As in other countries some placers carry monazite.

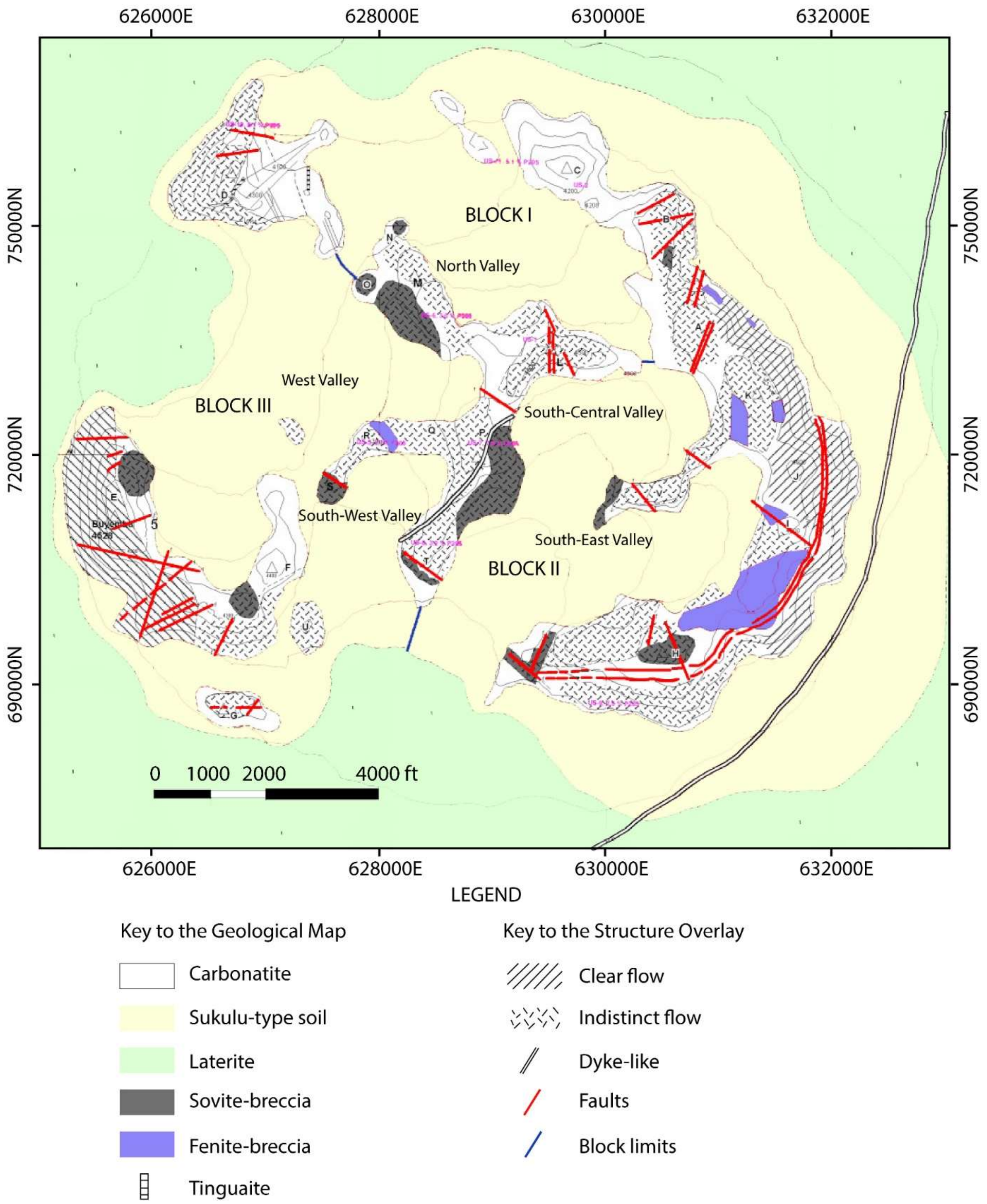

FIG. 32. Map of Sukulu carbonatite complex, Uganda (Presentation at the IAEA Technical Meeting on uranium from unconventional resources, Vienna, Nov. 2009) [72].

6.5.23. Zambia

Carbonatite rocks are found to have increased concentrations of thorium; however, they are not of any economic interest.

6.5.24. Summary for Africa

Thorium mineralisation occurs in various countries in placers, veins, carbonatites and granites. Resource estimates for thorium have been made for Egypt, Kenya, Malawi, Morocco, Nigeria and South Africa; however, in many cases estimates originate from the early years of observation (second half of 20th century). Figures therefore may be considered with caution.

Low grade concentrations of thorium-bearing minerals, mainly monazite, are reported both from the coast of the Gulf of Guinea and along the coast of Southeast Africa. Including low grade concentrations and not considering resource categories nor cost classes the total thorium resources for Africa are estimated at ~649 000 t Th. However, only a small portion (perhaps 5%) of the total could optimistically been recovered as by-product. In addition, thorium resources additional to the estimated total occur in various countries.

If commercial needs for thorium as a nuclear fuel would arise placer deposits already in operation e.g. in South Africa, would be an option of first importance. Once mining of the Steenkampskraal deposit starts its thorium resources may become of economic relevance, too.

6.6. ASIA

No detailed information on thorium was found for following countries: Afghanistan, Armenia, Azerbaijan, Cambodia, Georgia, Iraq, Israel, Japan, Jordan, Kuwait, Lao People's Democratic Republic, Lebanon, North Korea, Oman, Qatar, Syrian Arab Republic, Tajikistan, Turkmenistan, United Arab Emirates and Yemen.

6.6.1. Bangladesh

The Bangladesh Atomic Energy Commission has undertaken exploration for radioactive minerals in 1971 following the country's independence. As a result, heavy mineral deposits were found at the coast in the area of Cox´s Bazar and in the Ganges delta area (Fig. 33). A pilot plant was started at Cox´s Bazarin in 1975 with Australian assistance to investigate its economic viability, However, only small amounts of heavy minerals were produced. Plans for the erection of a commercial operation were not realised [73,74].

The composition of the heavy mineral sands varies between 7 and 42% of total heavy minerals, averaging 22%, with a low mean monazite content of less than 1%. The total tonnage of Bangladesh´s monazite resources were estimated at just over 17 000 t. In view of the low monazite content and the thorium concentration in the monazite these resources have very little economic significance [74]. Thorium resources are estimated at ~1 000 t.

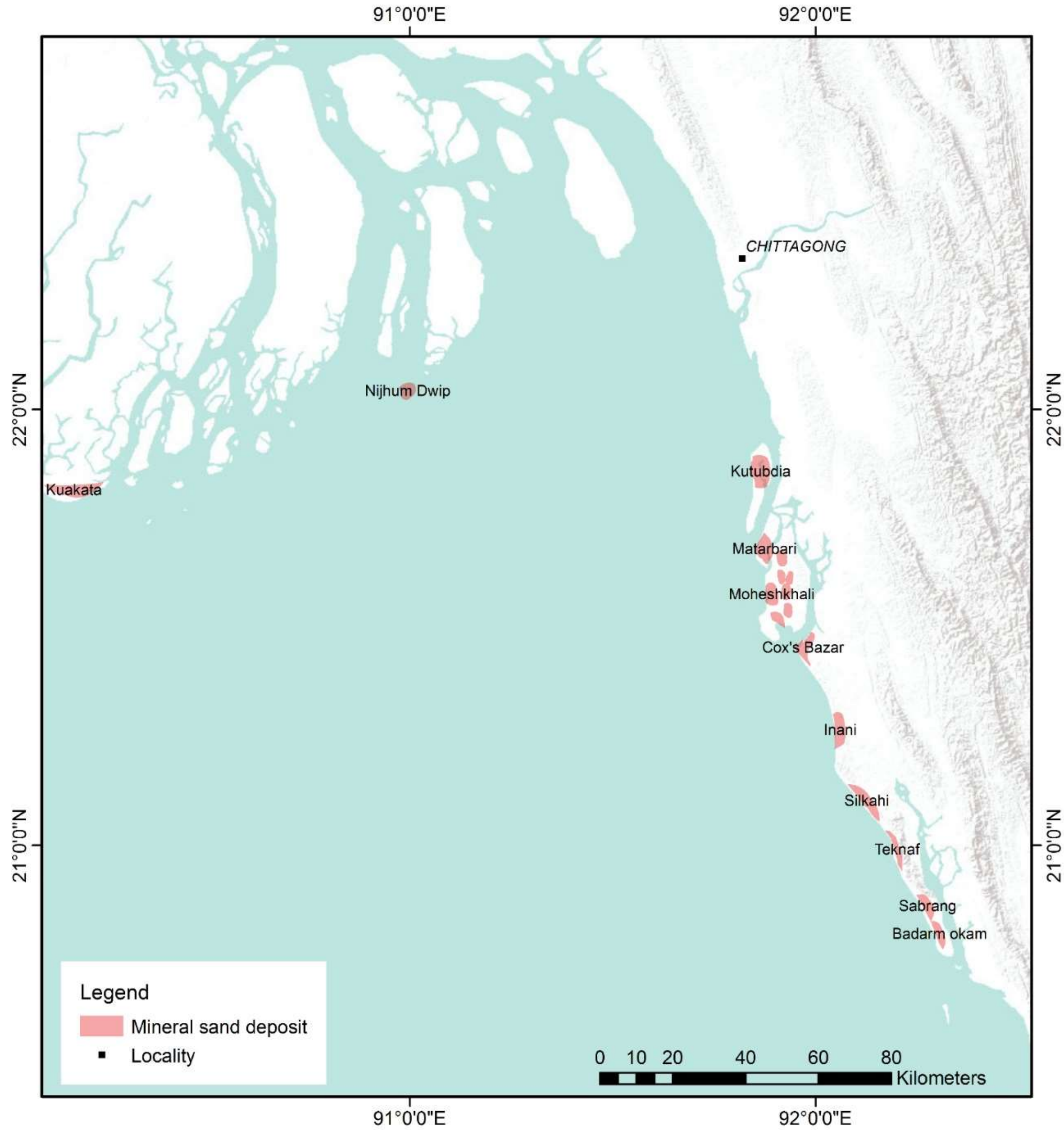

FIG. 33. Location of heavy mineral sand deposits, Bangladesh (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

6.6.2. China

In Inner Mongolia, the Bayan Obo deposit comprises an enormous polymetallic REE-Fe-Nb ore mineralisation, presenting the world´s largest accumulation of REEs (Fig. 34). At Bayan Obo, monazite, bastnaesite and huanghoite [Ba (Ce, La, Nd) $(CO_3)_2F$] the most abundant REE minerals. Thorianite and thorite are the chief thorium minerals. Thorium also occurs as isomorphic substitution in REE-fluorocarbonate minerals, REE-Nb minerals and aeschynite-type minerals. The deposit is situated on the northern edge of the Sino-Korean craton, close to the suture of the Caledonian subduction of the Mongolian plate beneath the craton [8, 75]. The host rocks of the deposit – dolomitic marble, quartzite and slate – have been metamorphosed before mineralisation (Fig. 35). Evidence for the epigenetic, hydrothermal and metasomatic origin of the ore deposit is provided by replacement textures [8, 76]. However, the complex type of mineralisation resulted in the proposal of a series of genetic theories. Similarities to deposits related to carbonatite or to the group of iron oxide Cu-REE-deposits have been found. Hydrothermal activity evidence ranges from 1.26 Ga to beyond 343 Ma. Radiometric U-Pb ages obtained from monazite and bastnaesite indicate that the episodes of REE mineralisation persisted for ~150 m.y. (555–395 Ma).

Bastnaesite, monazite and RE-bearing thorite have been reported to be important for the thorium content [8, 77]. However, there is lack of data on thorium content of the ore and a recent evaluation of the resources of this deposit. The bastnaesites and monazites in Bayan Obo ores characteristically contain very low U (<5 ppm) but contain up to 7000 ppm Th; however, lower concentrations were reported in other sources giving only 0.26% Th for monazite and 0.02–0.28% Th for bastnaesite. Ore and gangue minerals from Bayan Obo yielded Sm-Nd and Pb isotope data that support a crustal origin for the REEs [8, 78]. Geochemical data indicate an increase of Sr and light REE from dolomite through calcite-dolomite to calcite. The increases suggest a trend of evolution by crystal fractionation of magma of carbonatitic composition [78]. The rare earth and associated elements were scavenged from the underlying crust by acidic hydrothermal solutions activated by Caledonian subduction. The mineralisation is thought to be formed under multistage steps of fluid circulation [79].

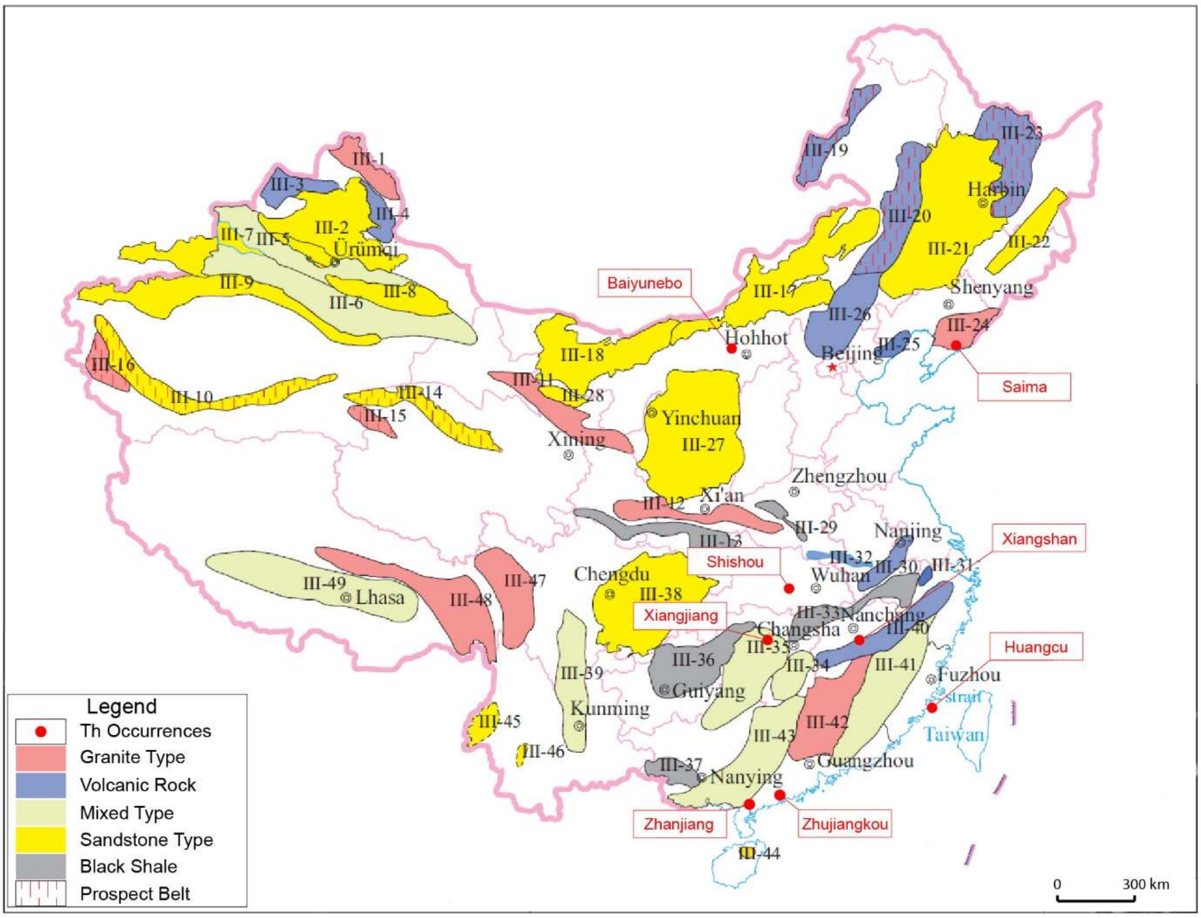

FIG. 34. Thorium occurrences in relation to Uranium provinces in China (modified after Z. Li et al) [80].

Many data suggest an evolution that is demonstrated by a multistage formational process. This would include a remobilisation of a Proterozoic alkaline/peralkaline (carbonatite) deposit by fluids generated by the Caledonian orogeny, or even the derivation of material from the upper mantle. As mentioned above, theories on the formation of Bayan Obo favour a carbonatite related model that is supported by geochemistry facts, stable isotopes and an alteration assemblage which resembles fenitisation.

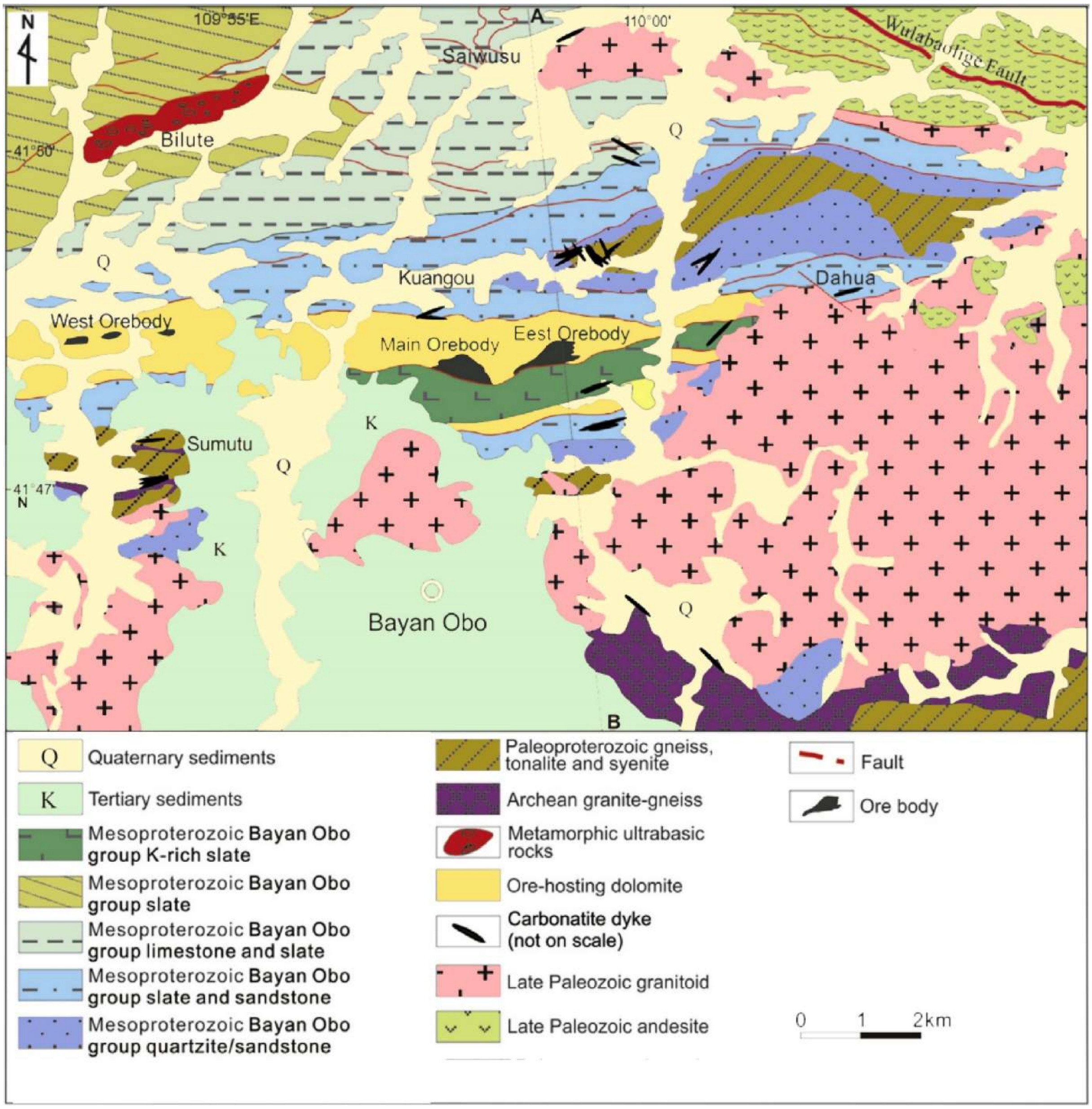

FIG. 35. Geological and structural map of the Bayan Obo ore deposit, Inner Mongolia, China, (modified after Hong Rui Fan et al, 2015) [81].

In various sources, some resource figures are given for the main commodities, however not for thorium. Ores of REO amount to ~40 Mt ore grading from 3–5.4% REEs. The huge reserves of niobium (>1 Mt Nb_2O_5) are not given in detail; however, it is noted that Bayan Obo is the largest niobium deposit in the world. The present mining activity reaches up to 1000 m in depth.

At present, 27 occurrences of carbonatite are known in China. They have been formed close to or at intraplate fractures [79]. A relation to major events of alkaline rock emplacement is manifested by most types. Three carbonatites were mined in 2005 for REE [82]. In addition, iron, phosphate and vermiculite are commodities of economic interest [79].

Monazite placers in southern China occur as extensive deposits in the Kwangtung Province and between Chianhua Hsien in southwestern Hunan and Kung Chen Hsien in northeastern Kwangsi [73]. In older publications, heavy mineral occurrences have been reported in the coastal area south of Shanghai, in the southern provinces of Guangdong and Guangxi and from the east coast of the island of Hainan (Fig. 36).

From Hainan the total monazite resources were reported as 60 000 t. Available data for the Beihai area in the Guangxi province indicate a monazite production of annually 70 t in the 1980s [49], whose thorium content was reported as 5.5% Th. Including estimated production data for all Chinese heavy mineral processing plants, a total of ~800 t monazite was reported for the early 1980s [74]. More recently, the processing may have been reduced or even terminated due to the huge Bayan Obo deposit. The lack of official figures both for the thorium concentrations and the thorium resources makes it difficult to estimate the thorium resources of China. The total may range between 100 000 and several 100 000 t Th.

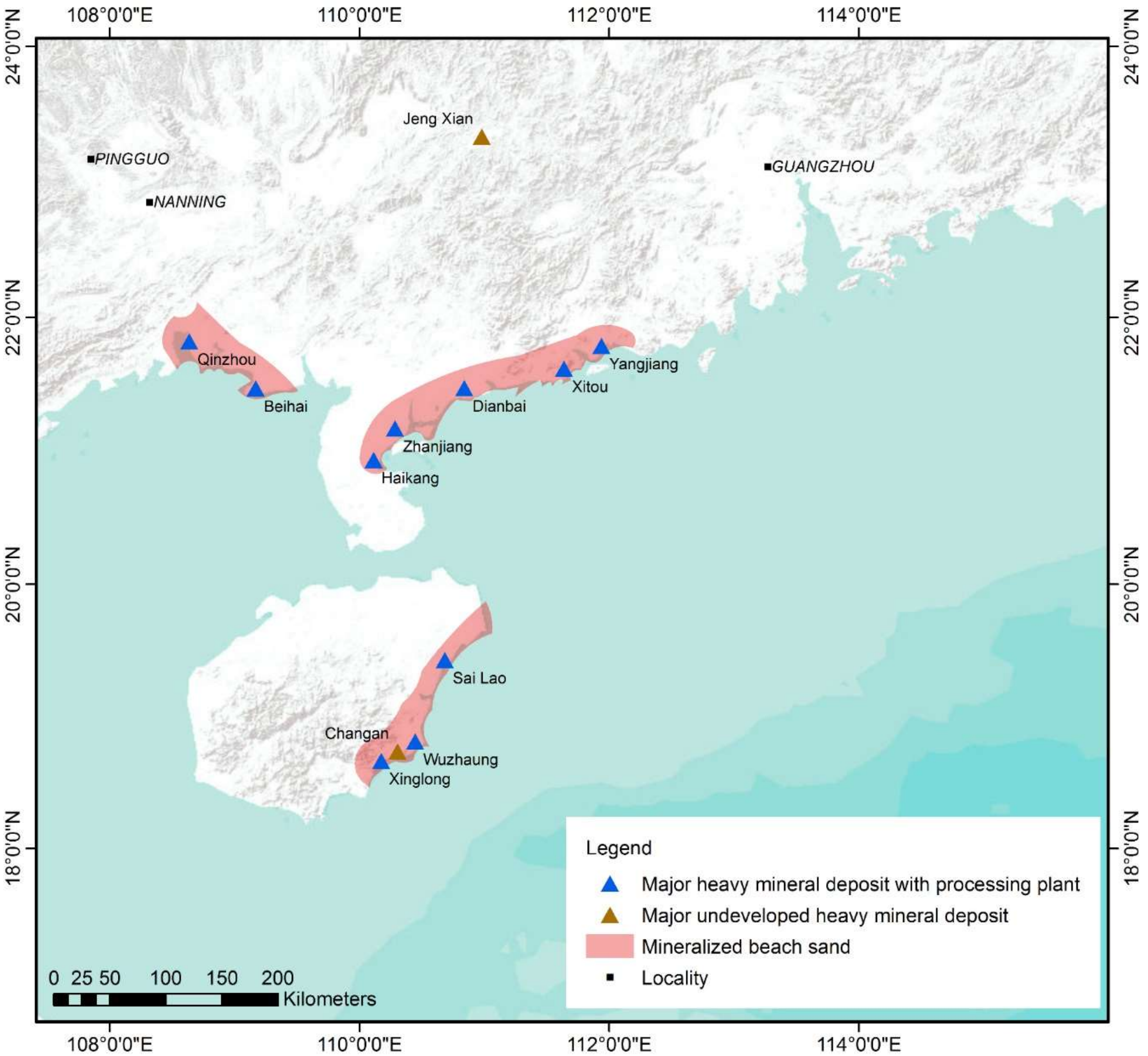

FIG. 36. Location of heavy mineral deposits, Guangdong and Guangxi Provinces, China (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

Offshore sand bars in the southwestern part of Taiwan, China contain monazite in the range of 12% of the heavy mineral fraction. The amount of monazite in the recoverable mineral concentrate is ~32 000 t of monazite [51]. The thorium content was not reported; however, the amount will be low. According to older reports (e.g. [74]), 200 000 t of heavy mineral sands containing ~4.4% monazite occurred in the country. Their resources are estimated at ~8 800 t Th.

6.6.3. India

6.6.3.1. Overview

The Special issue on "Beach and Inland Heavy Mineral Sand Deposits of India" – Vol. 13, Aug. 2001, published by the Atomic Minerals Directorate for Exploration and Research, under the title "Exploration and Research for Atomic Minerals" [83] contains a comprehensive overview of the placer deposits in India which in most cases contain thorium in the form of monazite occurring together with other heavy minerals like ilmenite, sillimanite garnet, rutile, leucoxene, and zircon. Based on older resource estimates, 4.5 Mt of monazite containing 7–9.2% Th, resulting in resources of 300 000–400 000 t Th were reported (Fig. 38). According to [84], total monazite resources amount to 7.99 Mt with mean concentration of 8–10% ThO_2 (7–9% Th) which in turn results in total resources of 559 300–719 100 t Th. According to [83], the thorium resources in India are 10.7 Mt of monazite containing 846 477 t Th (963 000 t ThO_2).

World Nuclear Association reported total reserves of 319 000 t Th. In July 2010, the same organisation reported 319 000 t of identified resources (i.e. RAR plus IR) [84]. The same amount was published in the Red Book 2010 edition [12]. Most publications refer to the amount of 319 000 t Th. During the Technical Meeting on World Thorium Resources organised in India (Trivandrum, Kerala 17–21 October 2011), Indian experts made presentations on thorium deposits and resources in India. The presentations were based on the estimates for monazite concentrations in heavy mineral sands (placers of inland and beach deposits) [83]. They point out the prime role of beach sands for the estimation of total thorium resources. According to [83] monazite as the prime mineral for thorium occurs in 104 placer deposits, of which 81 are classified as coastal beach and dune sand, 20 as inland Aeolian and 3 as riverine placer deposits (Figs 37, 38).

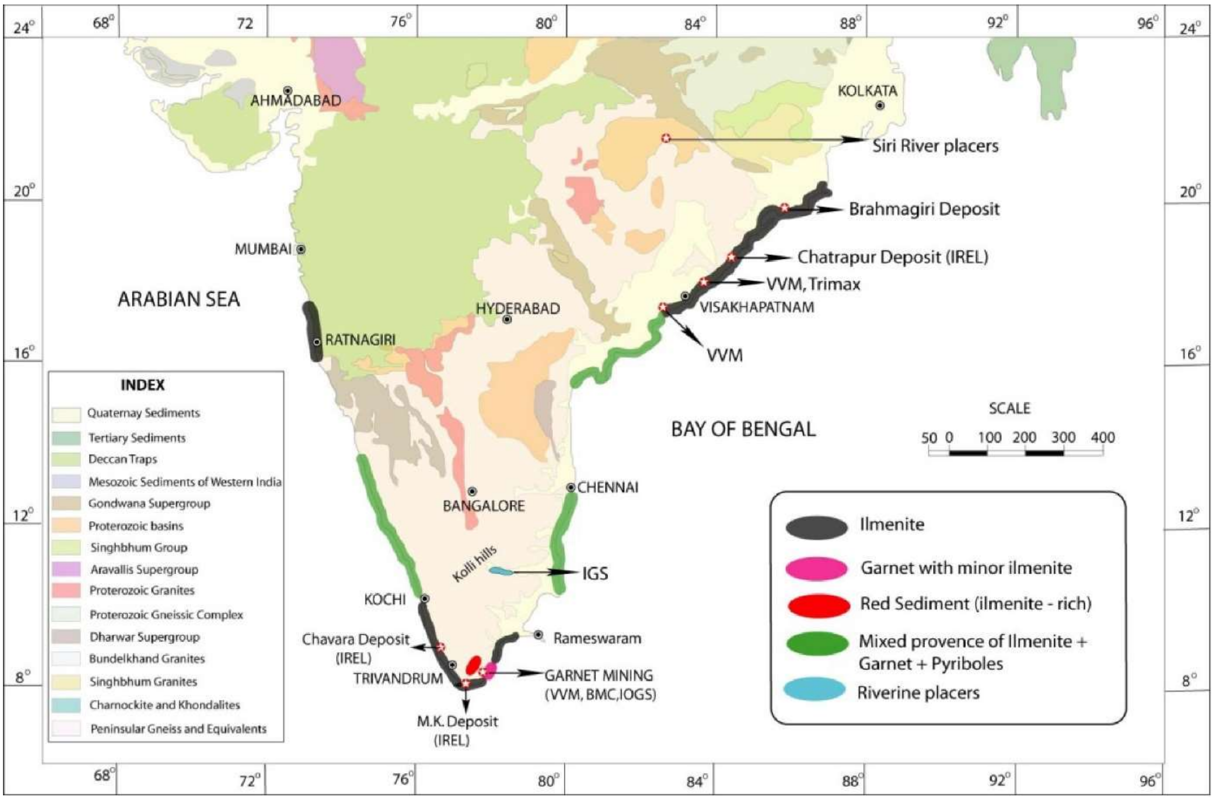

FIG. 37. Heavy mineral provinces and deposits of India (from P.B. Maithani, paper presented at IAEA Technical Meeting on World Thorium Resources, India, 2011) [84].

About 70% of the currently known monazite resources are located in deposits at the beaches, and ~30% are inland and sea-bed resources [85]. Thus, the potential areas at the extensive beach line of the country were investigated; however, not all beach areas could be explored in detail. Focus was put on the southwest coast (Kerala), southeast coast (Tamil Nadu) and the East coast in Andhra Pradesh, and Orissa (now Odisha). On average, the thorium content in monazite is 9–10% ThO_2; however, variations are frequent. The total of heavy minerals amounts to 948.16 Mt. More than half of it is ilmenite (504.31 Mt), followed by sillimanite (195.85 Mt), and garnet (154.26 Mt). Zircon (32.28 Mt) and rutile (29.11 Mt) represent the minor heavy minerals, together with monazite (10.7 Mt). In the 10.7 Mt of monazite recorded in 2011, the estimated total thorium content is 846 477 t Th [84]. For details see Table 9. All of the heavy minerals mentioned are of economic value.

Both ilmenite and rutile are sources for the manufacture of titanium oxide (white pigment), and for titanium metal/alloys. Sillimanite is mainly used for the manufacture of refractories. Garnet has a wide application, e. g. for the manufacture of abrasives, polishing, sand blasting and waterjet cutting. Zircon is used in foundries, ceramics, and refractories. Zirconium oxide is the source for zirconium metal/alloys and finds application in the chemical and nuclear industry (zircalloy).

6.6.3.2. Geology of deposits

In India, exploration for thorium was mainly a part of exploration for heavy minerals. Several deposit types were outlined [86] and grouped according to their mode of occurrence into:

- Shoreline/alluvial//inland aeolian placers;
- Igneous bodies (alkaline and carbonatite complexes, alkali granites);
- Pegmatite and vein deposits;
- Iron oxide breccia type and metamorphic rocks.

The most important and economically relevant type is the shoreline placer deposit.

6.6.3.3. Heavy mineral deposits (placers)

In general, the mineral assemblage of heavy mineral deposits consists of ilmenite, sillimanite, garnet, zircon, rutile and monazite (REEs, thorium) with varying amounts of magnetite. The sources for the heavy minerals vary from deposit to deposit, depending on the lithological composition of the hinterland. As a general rule, heavy mineral accumulations at the coast have been derived from highly metamorphosed rocks outcropping in the hinterland, e.g. charnockites and lepytinites. Granites of special composition and tertiary sedimentary rocks are also found in the hinterland. Generally, the source rocks are subject to deep tropical weathering (lateritisation), from which the heavy mineral fraction is transported by action of denudation (fluvial, pluvial, and aeolian).

Coastal placers are best developed along the beaches of the states of Kerala, Tamil Nadu, Andhra Pradesh and Odisha. Exploration of beach placer deposits is limited to a depth of 10 m, thus the deeper parts are yet to be explored [83]. On the west coast, in Kerala and on the southwestern coast of Tamil Nadu beaches are narrow or barrier deposits appeared with the development of dunes generated by prominent aeolian action during dry months, whereas on the east coast, in the states of Tamil Nadu, Odisha and Andhra Pradesh, beaches are well developed and extend over several kilometres width with a well-developed dunal system.

The placer deposits north of Trivandrum at Chavara, Kerala, occurring in the Kayamkulam–Neendakara Sector, are considered as one of the major sources for thorium. The deposit is separated into several blocks, some of which are located inland and others immediately at the beach (Fig. 39). Presently, around 820 000 t of monazite are recorded from different blocks, representing ~73 500 t ThO_2 (64 700 t Th). The heavy minerals of these placers are derived mainly from high grade metamorphosed and sedimentary rocks of the hinterland [3, 83].

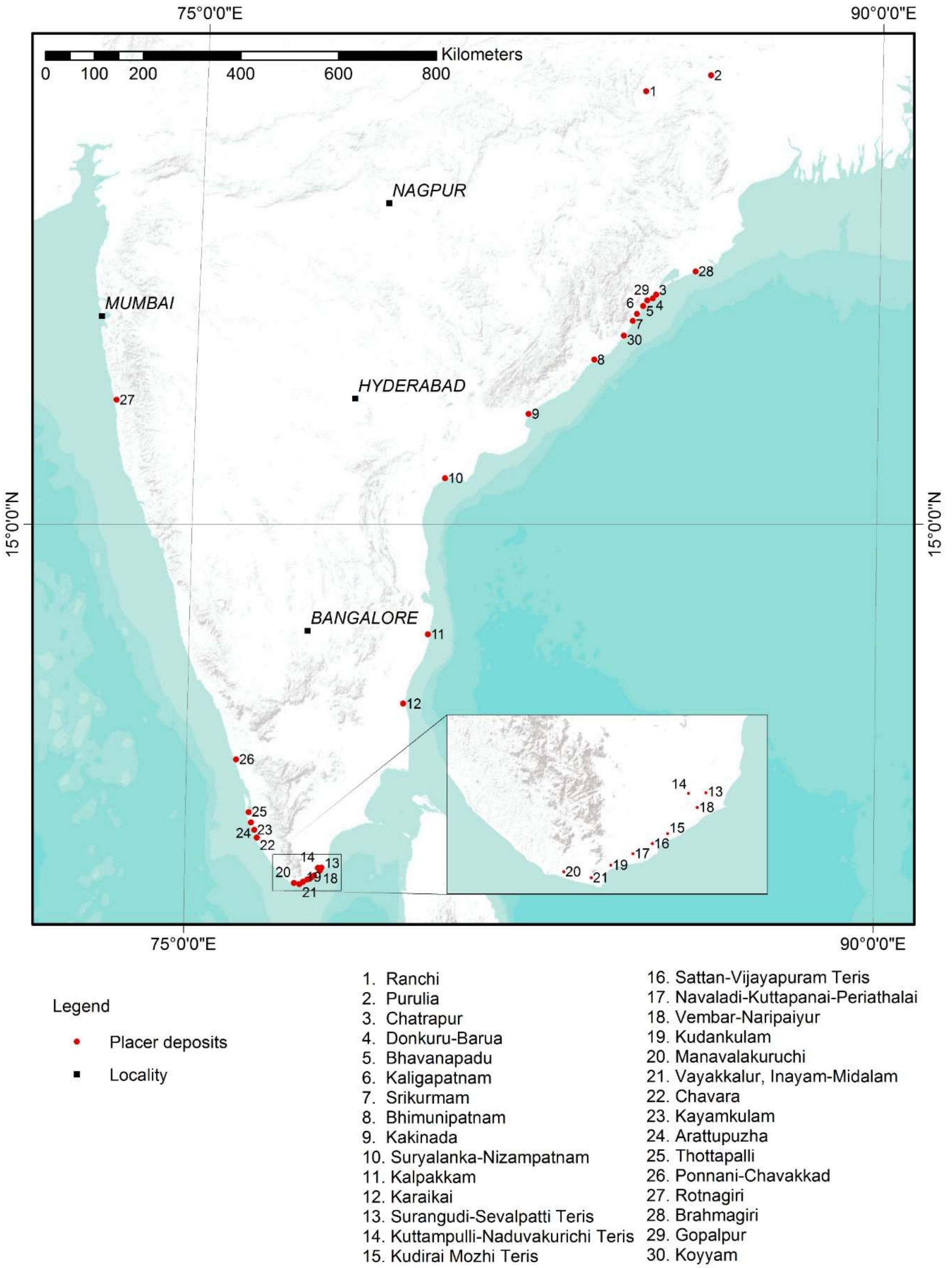

FIG. 38. Major Beach and Inland Placer deposits of India (Based on R. Dhana Raju et al, 2001) [83].

The Manavalakurichi deposit, in southwestern Tamil Nadu (Fig. 40), has a monazite content of up to 2% with a mean of 0.9%, and is rich in Th with 8–9% [83]. Near Manavalakurichi, at the mouth of the Valliyar River, placers of monazite are generated by aeolian action on the beaches particularly during the dry season. Manavalakurichi has ~125 000 t of monazite and was estimated to contain around 9 900 t of thorium. The heavy minerals originated primarily from Archean high grade metamorphic and tertiary rocks, which were transformed to laterite [83]. Participants of the Technical Meeting in Trivandrum in 2011 had a chance to visit the deposit of Manavalakurichi. The deposit consists of several blocks, of which some are located behind the beach blocks.

On the east coast of India, monazite concentrations are associated with extensive dunes fringing the coast in Andhra Pradesh, the Eastern part of the Tamil Nadu, and the Odisha (former Orissa) states [8; 83]. Deposits in Andhra Pradesh are considered as the largest in terms of total monazite tonnages, however are rather low in monazite concentrations (0.04–0.22% monazite), compared to Tamil Nadu and Kerala concentration is ~3000 ppm in sediment, with a mean concentration of 60 ppm. At Chatrapur in the Odisha state, where monazite content is 0.24%, the deposit is being mined by IREL. Recently, a new deposit has been established at Brahmagiri near Puri, Odisha (Fig. 39, 40) containing 610 000 t of monazite at a mean of 0.06% monazite (Fig. 41).

Offshore placers are known in India 600 m offhore from the Neendakara-Kayamkulam bar over 22 km length with 0.05% monazite at 8.3% Th [8; 83] and offshore from the Manvalakurichi coast.

Inland deposits of monazite are characterised by Teri sands (red sand dunes), located 100 m to 20 000 m inland. The accumulation of heavy minerals is the product of residual weathering (lateritisation), and fluvial transportation at gentle slopes. The light fraction of the mineral suite was largely decreased by aeolian action. The inland teri sands commonly contain 8–10% total heavy minerals with a few exceptions of up to 35% concentration. The monazite content in the teri sands ranges from 0.01–3% [87]. ThO_2 grades of teri sands may be higher (9–12%) compared to beach deposits. Teri sands contain ~15% (130 000 t Th) of India´s thorium resources.

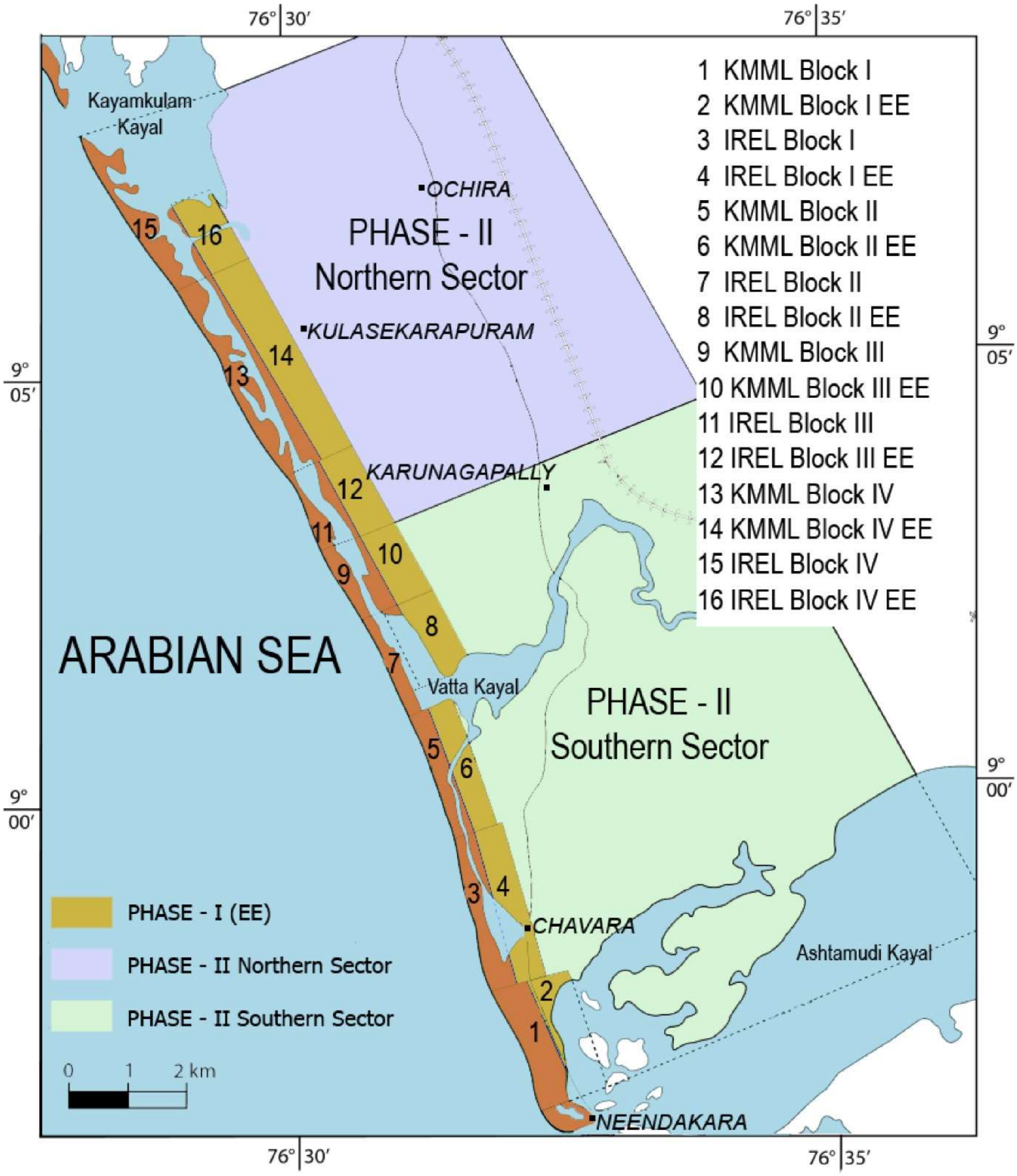

FIG. 39. Map of Kayamkulam–Needakara sector, India (from P. B. Maithani, paper presented at IAEA Technical Meeting on World Thorium Resources, India, 2011) [85].

State-wise, India's thorium resources can be separated as follows: Andhra Pradesh 36%, Tamil Nadu 20%, Orissa 17%, Kerala 14%, West Bengal 11%, and Bihar 2%. Of the estimated total of 846 477 t thorium in India ~493 000 t (~58%) are identified resources, the majority of which (~68%) are in beach placers. Undiscovered resources amount to ~353 000 t Th, of which ~ 2/3 are in beach deposits. According to [84] India's undiscovered resources are equal to IR. Assuming 15% losses for mining, milling and processing, recoverable identified resources will amount to 419 000 t Th. This amount is 100 000 t more than the reported resources in the Red Book 2009 edition of 319 000 t Th recoverable at costs up to US$ 80/kg Th.

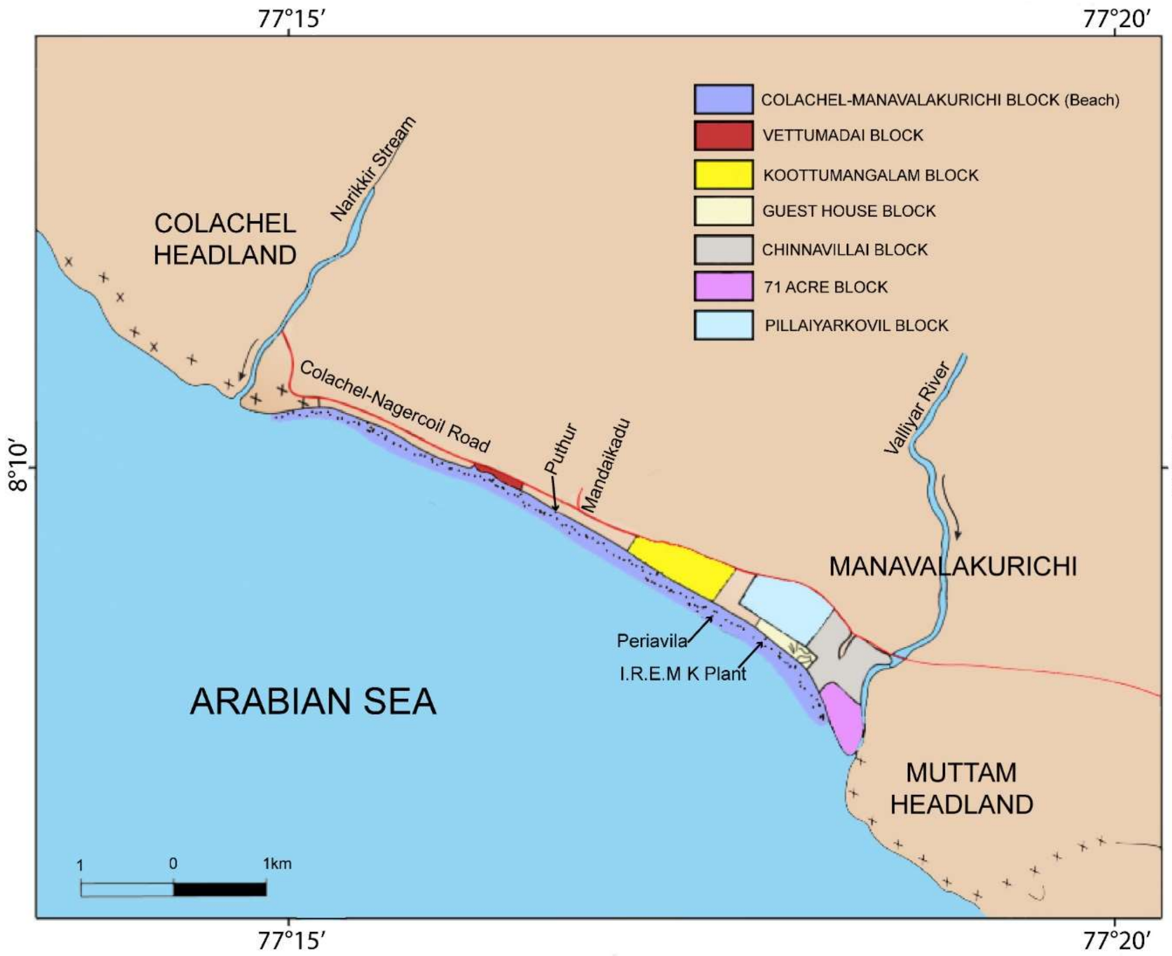

FIG. 40. Map of Manavalakurichi sector, India (from P. B. Maithani, paper presented at IAEA Technical Meeting on World Thorium Resources, India, 2011) [85].

TABLE 9. THORIUM RESOURCES IN INDIA [82]

State	Beach placer identified resources* (indicated resources), 1 000 t Th	Beach placers undiscovered resources*, (inferred resources) 1 000 t Th	Inland identified resources* (indicated resources), 1 000 t Th	Inland undiscovered resources* (inferred resources) 1 000 t Th
Kerala	85.6	33.8	--	--
Tamil Nadu	37.9	1.9	129.7	1.3
Andhra Pradesh	64.1	202.5	29.3	--
Odisha	146.4	--	--	--
West Bengal	--	--	--	96.5
Bihar	--	--	--	17.4
Total	334.0	238.2	159	115.2

*According to S. Chandrasekaran [88] identified resources should be classified as INDICATED and undiscovered resources as INFERRED.

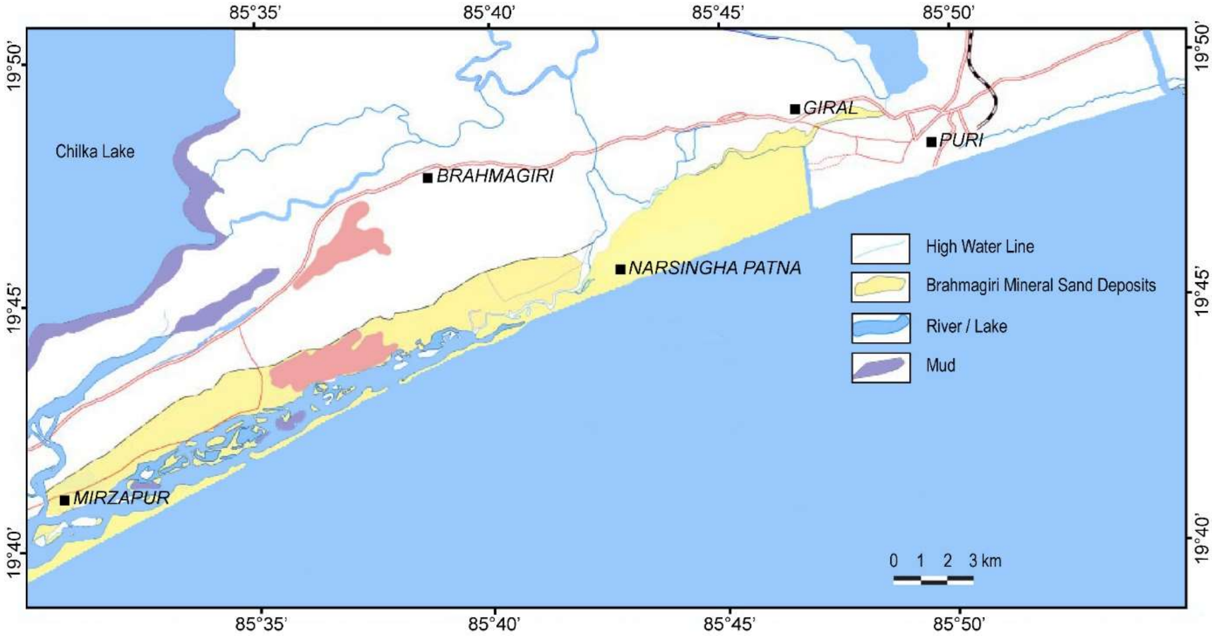

FIG. 41. Map of Brahmagiri deposit, Odisha, India (from P. B. Maithani, paper presented at IAEA Technical Meeting on World Thorium Resources, India, 2011) [85].

6.6.3.4. Other types of deposits

Apart from heavy mineral deposits in placers alkaline rocks, carbonatite (Fig. 41, 42), pegmatite, veins and sedimentary occurrences were explored. Several of these were found to have thorium mineralisations, however systematic evaluation needs to be done [82]. More than 24 carbonatite-alkaline complexes were found (Fig. 42).

Veins in the Samchampi Alkaline Complex in Assam, Northeast India (Fig. 43) were found to have 10% Th. A number of pegmatites and hydrothermal veins, related either to acidic intrusions, carbonatites or high grade metamorphic rocks, carry thorium together with Li, Be, Nb, Ta. Their potential is yet to be investigated.

Indian coal with high ash content (35–50%) may be regarded as a potential low-grade source for thorium [89].. Extraction of heavy minerals is undertaken at several locations along the beaches of the states of Kerala, Tamil Nadu and Orissa. Sales products are ilmenite, rutile, zircon, garnet, sillimanite, and monazite. Thorium is extracted from the monazite in special plants by chemical treatment, by which a separation of the suite of REEs and thorium is undertaken. The thorium cycle includes manufacturing of thorium nitrate for the fabrication of gas mantles and various reactor-grade thorium fuel compounds. Thorium fuel is the preferred option for nuclear reactors in India because of large thorium resources compared to the modest uranium resources.

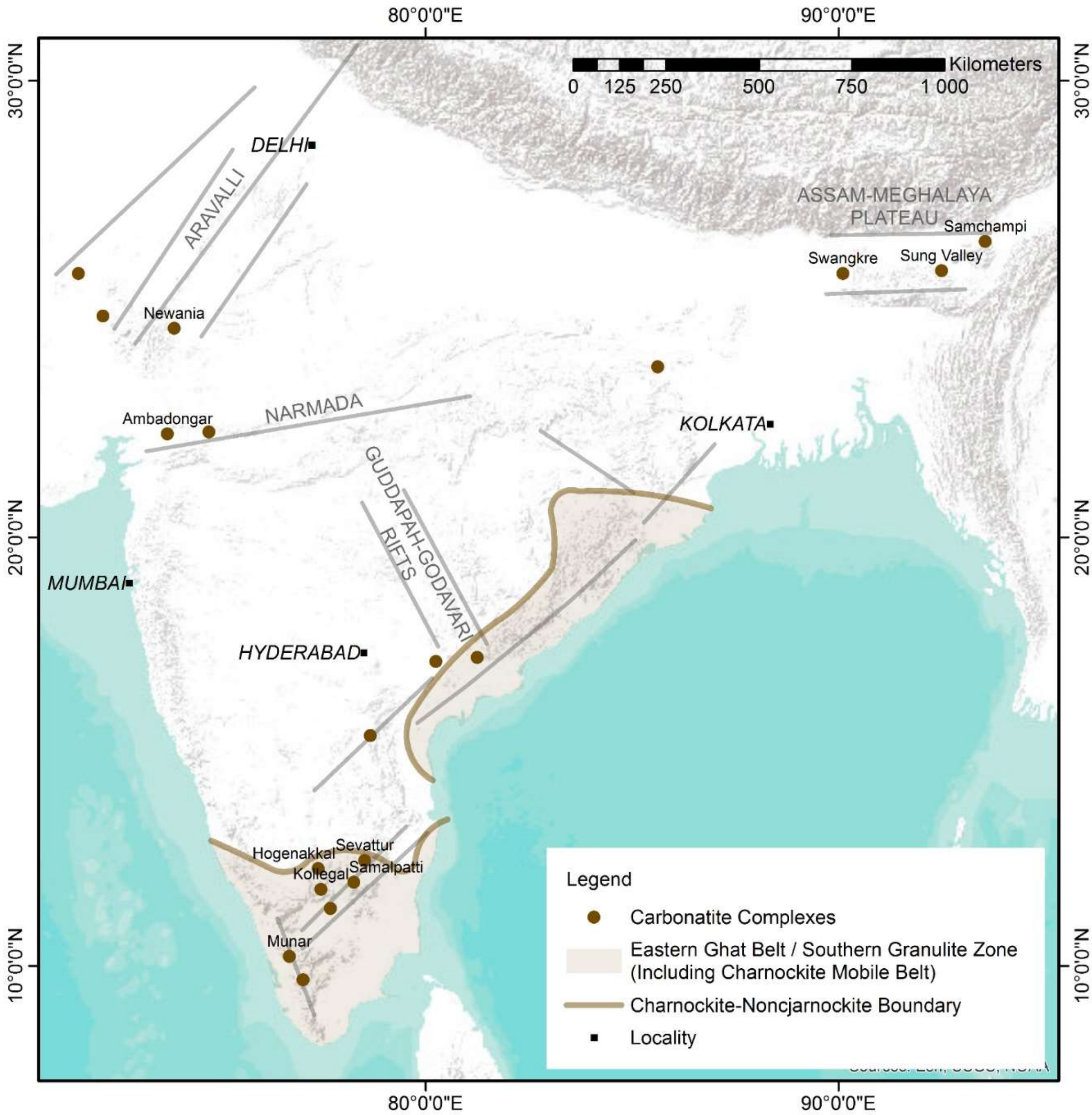

FIG. 42. Carbonatite Complexes of India: (Based on Krishnamunthy et al, Economic aspects of carbonatites in India, 2000) [90].

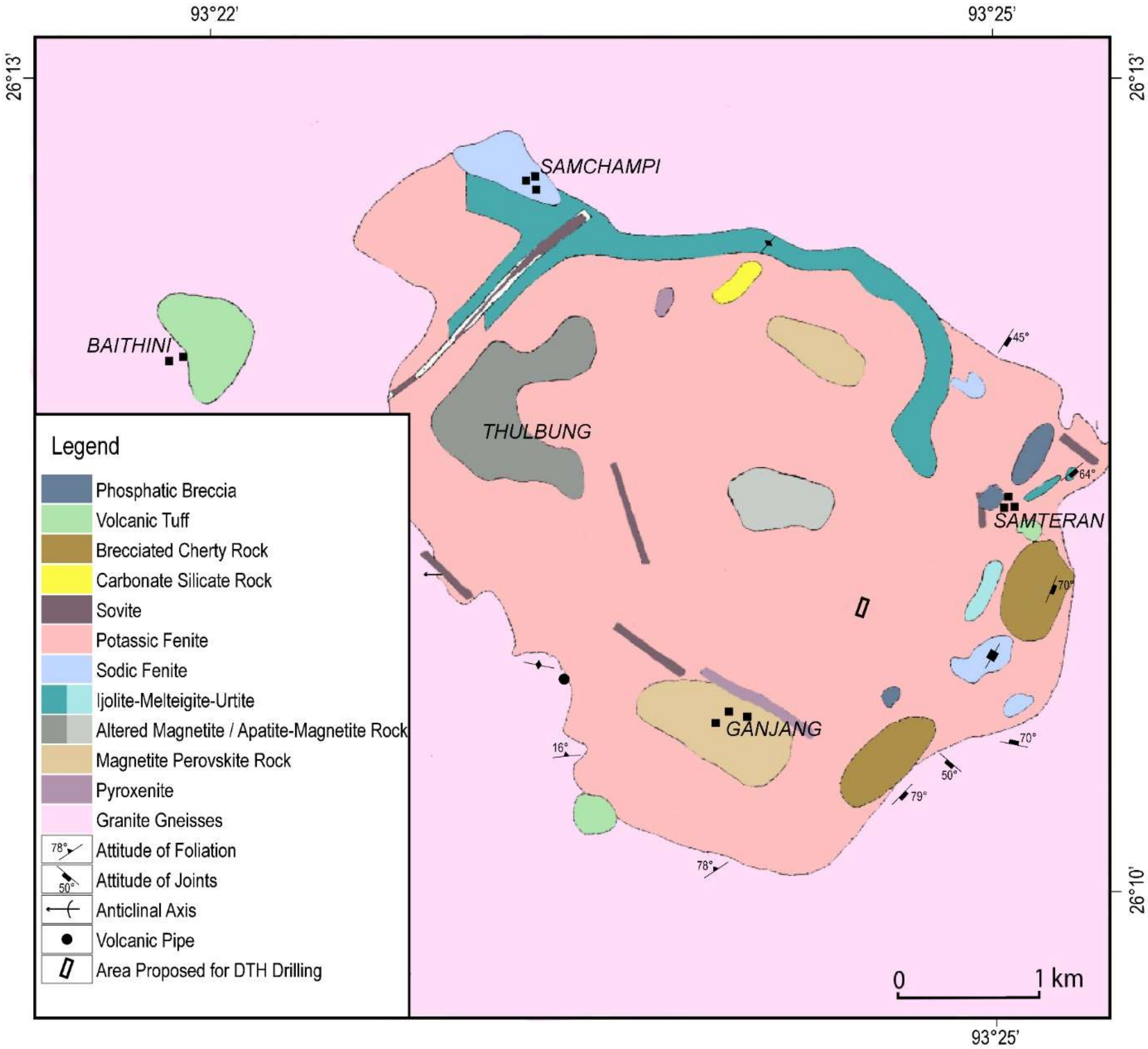

FIG. 43. Geological map of Samchampi alkaline complex, India (from P. B. Maithani, paper presented at IAEA Technical Meeting on World Thorium Resources, India, 2011) [85].

6.6.4. Indonesia

Alluvial mining of tin ore started in the early 18th century on the island of Bangka. Monazite is known to be associated with the tin ore and a total of 1 431 t of monazite was recovered as a by-product in the 1930s. According to [91], 1 570 t monazite was extracted from 1936 to 1938. Some of the monazite is reported to contain>5% Th. Consequently, exploration by the Indonesian Geological Survey led to the discovery of several heavy mineral concentrations in coastal areas of Bangka and Belintung islands (Fig. 44, 45). Most of them contain mainly iron ore apart from tin ore.

Most complexes are of Mesozoic age and only few are assigned to Precambrian age [91]. Further investigations pave the way for the discovery of elevated concentrations of thorium and uranium in the Tanjung Pandan granite of the Kelapa Kampit Formation (Triassic-Jurassic) (Fig. 46). Thorium ranges between 55 and 610 ppm and uranium between 10 and 77 ppm [91].

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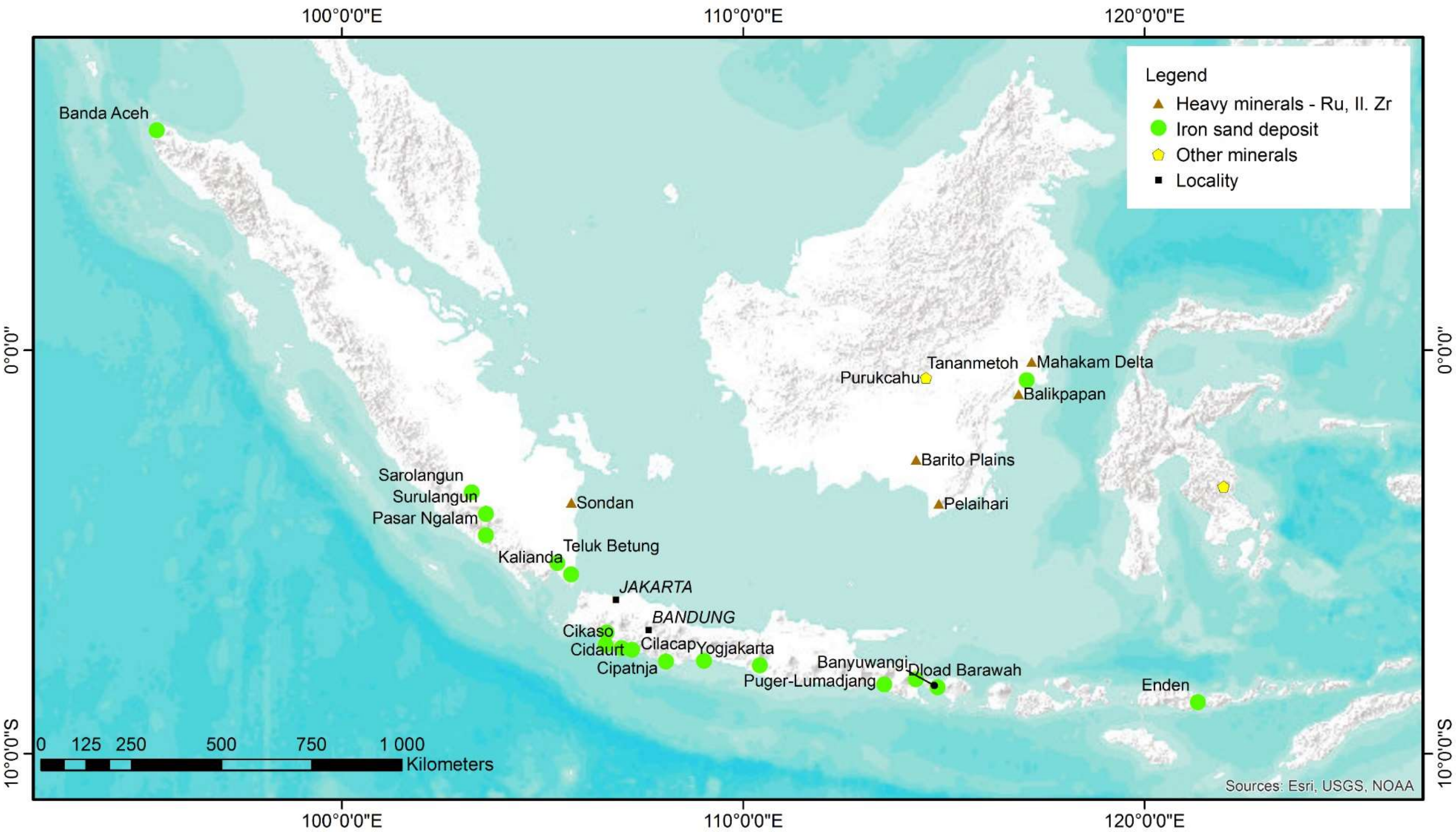


FIG. 44. Location of heavy mineral deposits, Indonesia (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

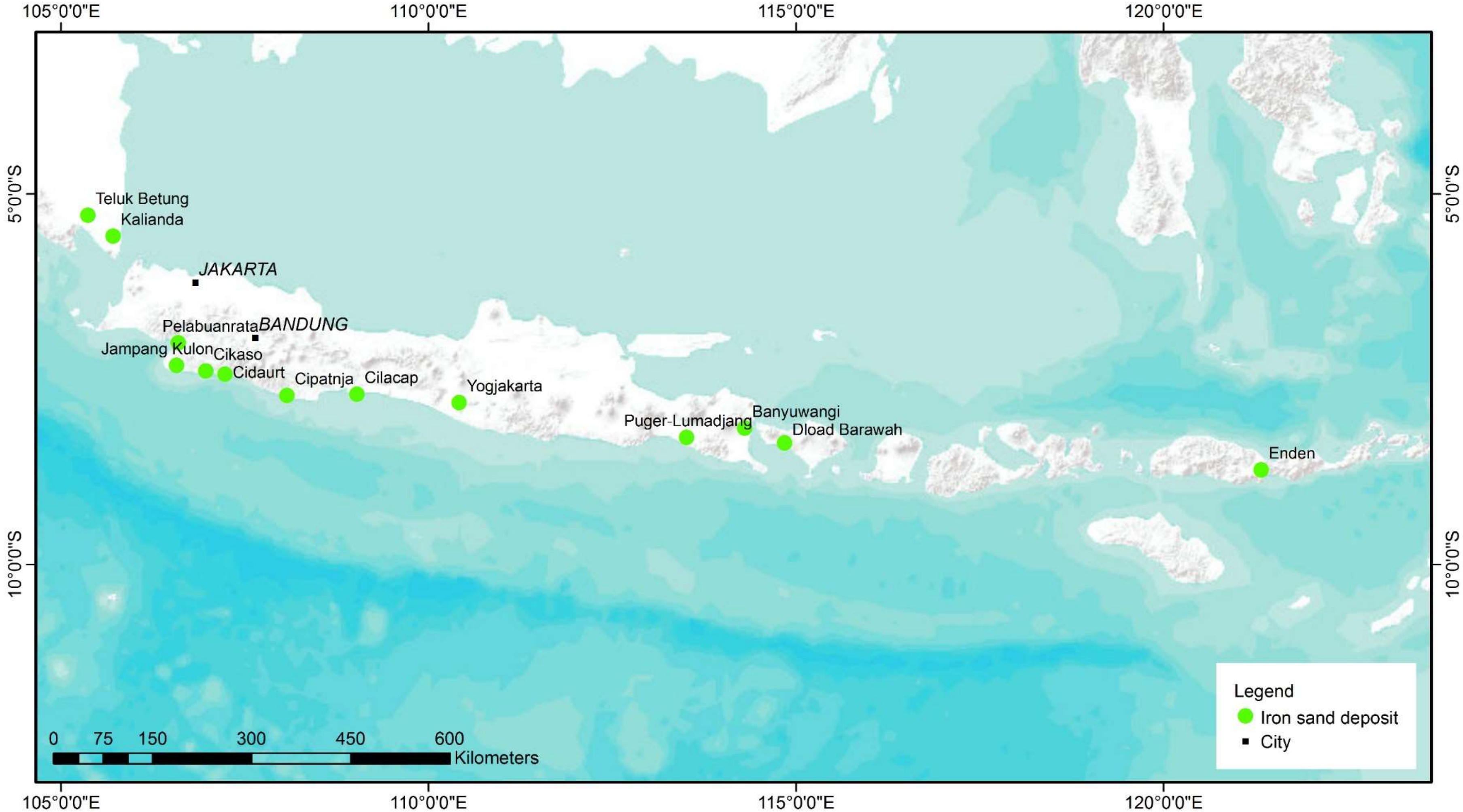


FIG. 45. Location heavy mineral deposits of Java, Indonesia (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

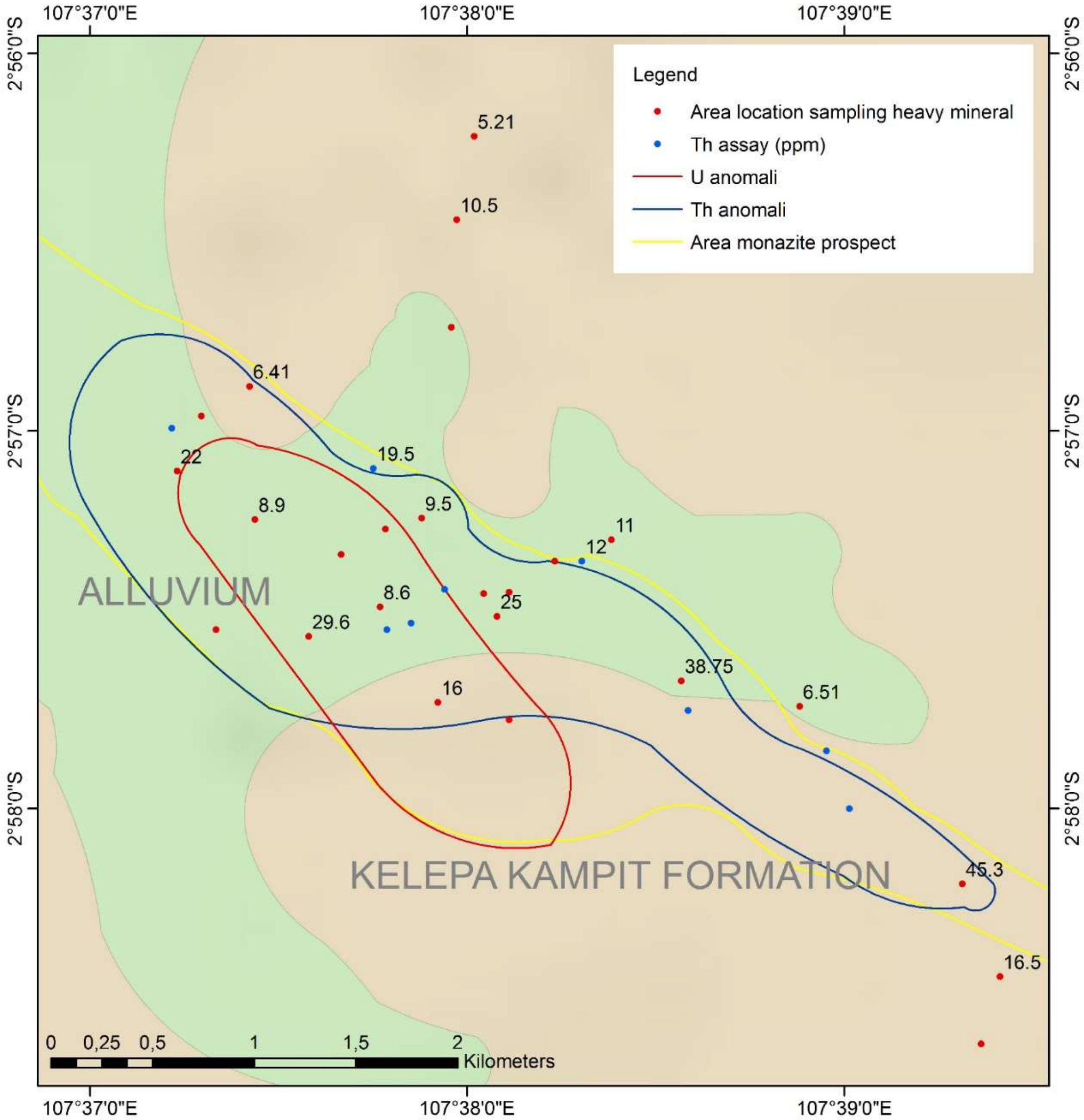


FIG. 46. Map of Placer alluvial sediments, Tumbang Rusa area, Belitung Island (Modified from paper presented at IAEA Technical Meeting on World Thorium Resources, Oct. 2011, India) [91].

Monazite-containing heavy mineral sands were reported from a number of locations at the coasts of Sumatra and Kalimantan and from the Momi River in Irian Jaya. From none of the locations neither data of the monazite resources nor the thorium content is reported.

6.6.5. Iran, Islamic Republic of

Igneous alkaline intrusions with ~30 000 t Th of unspecified category were reported in the 1970s. The mineralisation belongs to the igneous rocks suite in northern Azerbaijan, ranging in composition from granite to syenite. The presence of thorite, zircon and rare earth minerals was reported to be mapped in a well-defined ‘thoriferous province’.

6.6.6. Kazakhstan

An unnamed/undisclosed locality of an alkaline granite massif carries vein-type mineralisation of unusual combination of various base metals, uranium and thorium. The description indicates that the deposit might be the multi-element vein-type deposit of Zaosernoe. In addition to uranium, for which mining has been carried out, the ores of Zaosernoe contain fluorite, apatite and thorite. According to [15], concentrations of Th vary between 0.02 and 0.1%, up to 0.2% Th. Presently, the deposit seems to be dormant as large uranium deposits amenable to ISL are in operation in the south of the country. The location of a REE, thorium and iron mineralisation in fractures of a leucocratic granite is not disclosed. The mineralisation is multistage as adjacent massive magnetite, ferrithorite and monazite is reported [15].

6.6.7. Korea, Republic of

The Republic of Korea is one of the few countries were past monazite production from heavy mineral sands is reported [3, 14]. The Republic of Korea hosts a number of monazite deposits, both alluvial inland and at the coast (Fig. 47) [74]. Starting in the late 1940s with minor annual amounts, the maximum was reached between 1951 and 1958 with a total of ~5000 t of monazite. In later years, production dropped to ~10 t of monazite per year and ceased in the 1970s. A total of ~150 000 t of monazite was reported in the 1980s, with the largest deposit having 48 000 t of monazite [14]. Assuming grades of mean 4% thorium in the monazite, the total thorium resources amount to ~6000 t thorium. No information could be obtained on the content of thorium in the monazite nor on any extraction of thorium.

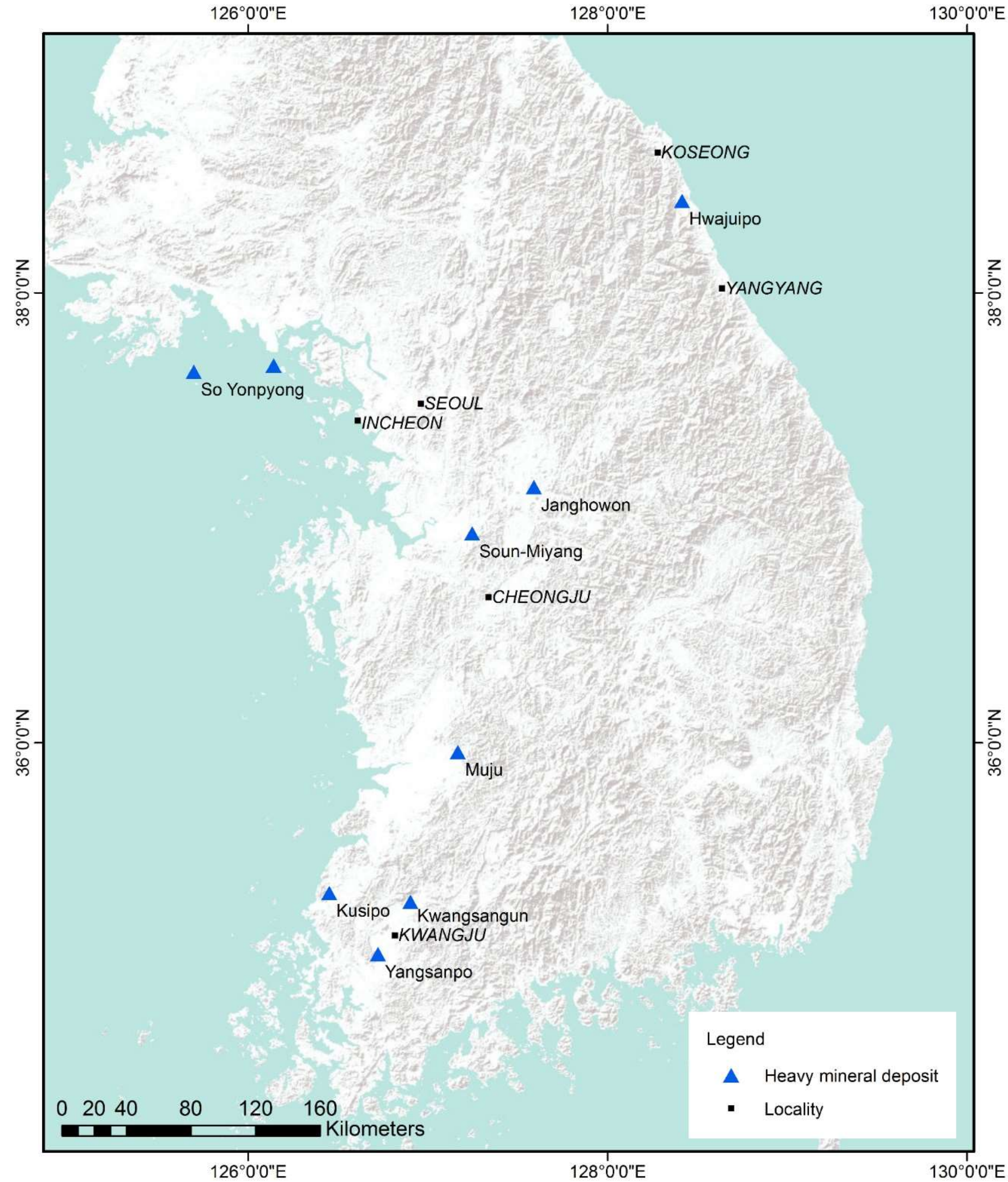


FIG. 47. Location of heavy mineral sand deposits, Republic of Korea (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

6.6.8. Kyrgyzstan

Two deposits located in the Tian Shan mountains, Kutessay and Aktuz, are known to exist in alkaline rocks. In Kutessay monazite and thorite were found. However, no details are available. Both deposits are listed in the ThDEPO database. Lack of specifics on concentrations and resources of individual deposits makes it difficult to estimate total resources. In view of the size of the country resources of unspecified categories may be significant.

6.6.9. Malaysia

The radioactive minerals monazite and xenotime occur together with tin ore and other heavy minerals inland in alluvial deposits, mainly close to underlying granitic intrusions (Fig. 48) [3, 92]. During the process of tin ore and ilmenite recovery, radioactive minerals are concentrated in the ‘amang’ (rejects of tin ore recovery) [92]. Beside monazite (0.5–1% in ‘amang’), the main carrier of thorium, the minerals xenotime (0.5–4% in ‘amang’), zircon and ilmenite were found to contain thorium in varying amounts. Investigations have shown the thorium content in monazite was between 6.05 and 6.78%, in xenotime 0.61–0.76%, in zircon 0.15–0.18%, and in ilmenite 302–605 ppm Th.

At several locations ‘amang’ is treated to recover remaining valuable ore mineral. In some of the ‘amang’ treatment plants, e.g. at Ipoh, Province of Perak, thorium was separated from the REE concentrate in order to sell non-radioactive products. between 1985 and 1994 [92]. Thorium was precipitated as thorium hydroxide as waste (30–32% Th).

The total recovery of monazite amounted to approximately 60 000 t up to the mid-1980s. It dropped to around 500 t annually at the beginning of the 21st century. During the period 2003–2007 production of monazite concentrates amounted to ~4 500 t and fluctuated between 320 t (2005) and 1 683 t (2004) [100]. The present resources of thorium are not available in official reports. They were estimated at 18 000 t Th.

Facilities in Malaysia will be used for treatment of rare earth minerals originating from operations at Mt. Weld in Western Australia. It is planned to store resulting ‘thorium waste’ locally [92], however research and development is required to solve problems related to the radioactivity of the waste. The capacity of the plant is 60 000 t waste per year.

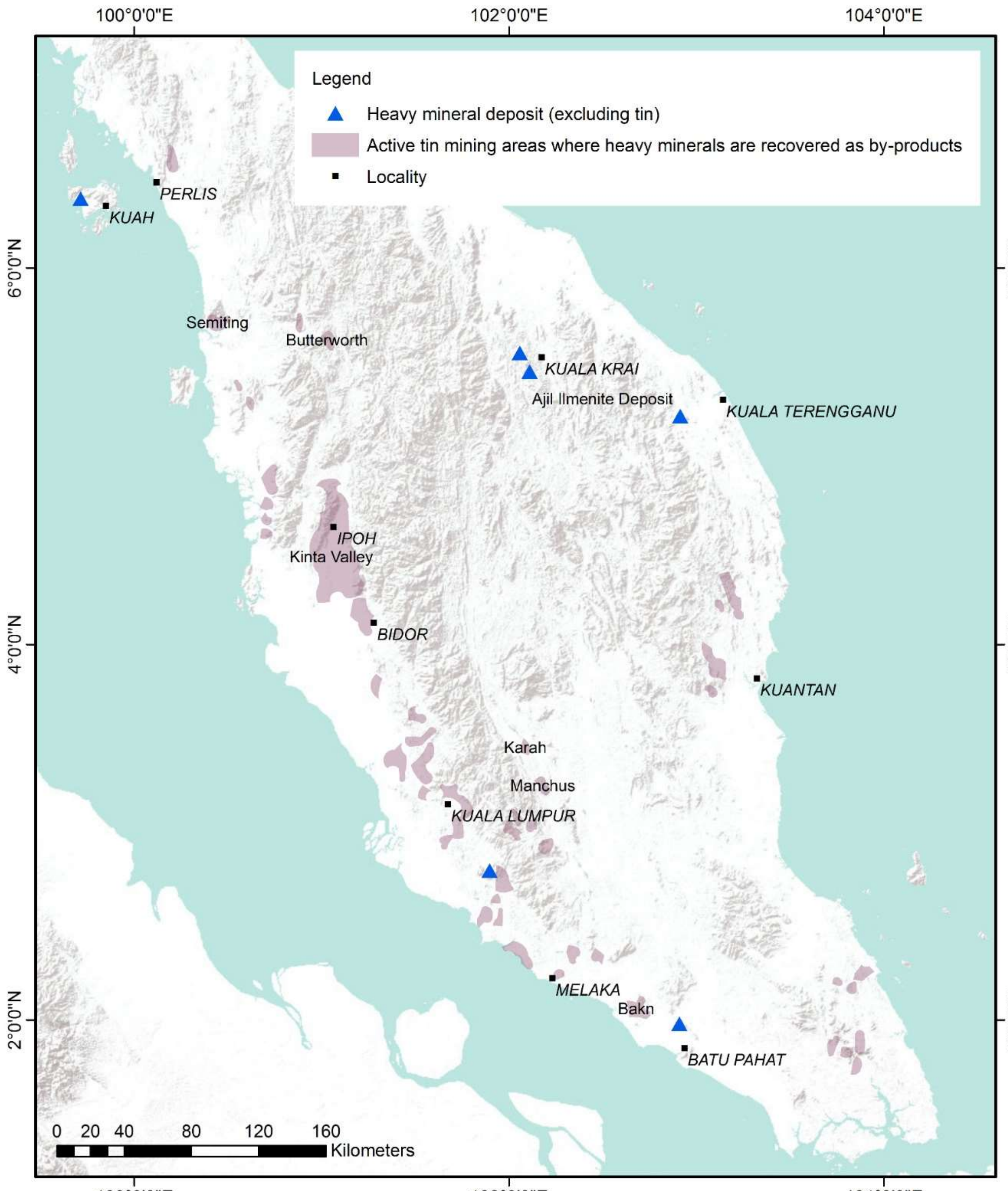


FIG. 48. Location of heavy mineral deposits, Malaysia (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

6.6.10. Mongolia

In the Mongolian part of the Altai Mountains alaskitic intrusions are reported, indicating the existence of potential rare metal mineralisations, including thorium. Carbonatite intrusions were reported to contain thorium; however, no details for the occurrences mentioned are available.

6.6.11. Myanmar

The tin mining district of Tenasserim in the southern part of the country may carry in its heavy mineral products some monazite; however, no details are available. In the country several intrusions of favourable chemistry for the formation of thorium enrichments and/or deposits exist; however, further information is lacking.

6.6.12. Pakistan

The presence of radioactive minerals in the costal heavy mineral fraction in beach sands at the Makran Coast, west of Karachi was reported. The sediments deposited in the delta of the Indus River carry heavy minerals too. Details, however, are not available. Heavy mineral sands with monazite are reported elsewhere along the Indus River. No information was published whether carbonatites occurring at several locations contain thorium mineralisations.

6.6.13. Philippines

Most of the heavy mineral sands in the Philippines contain titanomagnetite and/or other non-radioactive minerals, with the exception of beach sands of the Imuruan Bay, NW Palawan Islands where thorium in monazite (pan concentrates) was found during exploration for REE. The occurrences are not of economic interest (Fig. 49, 50) [93]. In addition, granitic intrusions were investigated; however, only Tertiary granites have shown elevated thorium concentrations [94], which are not of economic interest. Offshore radiometric survey within Imuruan Bay has indicated high K, U and Th measurements at the northeastern half of the survey area. These are interpreted to be due to sediments inferred to contain granitic debris–the presumed source of heavy minerals.

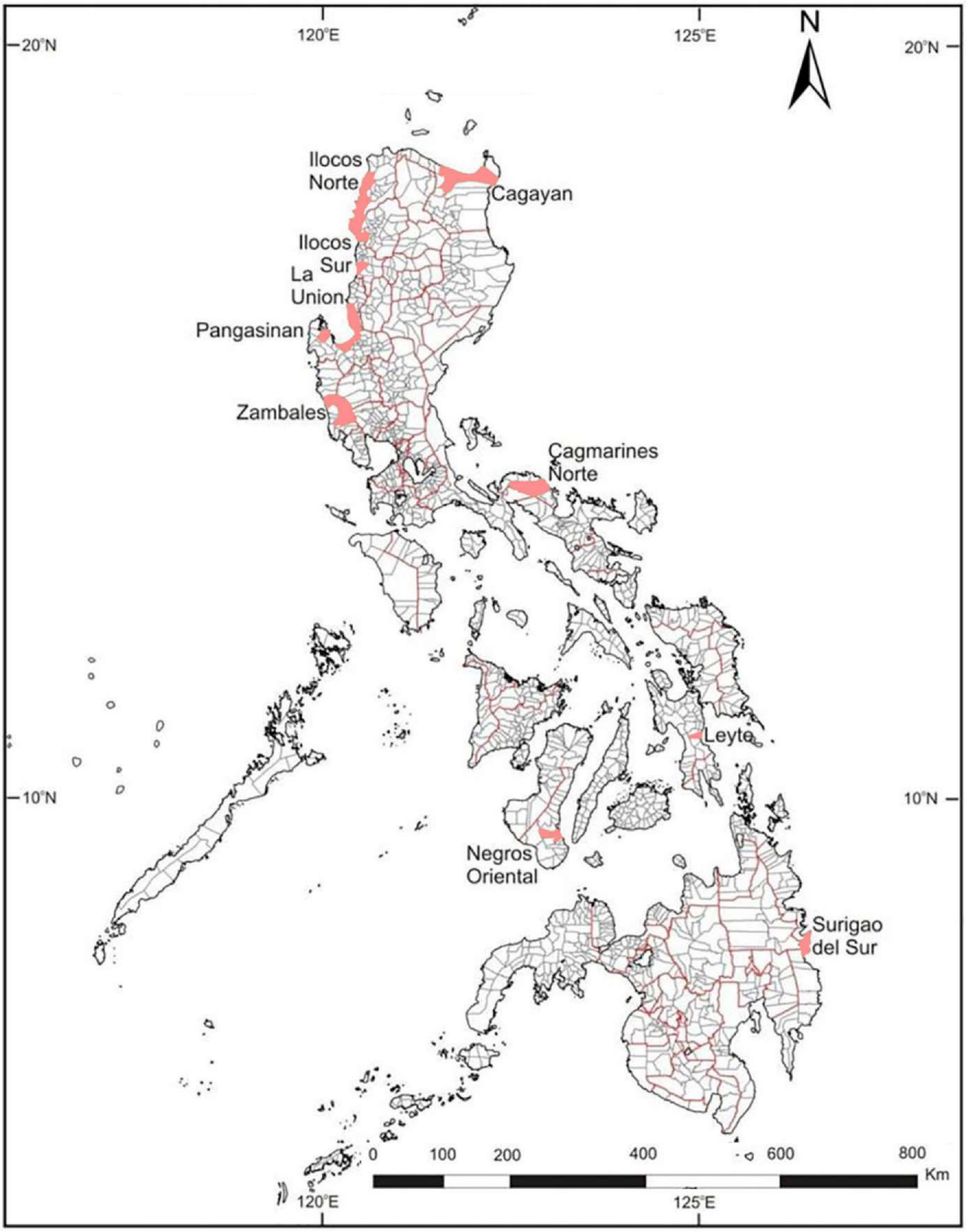


FIG. 49. Location of black sand deposits, Philippines (Reproduced with the permission of the Philippine Nuclear Research Institute) [95].

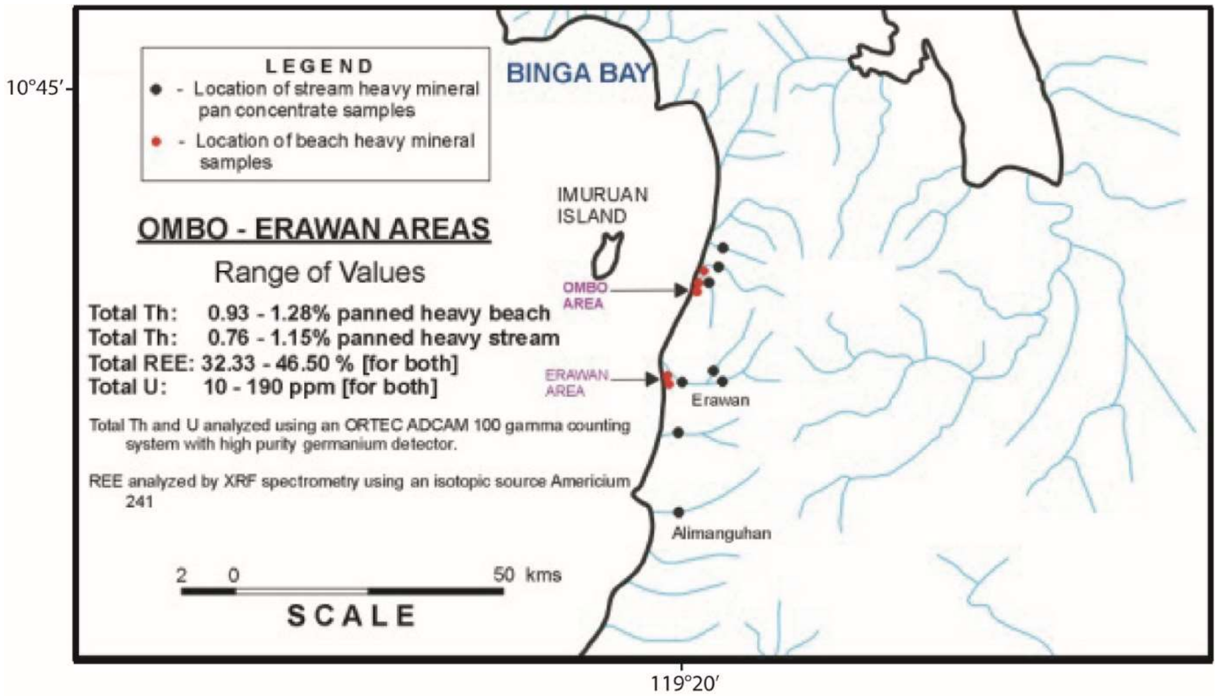


FIG. 50. Location of heavy mineral samples with high Thorium and REE values in Ombo and Erawan areas, Philippines (Reproduced with the permission of R. Reyes et al, paper presented at the IAEA Technical Meeting on World Thorium Resources, 2011) [96].

6.6.14. Russian Federation, Asian region

An IAEA publication on thorium resources was published in 1997 [15]. The publication deals with the Commonwealth of Independent States; however, descriptions of deposits are also given for those occurring in the Russian Federation, and mentions only shortly monazite containing placers. According to [15], no special exploration for thorium was undertaken after 1951. If required, thorium could be extracted as a by-product.

According to a 2007 communication written by Borodin for “Gornyi Vestnik Uzbekistana” [97], many monazite-bearing deposits have been described in the Asian region of the Russian Federation, e.g. the deposits Novo Troickoye and Sanarskoye, and the regions of Chitinsk (56–60% REO, 6.7–7% Th), Tarakskoye/Krasnoyarsk (50% REO, 4.5% Th), Bashtshelavskoye, and Altai (63.5 REO, 4.5% Th). The present status of these deposits is not known.

In the Asian region of the Russian Federation, up to now ~14 deposits with the association Nb/Ta and REEs are described. Among them, six are carbonatites and another six are in alkali granites. Most of the deposits seem not to be economically interesting for exploitation of the metals present. The deposit of Kiey is described in detail [15]. It is located in the region of the Yenissei massif in alkaline rocks and carbonatite. The ore body, ~2.5 km long and 300–400 m wide, occurs in the form of stockwork consisting of microcline, siderite, rare calcite and dolomite. Thorium ore minerals are metaloparite, thorite and thorianite. REEs are bound to bastnaesite. The mean Th content in the fresh rock is 0.043% Th. The carbonatite is overlain by a weathering crust which ranges in thickness from 10–15 m to 60–70 m and was formed during Upper Triassic to Jurassic time. In the weathered zone iron oxide occurs in quantities (and grades) of economic value, together with halloysite and fluorite. Beside a wide range of minerals thorium-bearing mineralisation both occurs as thorite and thorianite and in rare earth minerals.

Similar to the mineralisation occurring in the weathered zone of Kiey, the deposit of Beloziminskoye is enriched in apatite. No details on the thorium content are reported [15].

The deposit of Ulug-Tansek is situated in the southeastern part of the Tuva region, at the upper course of the Yenissei River, close to the border with Mongolia [15]. The deposit is situated in an alkaline intrusion which took place 260–265 m.y. ago. The intrusion is overlain by metasomatites of granitic composition, characterised by the presence of lithium mica and rare metals. The mineralisation obviously penetrated the entire rock suite and consists of Nb-Ta ore, iron-rich thorite and lithium mica. The mean content of the massif rocks is 0.084% Th and in the lithium mica-bearing part 0.13% Th, being concentrated in the central part of the massif. At present, the deposit is regarded as non-economic.

Close to Ulug-Tansek, the deposit of Aryskanskoye was explored, which is similar in origin to Ulug Tansek. In the region north of the Baikal a number of thorium mineralisations, preferentially of vein-type, have been described, e.g. Prjamoy, Chesten, Akit. Details on the contents of thorium are not reported. The mineralisation is bound to various minerals, of the rare-metal type (niobium, tantalum) and monazite, thorite and thorianite. It is not known whether the carbonatite of Tomtor (niobium, REEs) in the central part of Siberia contains thorium in appreciable concentrations [34].

No details are reported on thorium resources. The authors estimate resources in the Asian region of the Russian Federation at more than 100 000 t Th, mainly associated to multi-element mineralisations in carbonatite rocks and alkaline intrusions.

6.6.15. Saudi Arabia

Several intrusives, mainly of alkaline composition, are reported to contain elevated concentrations of thorium, of which details were not published. In the Haql granite, up to 470 ppm Th were measured by spectrometry. The alkali microgranite/microsyenite of Jabal Tawlah, Midyan region, was investigated by drilling resulting to an ore body of ~6 Mt containing Zr, Y, Nb and Th.

6.6.16. Sri Lanka

Relatively thorium-rich deposits exist along the N and NE coast of Sri Lanka (Fig. 51). In the Ratnapura district, alluvial deposits are found on the lower valley of Kaleganga and the largest of which (12 000 t of monazite) in the vicinity of Pulmoddai measures 50 m wide and 3 km long containing 3 Mt of sand with 0.4% monazite, which has ~8% Th. The presence of thorite and thorianite has been mentioned as well.

In the area south of Colombo (Kaikawela, Polkotuwa), placers with 15–40% monazite were reported; however, there are no details on the thorium content. According to reports, monazite has been exploited prior to 1970 and was exported to Japan [98]. Thorium resources were estimated at ~4000 t Th.

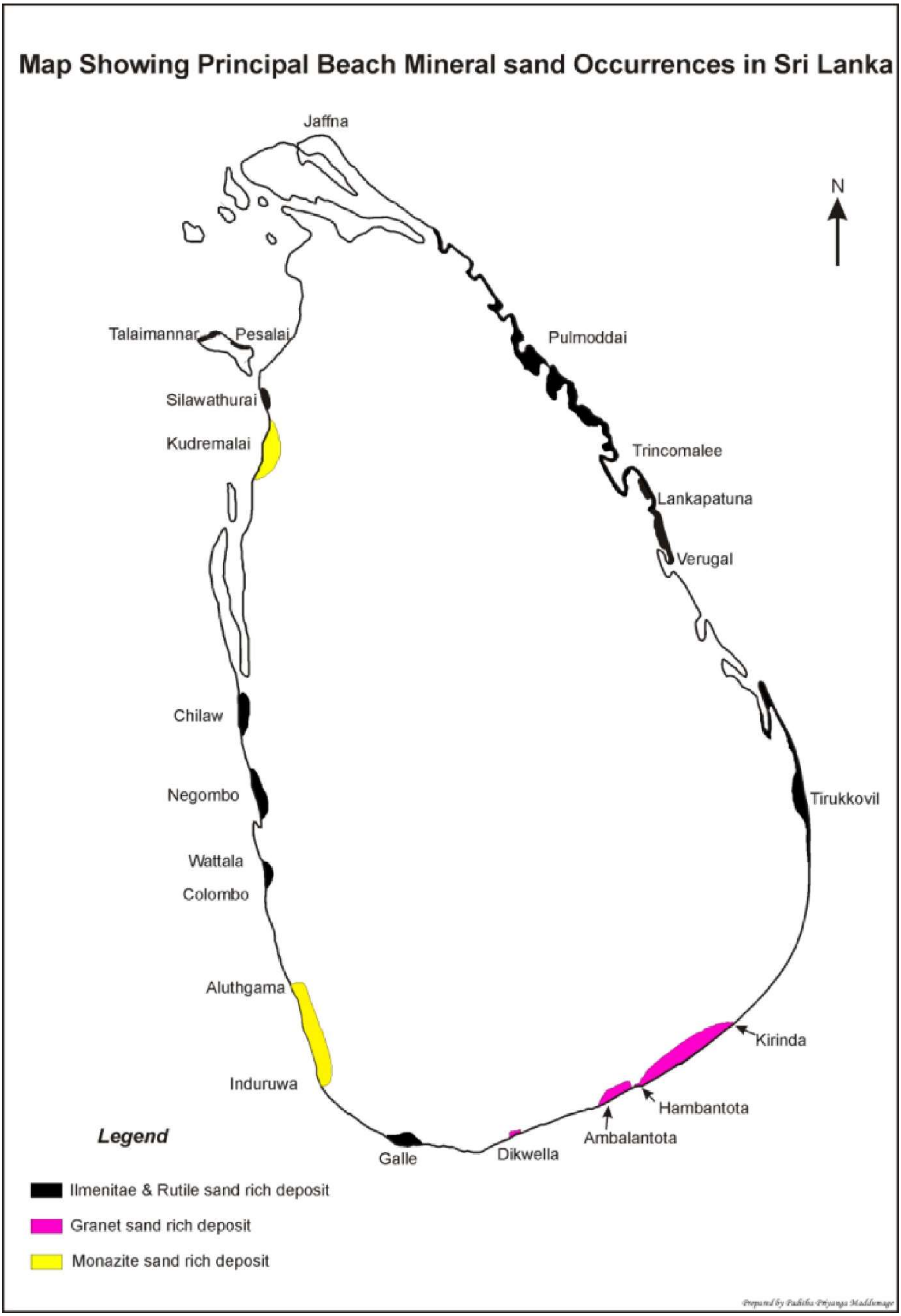


FIG. 51. Location of mineral sand occurrences, Sri Lanka (modified from B.A. Peiris, 2013) [99].

6.6.17. Thailand

The tailings from tin mining operations contain monazite, which was deposited in dumps amounting to ~6 400 t of monazite. The thorium content ranges between <1% and 9%. This would amount to ~60–600 t of thorium.

Beach sands in the Phuket area, southern Thailand, contain thorium in monazite. Depending on the site of the tin mine operations, values between 1–14% Th in monazite were obtained (Fig. 52). According to previous estimates unclassified total resources amount to 10 000 t Th [14].

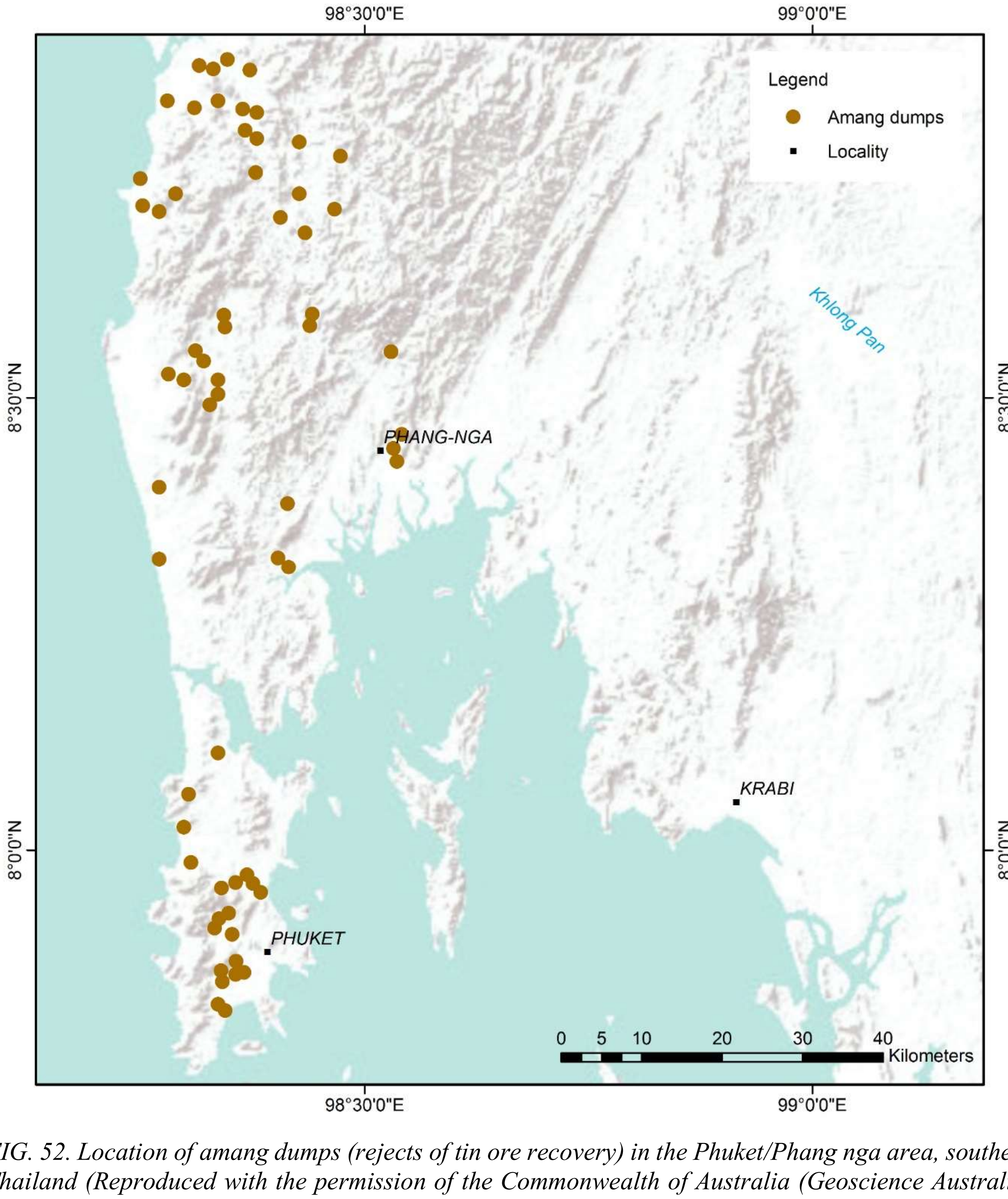


FIG. 52. Location of amang dumps (rejects of tin ore recovery) in the Phuket/Phang nga area, southern Thailand (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

6.6.18. Uzbekistan

Prospecting for radioactive minerals started in Uzbekistan in the 1940s; however, mostly monazite concentrations of unspecified nature were found. Prospecting continued in the following decades, however with the main focus on uranium. The presence of thorium is mentioned for several locations in the western part of the country, e.g. Tosbulakski, without specifications.

Exploration was undertaken after 1941 in the mountains of Nuratau and later several other locations followed where radioactivity is caused by enrichments of Th. Scientific investigations and limited field work has continued over many years. The occurrence/deposit of Tosbulaski has been investigated in the 1990s for base metals, Au, Ag and rare elements were subject of commercial interest.

No details are reported for resources in Borodin written communication [97]. They are estimated to 5000 t of thorium.

6.6.19. Vietnam

Deposits of REEs containing thorium were investigated in alkali igneous rocks and carbonatite at Nam Xe North (Mau Xe North), Nam Xe South, Dong Pao, all located in the province of Lai Chau, and Yen Phu in the province of Hoang Lien Son (Fig. 53). Thorium occurs in the minerals bastnaesite, monazite and xenotime. Detailed investigations, including a feasibility study, prior to 1989, concluded that the deposits were not economic (difficulties in mineral dressing) [100]. According to estimates made by the authors, resources may amount to 5000 t Th.

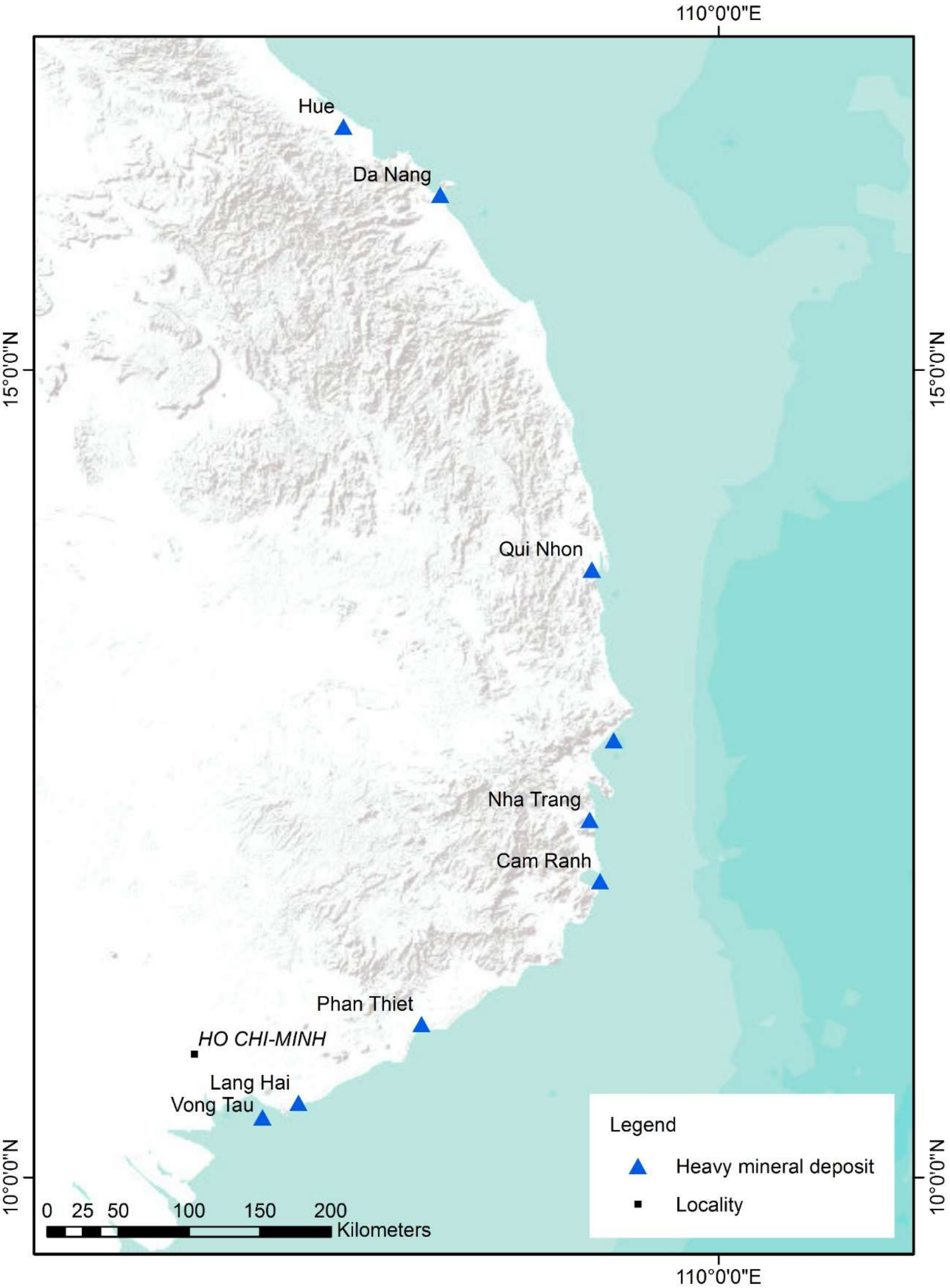


FIG. 53. Location of heavy mineral sand deposits, Vietnam (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

6.6.20. Summary for Asia

Information on thorium deposits and resources in Asia still remain incomplete. Low commercial interest for thorium combined with low demand and substantial amounts theoretically available, e.g. as by-product, has not encouraged detailed investigation for this commodity. However, as experience in India shows, thorium is a commercial commodity, obtained as by-product of extraction of REEs from heavy mineral sands. Thorium is used in India as nuclear fuel. The recent increase of interest in thorium has encouraged countries to start to investigate in more detail. For example, official Chinese delegates declared that interests for this commodity only recently were taken up.

Difficulties obtaining reliable figures are observed, because in many countries information was withheld for strategic reasons. Information for thorium was collected in the past for the entire Former Soviet Union and difficulties arise in the localisation of deposits from the few publications obtained. The publication [15] mentions that out of 2 500 sites where thorium was found, reserves and resources have been calculated for 241 sites only. There are 66 sites of endogenic nature, the majority of which are placers of various ages and composition.

A total of 1 700 000 t of thorium have been calculated as PR for the region of the Commonwealth of Independent States. In deposits with uranium classified as ‘off grade’ and with poor thorium ores, resources have been calculated amounting to ~53 000 t of thorium, which are out of economic consideration.

Close to 99 000 t of thorium are associated with complex buried placers, thus out of commercial value. Excluding the European part of the Commonwealth of ndependent States, total resources of that area (most are PR and low grade) would amount to ~1 500 000 t of thorium. About 75 000 t of thorium are located in deposits at 0.1–2% or more and may be regarded as RAR (estimated by the authors).
Until recently, official resource figures for Asian countries are known for India (846 477 t Th, estimates done in 2010 and 2011), Iran (30 000 t Th, estimated in the 1970s) and the Republic of Korea (estimated in the 1980s), bringing the officially reported figures for Asia to >1 Mt of thorium (without China and Asian countries of the former USSR).

Estimates in this publication are made for thorium resources for the Asian Region of the former Union of Soviet Socialist Republics (~1 500 000 t), China (>100 000 t) and Thailand (~10 000 t).

Total resources for Asia are estimated to be more than 2 500 000 t of thorium.

6.7. AUSTRALIA AND NEW ZEALAND

6.7.1. Australia

6.7.1.1. General Information

In 2015, total inferred and indicated in-situ resources were reported to amount to ~595 200 t Th. Public data from mining and processing losses for extraction of thorium are not available; therefore, the recoverable resource of thorium is unknown. The estimate takes into consideration, however, an arbitrary figure of 10% for mining and milling losses [101]. A breakdown of the recoverable thorium resources according to deposit type is discussed in [101–107]. The latest resource figures in [101] show 386 800 t Th (65 %) for heavy mineral sands (placers), 125 000 t Th (21 %) for vein-type deposits (mainly Nolans Bore), 50 900 t Th for alkaline complexes and 30 500 t Th for carbonatites.

Information is insufficient to quantify what proportion of Australia’s thorium resources are viable economically, because large scale demand and associated costing information are lacking [104]. The following sections give details on thorium resources:

- In heavy mineral sand deposits/placers;
- In vein-type deposits;
- Associated with carbonatite intrusions;
- Descriptions and deposits taken from [100–106].

6.7.1.2. *Thorium resources in heavy mineral sand deposits/placers*

In Australia, REE-thorium phosphate mineral monazite within heavy mineral sand deposits, which are mined for ilmenite, leucoxene, rutile, and zircon, comprise most of the known thorium resources (Fig. 54). Heavy mineral sand operations prior to 1996 produced monazite, which was exported for extraction of REEs. Currently, monazite is returned back to the pit in dispersed form so as to avoid radioactivity concentration when a mine site is rehabilitated to land use. Accordingly, the thorium and REEs present in the monazite are nullified as resource, a recovering the dispersed monazite for its thorium and REE content would be non-economic. Mining companies seldom record in published reports the monazite content of heavy mineral resources. Several reports [101, 108] show that the monazite content varies regionally between 0.2% in the fossil shore line type deposits and 3.0% or more in the fine-grained fossil offshore deposits. Monazite resources in heavy mineral sand deposits in Australia are estimated to be ~7.8 Mt [101], as assessed by Geosciences Australia from data on monazite and its thorium content. Inferred resources in mineral sands in Australia were estimated to be ~386 800 t Th. Table 9 shows the 2012 estimates for major placer deposits of Australia.

TABLE 9. TOTAL THORIUM RESOURCES* [101]

Region	Murray Basin	SW Coast	East coast, N of Brisbane	Eucla Basin	East coast, N of Sydney
Resources	302 000	51 000	12 600	5 000	500

* In t Th

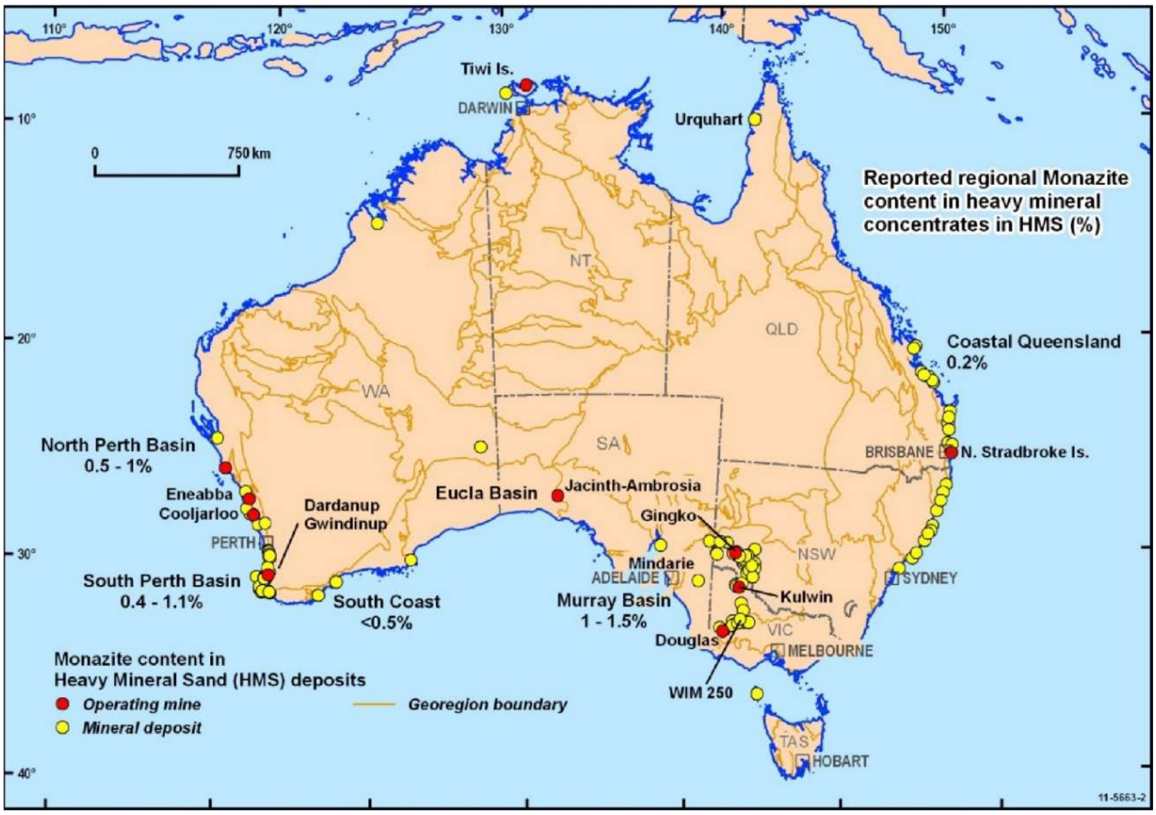


FIG. 54. Distribution of heavy mineral sand deposits in Australia showing regional monazite content in heavy mineral concentrate (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [101].

In Victoria and Western Australia are most of the known monazite resources. Heavy mineral sands are being mined from the Murray basin deposits at Douglas and Kulwin in Victoria and at Ginkgo and Snapper in New South Wales. Deposits of heavy mineral sands can be separated into:

- 41 000 t in Tertiary fossil beach sand deposits, Murray Basin (NSW, Victoria, South Australia);
- 5000 t Th in Eucla Basin, (South Australia, Western Australia) (Fig. 55);
- 51 000 t Th in Western Australia;
- High dune sands: 12 600 t Th mostly in Queensland (Fig. 56);
- Fossil offshore deposits: 261 000 t Th in Murray Basin mostly in Victoria (Fig. 57).

The most active area is in the Southwest Coast of Western Australia with 5 active heavy mineral sand mines (status 2010). The largest resources are located in the Murray Basin area (Table 9). In 2010 two operations were active [108]. It should be noted that as mentioned previously, the mining operations are for the recovery of titanium and zirconium minerals (ilmenite, leucoxene, rutile, and zircon). The thorium and rare earth bearing monazite is not recovered.

Thorium also exists in other geological settings in Australia, such as alkaline intrusions and complexes, including carbonatites, dykes and veins, and is typically associated with other commodities such as REEs, Ta, Nb, Zr and other elements. The following sections describe important deposits.

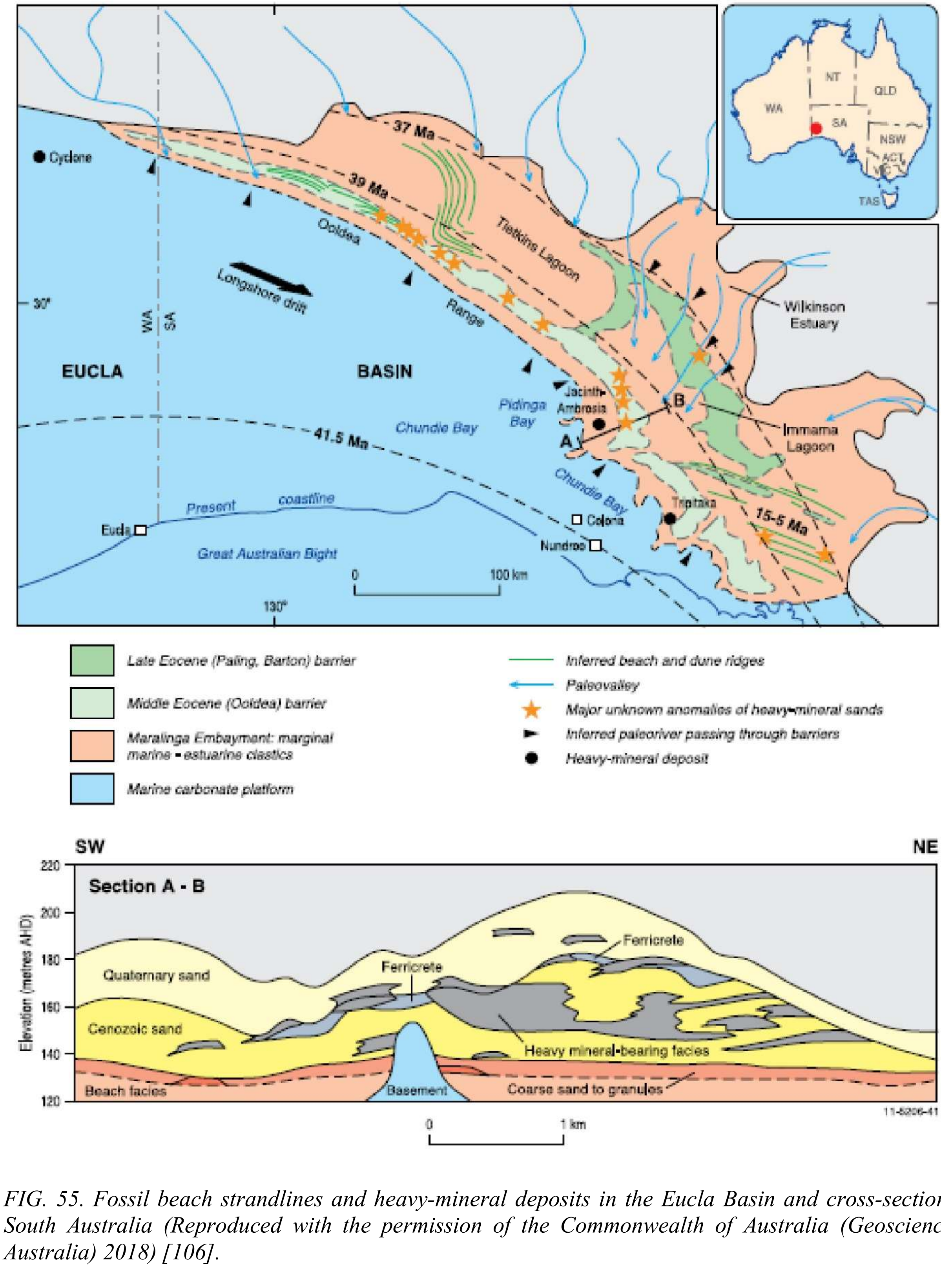


FIG. 55. Fossil beach strandlines and heavy-mineral deposits in the Eucla Basin and cross-section, South Australia (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

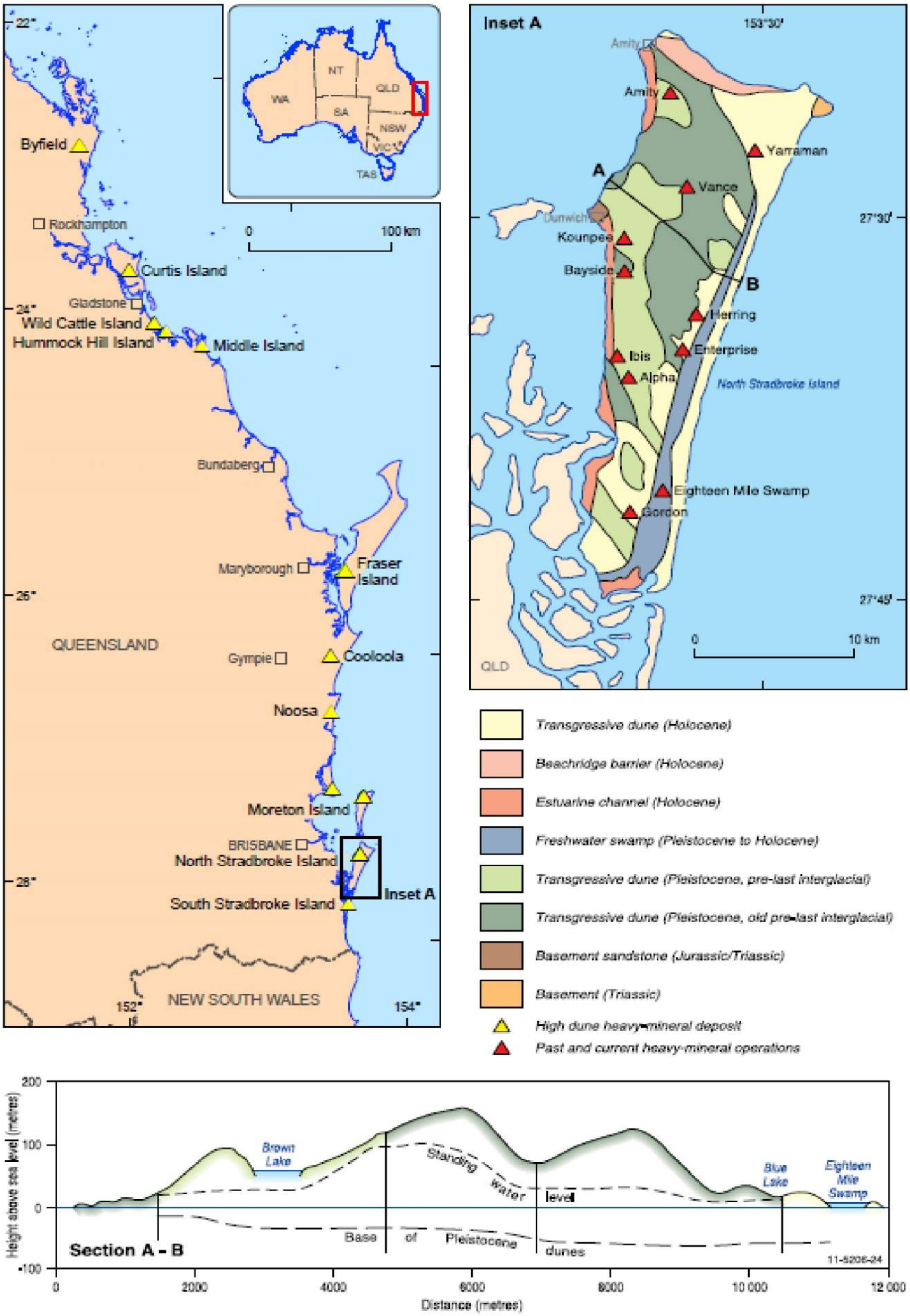


FIG. 56. High dune sand heavy-mineral deposits along the southern Queensland coast, including geology of North Stradbroke Island (Inset A) and cross-section (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

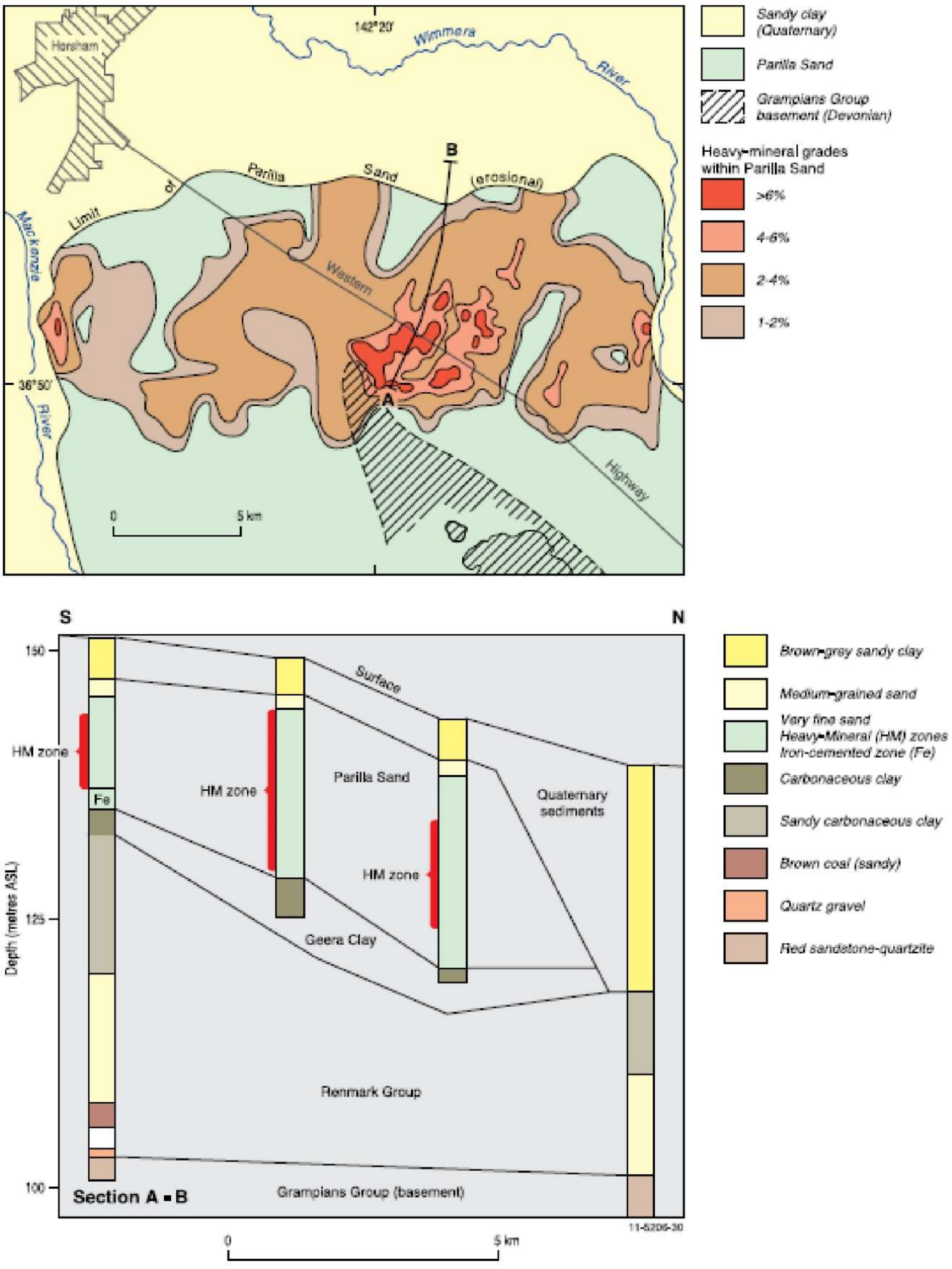


FIG. 57. Geological map and cross-section of the WIM 150 heavy-mineral deposit, Victoria (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

6.7.1.3. *Thorium resources in vein-type deposits*

The Nolans Bore deposit of REE-P_2O_5-U-Th is situated 135 km NW of Alice Springs in the Northern Territory (Figs 58, 59). At present the deposit is regarded as of hydrothermal origin. Fluorapatite dykes and veins host the mineralisation (Fig. 60). This deposit contains ~81 500 t of Th in 30.3 Mt of measured, indicated and IR grading 12.9% P_2O_5, 2.8% REO, 0.27% Th and 0.02% U_3O_8 [100].

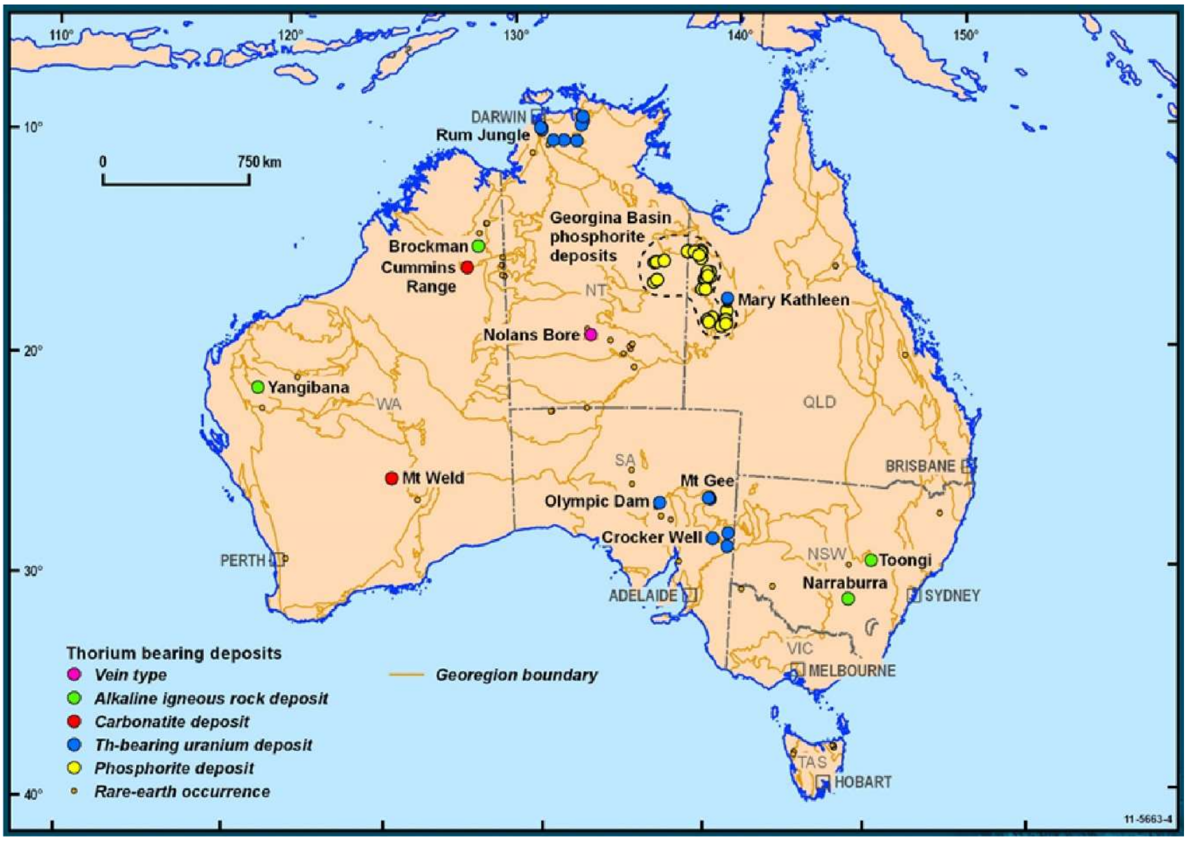


FIG. 58. Thorium deposits and occurrences excluding those in heavy mineral sands, Australia (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [101].

6.7.1.4. *Thorium resources in alkaline rock complexes*

The Toongi deposit of Zr-Nb-REE is hosted in an alkaline trachyte plug located ~30 km south of Dubbo in New South Wales (Fig. 61). It has measured and inferred resources of 35.7 Mt and 37.5 Mt, respectively, grading 1.96% ZrO_2, 0.745% total REO, 0.46% Nb_2O_5, 0.14% Y_2O_3, 0.04% HfO_2, 0.03% Ta_2O_5, 0.014% U_3O_8, and 0.0478% Th, for a total of ~35 000 t of contained Th.

At the Australian Nuclear Science and Technology Organisation, Lucas Heights, a demonstration pilot plant (DPP) was designed and constructed to test the ore from the Toongi deposit and provide products for distribution to potential end users. The plant operated efficiently and produced high quality zirconium and niobium products [105].

Known REE and thorium mineralisation in other alkaline complexes in Western Australia include the Brockman deposit, which is a large low-grade Zr-Nb-REE deposit hosted in altered Paleoproterozoic trachytic tuff. It contains mineralised material of 50 Mt at 1.04% Zr, 4 400 ppm Nb, 900 ppm REE, 270 ppm Ta, 1240 ppm Y, 350 ppm Hf and 110 ppm Ga. Historic reports, i.a. Aztec Resources, show analyses for thorium in six drill hole intersections (in tuffs) of 16–28 m with 259–371 ppm Th.

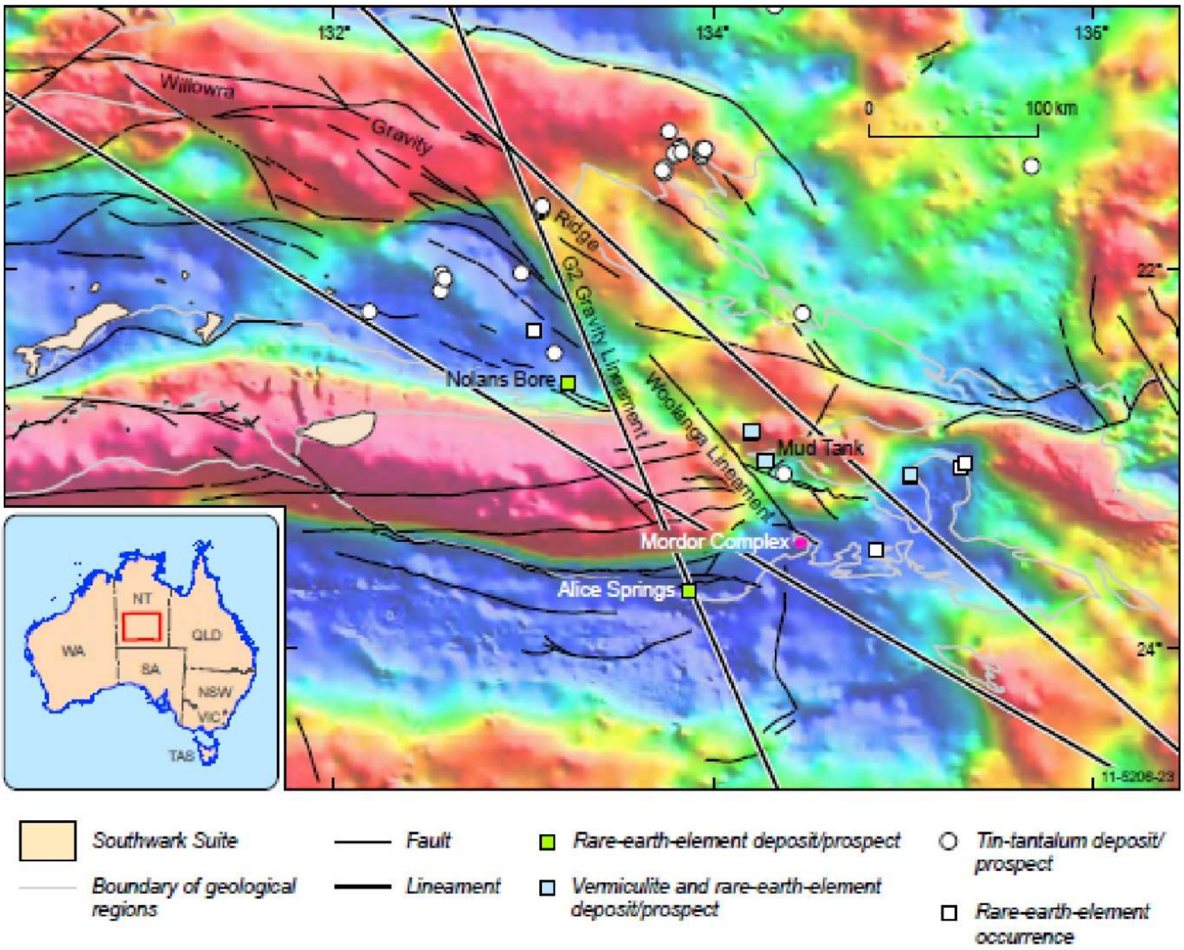


FIG. 59. Central Australia: locations of Nolans Bore and other REE-bearing deposits and prospects. Overlain on a background gravity image are major structural and gravity lineaments (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

6.7.1.5. Thorium resources associated with carbonatite intrusions

In Australia, data on thorium content of carbonatite intrusions are scant. For carbonatites in Australia, Cummins Range and Mount Weld in Western Australia contain the most important REE resources reported to date (Fig. 62). For Cummings Range thorium in a weathered profile, and for Mount Weld ~600 ppm Th are reported in laterite.

For the Cummins Range carbonatite deposit, Navigator Resources Ltd reported IR of 11.2% P_2O_5, 3.55 Mt at 2% REO, 216 ppm U_3O_8 and 36 ppm Th. Historic analyses of samples from other parts of the intrusion averaged ~500 ppm Th in the top 48 m of weathered zone in one drill hole. In carbonated magnetite amphibolite and fresh carbonatite to depths of 400 m, zones of 200–400 ppm Th were intersected in two historic drill holes [105].

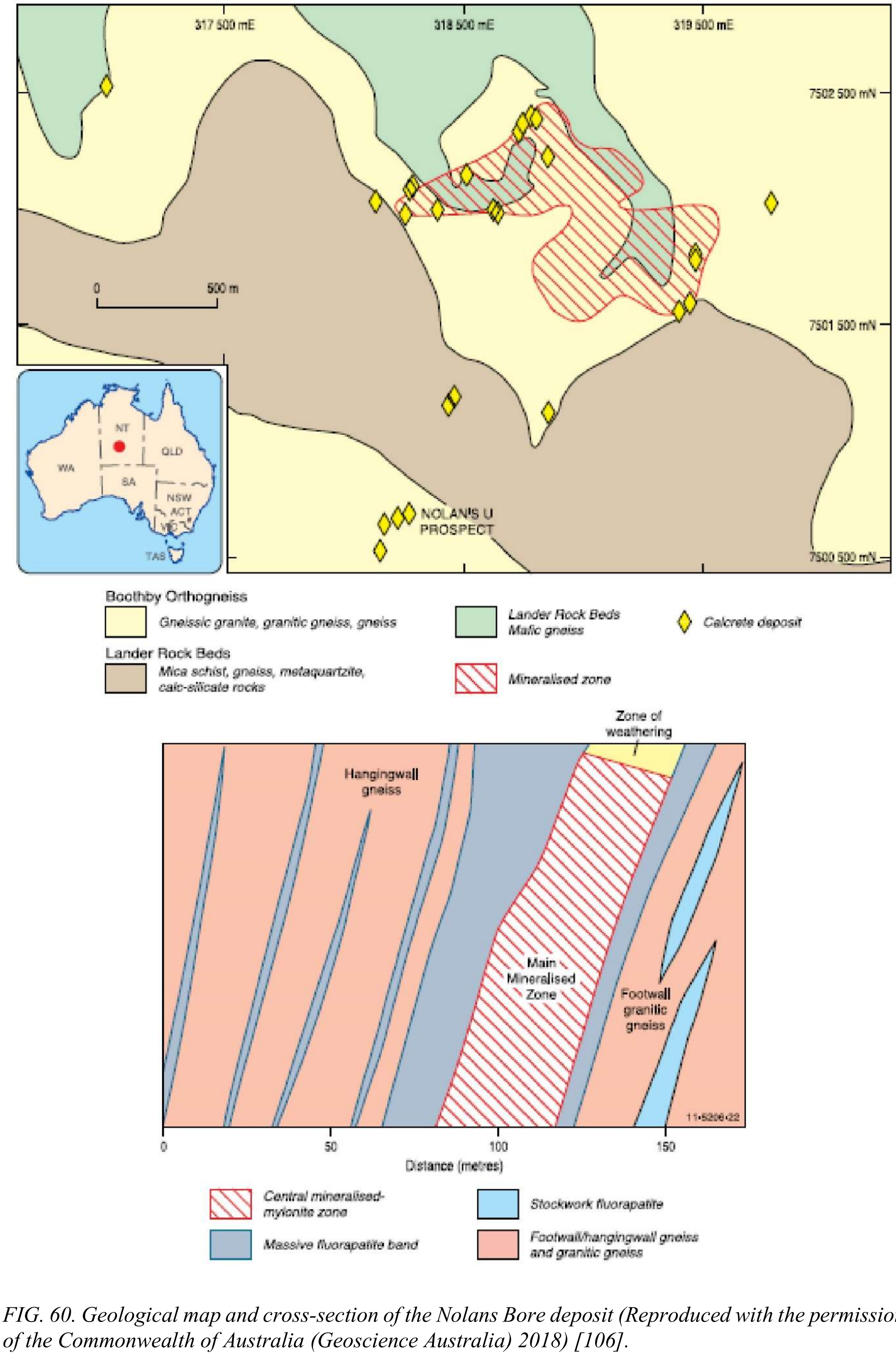


FIG. 60. Geological map and cross-section of the Nolans Bore deposit (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

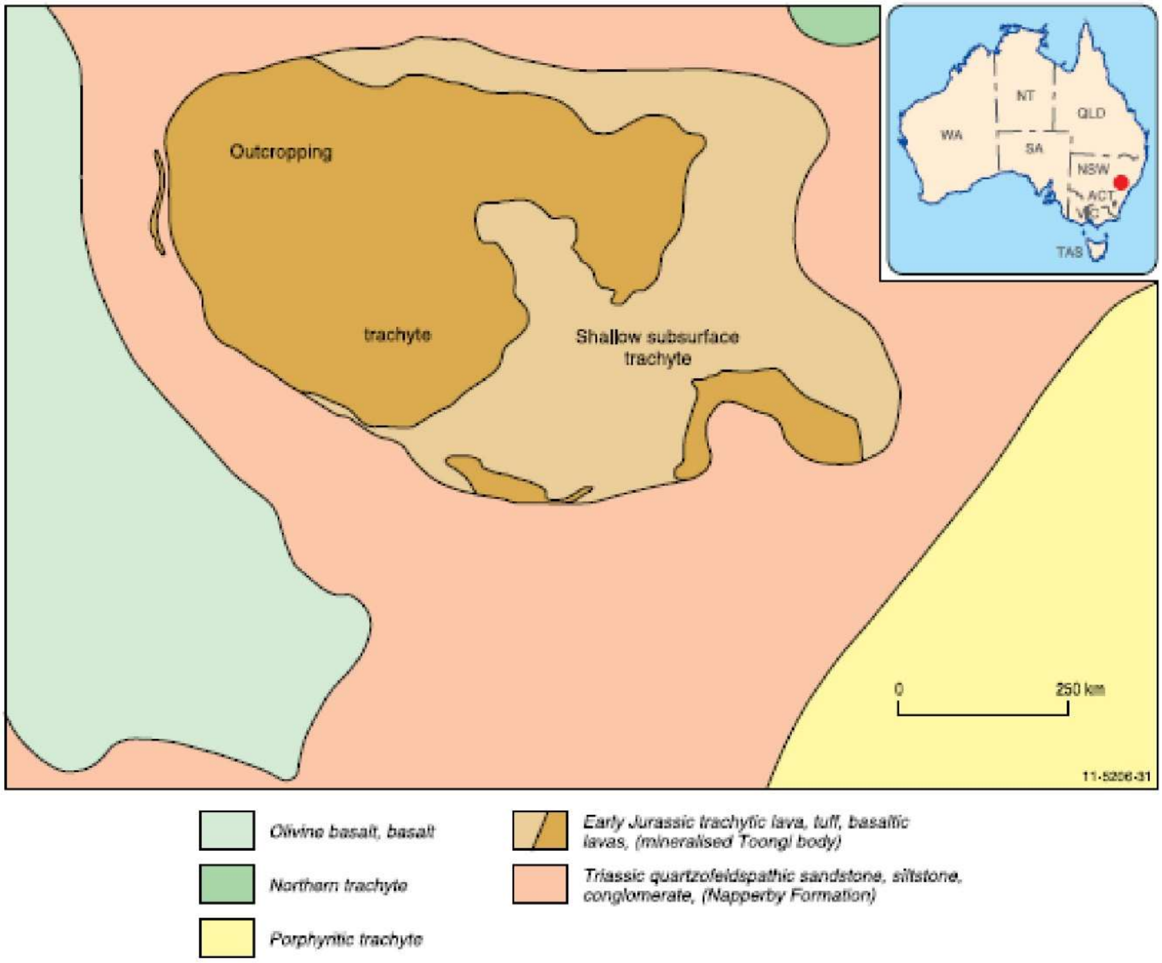


FIG. 61. Geological map of the Toongi polymetallic deposit, Lachlan Orogen, New South Wales (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

The Mount Weld deposit exists within a lateritic profile over a carbonatite complex. It has inferred, indicated and measured REO resources of 12.24 Mt at 9.7% REO. Its thorium content is estimated to be 626 ppm. Additional REO resources in the Southern Zone ore body are estimated at 2.78 Mt of inferred, indicated and measured resources at 4% REO with estimated Th content of 388 ppm. There are, in other areas, 37.7 Mt of mostly IR; these comprise total lanthanides at 1.16% and 0.09% Y_2O_3 and a Th content of 421 ppm [104].

The Yangibana ferrocarbonatite-magnetite-rare earth-bearing dykes (termed ‘ironstones’) are exposed over an area of 500 km² in Western Australia. The dykes, occurring as lenses and pods, are part of a carbonatitic episode in the Gifford Creek Complex, which intrudes the Proterozoic Bangemall Group. The ‘ironstones’ characteristically represent the latter phase of carbonatite fractionation and are enriched in REEs, fluorite and thorium-uranium mineralisation. The REEs are associated with coarse-grained monazite with up to 20% Nd_2O_5 and 1600 ppm Eu_2O_3. The recorded resource in the Yangibana prospect is 3.5 Mt at 1.7% REO. Whole rock chemical analyses of 21 ironstone samples yielded 1 062–5 230 ppm Th for 10 of the samples [104].

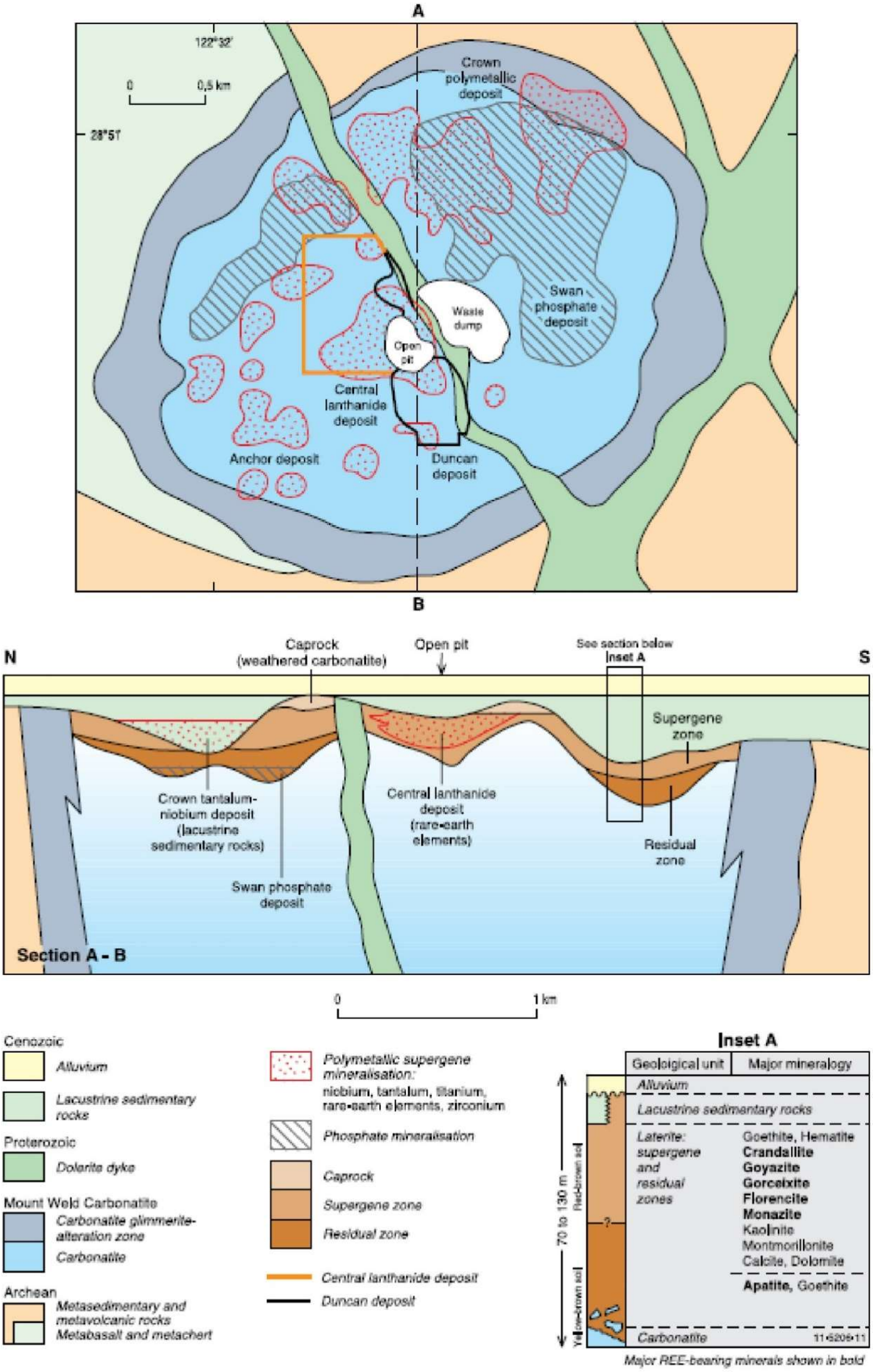


FIG. 62. Geological map (Cenozoic units above carbonatite have been removed) and cross section of the Mount Weld Carbonatite, Western Australia (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018) [106].

6.7.1.6. *Other occurrences*

Heavy mineral concentrates from the Warton Sandstone and the King Leopold Sandstone, (Durack Range uranium project; WA) contain up to 2% Th. Thorium is one of the commodities being explored for at the Cloughs Dam and Blueys prospects near Alice Springs, NT. Rock chip samples from the Blueys rare earth prospect reportedly yielded 599–1 400 ppm Th. Phosphorite deposits in the Georgina Basin (QLD, NT) contain low grade Th concentrations, usually lower than 100 ppm. The iron oxide copper gold uranium deposit of Olympic Dam has concentrations of 40–50 ppm Th, and ore resources (measured, indicated, inferred) were estimated at ~8 billion t [12, 100], which would bring the deposit to a large very low-grade thorium mineralisation.

6.7.1.7. *Summary for Australia*

The IAEA [12] and the OECD/NEA have classified thorium resources into four main types of deposits (Table 3). Apparently, worldwide thorium resources are concentrated modestly in the carbonatite-type deposits comprising ~30% of the world total. The rest of the thorium resources are somewhat equally distributed among the other three deposit types, but with increasing order of abundance in alkaline rocks, vein-type deposits and placers.

In contrast to the overall world distribution of thorium, a larger proportion of Australia´s resources are associated with placers, and heavy mineral sand deposits comprise ~70% of the known thorium resources. Some ~15% are associated with one vein-type deposit and ~10% with alkaline complexes (Table 10).

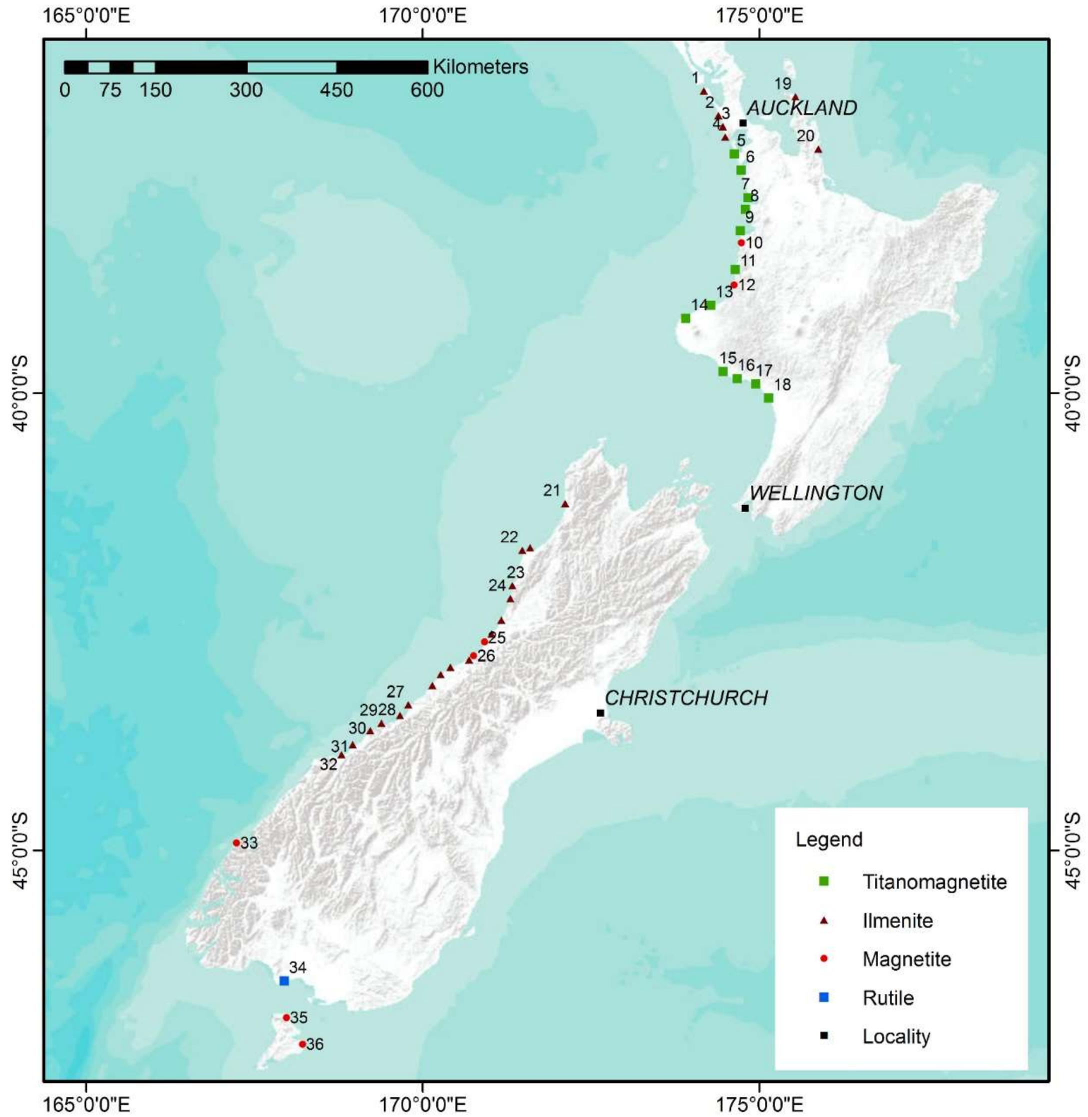
Considering future uses, thorium deposits in placers would have first order choice due to the by-product character of thorium minerals with other useful heavy minerals. The large amounts of thorium in placers give this deposit type priority.

TABLE 10. AUSTRALIA'S THORIUM RESOURCES IN DEPOSIT TYPES [102]

Deposit type Heavy mineral sands	Total (1 000 t Th)
Carbonatite	30.5
Placer deposits	386.8
Vein-type deposits	125
Alkaline rocks	50.9
Other	2
Total	595.2

6.7.2. New Zealand

Beach sands on the North Island, South Island and Stewart Island were reported to contain monazite and uranothorite (Fig. 63). Thorium contents are not officially published, although believed to be not of economic significance.



North Island

1. Kaipara Harbour
2. Muriwai
3. Piho
4. Manukau Head
5. Maioio
6. Waikato Head
7. Raglan Harbour
8. Aotea
9. Kawhia Harbour
10. Tagaroa
11. Awakino
12. Mokau
13. Waitara
14. Fitzroy
15. Patea
16. Waipipi
17. Wanganui River
18. Wangachu River
19. Cape Colville
20. Waihi Beach

South Island

21. Karamea
22. Buller River
23. Westport
24. Barrytown
25. Hokitika
26. Ross
27. Okarito
28. Gillespies Beach
29. Hunts Beach
30. Bruce Bay
31. Haast River
32. Jacksons Bay
33. George Sound
34. Orepuki

Stewart Island

35. Port William
36. Kingaringa

FIG. 63. Location of heavy mineral deposits, New Zealand (Reproduced with the permission of the Commonwealth of Australia (Geoscience Australia) 2018 and modified from Mineral Sands in Asia and the Pacific, ESCAP, Vol. 4) [74].

6.8. PACIFIC OCEAN ISLANDS AND ANTARCTICA

No thorium occurrences in beach sands or in other geological environments have been reported from the islands in the Pacific Ocean (Oceania) [74]. On the islands of Papua New Guinea, heavy mineral occurrences were reported from several places; however, none of them has shown any radioactive concentrations [74]. The reason for the absence of radioactive minerals in beach sands or in other geological environments is seen in the geological development of the countries scattered over the Pacific Ocean [49].

Some radioactive anomalies on the Antarctica turned out to be related to thorium, e.g. in sandstone and conglomerate in the Transantarctic Mountains and Marie Byrd Land. The association of thorium with REEs and some base metals suggests the occurrences being associated to alkaline intrusions. According to the International Treaty on Antarctica mining is presently prohibited.

7. SUMMARY OF WORLD THORIUM RESOURCES AND SUPPLY

Estimates of most thorium resources relate to potential resources, as individual exploration and comprehensive resource assessments of thorium deposits have been carried out randomly or have never been really carried out. Published estimates of thorium resources were derived chiefly from exploration undertaken in the 1950s–1980s for uranium and other commodities, and thus are not always certain. Therefore, detailed studies of the resources and ore processing tests are needed for decision-making on their economic relevance.

Resource assessments for mineral commodities are the base for analysis of their economic availability, which is essential for national planning purposes, in the case of nuclear fuel, for energy planning. Many efforts, both on national and on industry scale, were made to establish uniform terms for resources, e.g. in order to compare national estimates or in a country for assessments made by different bodies.

Recently, efforts were initiated to introduce the United Nations Framework Classification as a systematic tool for the classification of thorium resources. The efforts are directed to harmonise both national and international classification systems and to achieve uniform reporting for mineral and energy resources in solid, liquid and gaseous form.

7.1. HISTORICAL DEVELOPMENT OF THORIUM RESOURCES

World resource estimates for thorium have been made since the publication of the first Red Book in 1965. In 1965, total resources of thorium were estimated at ~1.5 Mt Th. In 1973, ~2.9 Mt Th were estimated worldwide. The resources for 1979 were estimated at 3.9 Mt Th. Due to revised estimates in 1982 resources were estimated at 2.7–3.7 Mt Th and for 1986 only to 2.4 Mt Th. No information on thorium resources were published until 2003, when more than 4.5 Mt Th were estimated, and the same amount again for 2005. World total resources were estimated at ~6 Mt Th [14].

Facing sufficient availability of uranium, the collection of thorium resources data on a country by country base was discontinued in 1985. The last assessment for thorium resources was published by the NEA/IAEA in the 1986 edition of “Uranium, Resources, Production and Demand”. From this time onwards, only aggregated information was published in the Red Books. Other resource information on thorium is published by the World Nuclear Association, e. g., mainly based on data from appropriate Red Books. An independent source for thorium resources, different from those mentioned, is the “Mineral Commodity Summaries” by the US Geological Survey [29], which bases its assessments on individual country information.

TABLE 11. ESTIMATED MAJOR TYPES OF THORIUM DEPOSITS, AS OF RECENT INFORMATION

Deposit type	Resources (1 000 t Th)	Percentage
Placer	2 182	35.1
Carbonatite	1 783	28.7
Vein-type	1 528	24.6
Alkaline rocks, incl. granites	584	9.4
Other	135	2.2
Total	6 212	

Totals in Table 11 and Table 14 differ due to individual roundings.

The amount of 6.2 Mt Th is perhaps the upper range of total resources according to estimates available in 2015 (Table 11). It should be noted that updated information was available for few countries only; thus, the data may not reflect the recent situation. In some cases, it could not be clearly estimated if and to what extend resource of speculative nature are included in the national submissions. The estimates shown in Tables 12 and 13 demonstrate to what extent estimates can differ from each other and how much the year of estimate may influence the figures. Totals in Table 12 and 13 differ due to individual roundings. Table 13 compares estimates made during the years 2009 and 2010 for different resources categories by the NEA/IAEA and the USGS in 1000 t Th. There are some remarkable facts in the differences between the estimates given in Table 13.

TABLE 12. COMPARISON OF ESTIMATES OF THORIUM RESOURCES (OECD/NEA 2001 [14] AND USGS 1997–2006 [29])

Country	OECD/NEA 2001		USGS	
	RAR (1 000 t Th)	EARI (1 000 t Th)	Reserves (equivalent to resources in the terms of IAEA) (1 000 t Th)	Reserve base (1 000 t Th)
Australia	19	-	300	340
Brazil	606	700	16	18
Canada	45	128	100	100
Egypt	15	309	-	-
Greenland	54	32	-	-
India	319	-	290	300
Malaysia	-	-	4.5	4.5
Norway	132	132	170	180
South Africa	18	-	35	39
Turkey	380	500	-	-
United States of America	137	295	160	300
Others	505	-	95	100
World total	2 230	2 130	1 200	1 400

The NEA/IAEA data for Turkey were deleted from Table 13 due to official statements on the resource situation for Th. In the Red Book 2007 edition, Turkey was included with 344 000 t Th as identified resources and 400 000–500 000 t Th as PR (see Turkey above).

In the assessment of the USGS, countries such as the Bolivarian Republic of Venezuela, Egypt, Greenland, Norway, and the Russian Federation do not appear. Missing data for Norway are explained as being deleted from previous exercises due to updates made by the Geological Survey of Norway. No explanation is given for the other countries not included in the USGS list. The USGS states that for world resources ~2.5 Mt Th may be contained in placers, vein, carbonatite and alkaline rocks, the majority occurring in the United States of America, South Africa, India, Greenland, Canada, Brazil, and Australia. This statement however does not explain the differences.

Geosciences Australia (GA) has published thorium resources based on assessments of the Red Book 2007 edition and its own assessment for Australia. The Australian identified resources are increased to 474 000 t Th [102], whereas the resources for Turkey are 344 000 t Th as in previous Red Books. The world total is estimated by GA as 6 190 000 t Th (no resource category, no cost of recovery).

TABLE 13. RESOURCES ESTIMATES FOR THORIUM AS OF 2009 AND 2011 NEA/IAEA, RED BOOK 2009 [12] AND USGS 2010 [29]

Country	RAR* RB 2009	Inferred resources * RB 2009	Identified resources* RB 2009	Prognosticated resources* RB 2009	Reserves** USGS Jan. 2010
Australia***	46	406	452	NA	300
Brazil***	172	130	302	330	16
Canada	NA	44	44	128	100
Egypt	NA	100	100	280	
Greenland	54	NA	54	32	
India	319	NA	319	NA	290
Malaysia					4.5
Norway	NA	132	132	132	
Russian Federation.	75	NA	75	NA	
South Africa	18	NA	18	130	35
Turkey***	NA	NA	NA	NA	
United States of America	122	278	400	274	440
Venezuela, Bolivarian Republic of	NA	300	300	NA	
Others	23	10	33	81	90
TOTAL	829	1 400	2 229	1 387	1 300

* NEA/IAEA Uranium 2009, Resources, Production and Demand, Paris 2010;
** should be corrected to resources;
*** revised estimates.

At the IAEA meetings on Thorium Resources in March 2010 and July 2012, the following resources were mentioned:

- Australia: 595 000 t Th;
- China: started estimation in 2009. See Baiyan Obo;
- India: 846 477 t Th in monazite only;
- United States of America: 440 000 t Th in [29], 404 800 t Th in [45].

Resources for the Commonwealth of Independent States were estimated at 1.7 Mt of thorium, including very low-grade deposits [15], however details on resource categories or recovery are not reported. Resource estimates amounting to a total of 1.7 Mt of thorium may be regarded as potential.

Thorium resource estimates for individual countries presented in this paper, notwithstanding resource category or cost class, are listed in Table 14. According to the presented estimates of world thorium resources a total of ~6.2 Mt of thorium are estimated not considering any resource category or cost class.

TABLE 14. TOTAL WORLD THORIUM RESOURCES (ESTIMATES)

Country	Total thorium resources, t Th (rounded)
Europe	
Turkey*	374 000
Norway	87 000
Greenland (Denmark)	86 000–93 000
Finland*	60 000
Russian Federation, European part*	55 000
Sweden*	50 000
France	1 000
Total Europe	**713 000–720 000**
America	
United States of America	595 000
Brazil	632 000
Venezuela, Bolivarian Republic of*	300 000
Canada	172 000
Peru	20 000
Uruguay*	3 000
Argentina	1 300
Total America	**1 723 300**
Africa	
Egypt*	380 000
South Africa	148 000
Morocco*	30 000
Nigeria*	29 000
Madagascar*	22 000
Angola*	10 000
Mozambique	10 000
Malawi*	9 000
Kenya*	8 000
Democratic Republic of the Congo*	2 500
Others*	1 000
Total Africa	**649 500**
Asia	
CIS*, (excl. Russ. Fed European part) #	1 500 000
India	846 500
China, est.**	>100 000
Iran, Islamic Republic of*	30 000
Malaysia	18 000
Thailand* est.	10 000
Vietnam* est.	5 000–10 000
Korea, Rep. of*	6 000
Sri Lanka* est.	4 000
Total Asia	**>2 519 500–2 524 500**
Australia	**595 000**
World total:	**6 205 300–6 212 300**

* data not updated
\# includes Kazakhstan, est. > 50 000; Russian Federation, Asian part, est. > 100 000; Uzbekistan, est. 5 000–10 000
** includes 9 000* in Taipei, China
CIS = Commonwealth of Independent States

7.2. GEOGRAPHIC DISTRIBUTION

As shown in Table 14, the highest amount of thorium resources is estimated for the Asian continent at ~2.5 Mt of thorium. This figure however should be considered with some reservations due to estimates made for a number of countries. For example, it has to be proved officially whether estimates for Commonwealth of Independent States are still valid and how the resources are distributed among the different countries. Data presented here were presented at a meeting and published in 1997. They originate from past estimates and it is not known whether an update has been made since. The data for China are estimates made by the authors and are based mainly on assumptions for the Bayan Obo deposit with respect to its geological characteristics. Indigenous resources are considered by the authors to be sufficient for national demands. Resources in India (846 500 t Th) are based on placer deposits. Their availability depends on the recovery of the main thorium-bearing mineral monazite. India has ambitious plans for nuclear power reactor using thorium as fuel. Indigenous resources of thorium exceed national demand. India may be able to provide thorium for exports if international demand arises. The Asian continent has a size of ~43 800 000 km^2 (excluding Turkey which is recorded for Europe) and its density is 57.75 kg Th/km^2.

The Americas (N+S) range second on the world thorium resources statistics, having estimated 1.9 Mt of thorium. The largest resources are estimated in the carbonatite of Araxa amounting to more than 500 000 t of thorium. Araxa contains the niobium mineral pyrochlore which has ~2% Th. Araxa is presently the largest mined niobium deposit, however thorium is not recovered. It is not known whether the recovery of Th is envisaged. However, the large resources of Th are interesting in case of emergent demand. The recoverable portion of Araxa (RAR < US$ 80/kgTh) was estimated in 1986 as 150 000 t Th. Brazil has placer deposits in which the recovery of monazite and its thorium content has been done in the past. The present situation is not known. RAR< US$ 80/kg Th in beach sands were estimated in 1986 at ~1700 t Th. Thorium resources of the United States are estimated at 595 000 t. Latest resource estimates was done in 2012. The largest amounts are in veins for which totals of ~350 000 t were estimated. Most identified vein-type has close connections to carbonatite stocks and peralkaline intrusions, making a separation rather difficult. For carbonatites, low grade resources of ~33 000 t Th are estimated. According to estimates Canada's resources amount to ~172 000 t Th, mostly associated with deposits of quartz pebble conglomerates, in the past subject to uranium mining, presently dormant. Venezuela´s thorium resources were reported in 1986 at 300 000 t of thorium in the carbonatite of Cerro Impacto. According to [63], the amount is 324 000 t of thorium, located in a thick layer of laterite overlaying an intrusive body which is believed to be a carbonatite. The Americas have a size of 42 000 000 km^2, the density amounts to 45.20 kgTh/km^2.

For Europe resources of thorium have been estimated at 946 000 t, due to earlier estimates for Turkey (reported for Europe), and Greenland. Resources in Turkey are referred to estimates dating back to the 1980s and are mainly associated with the vein-type deposit at Kizilcaören. One publication of 2003 refers to the higher resources however the original source goes back to older estimates. It should be noted that resource figures for Turkey may no longer be valid as the Red Book 2009 edition [16] and assessments published by the USGS in 2010 [29] do not contain any figure for resources in Turkey. The resource figures originate from assessments in the 1980s and may be reconsidered. Norway is listed in some past publications to have total resources of 320 000 t Th of which 170 000 t are quoted as reserves. The publication has put the resources into firm categories and recent publications [12, 29] do not refer to these figures. Resources are mainly localised in a carbonatite of the Fen district. Europe has a size of 10 000 000 km^2, and a density of 94.6 kgTh/km^2, which is the highest among all continents.

Thorium resources for the African continent are estimated at 649 000 t Th. More than 50% of the resources are in Egypt and another 23% in South Africa. The quantities reported for Egypt are old estimates and may be reconsidered. Compared with the size of the continent of 30 000 000 km^2, the density is only 21.63 kgTh/km^2 and the lowest of all continents, which may reflect either the low amount of exploration or of data publication.

Australia has estimated resources of ~595 000 t Th. Its size is ~9 000 000 km^2 and its density amount to 66.11 kgTh/km^2.
Densities of thorium resources for the individual continents show that densities for Asia, South America and Australia, ranging between 52 and 66 kgTh/km^2, are comparable. The highest density is in Europe (>131 kgTh/km^2) and lowest in Africa (~22 kgTh/km^2).

7.3. GEOLOGIC-METALLOGENIC DISTRIBUTION OF RESOURCES

Thorium is often associated with uranium in some of the deposit types and also in certain uraniferous minerals. In addition, thorium deposits are found independently of uranium. Many rocks, mostly of igneous origin, have elevated thorium contents, however too low to be considered as mineable deposits in present economic conditions.

The IAEA [12] and the OECD/NEA have classified thorium resources into four main types of deposits (Table 3). Apparently, worldwide thorium resources are concentrated modestly in the carbonatite-type deposits comprising ~30% of the world total. The rest of the thorium resources are somewhat equally distributed among the other three deposit types, but with increasing order of abundance in alkaline rocks, vein-type deposits and placers. In contrast to the overall world distribution of thorium, a larger proportion of Australia´s resources are associated with placers, and heavy mineral sand deposits comprise ~70% of the known thorium resources. Similar to Australia, most of thorium resources in India are associated with placer deposits at the coast. In contrast to these countries, the majority of thorium resources, ~80%, in the United States of America are associated with vein-type deposits linked to alkaline intrusions and carbonatites. Vein-type deposits are reported to contain the largest amounts of thorium in South Africa and Turkey; however, no recent update has been made in Turkey. According to available figures, the majority of thorium resources in Brazil is estimated to occur in carbonatites. Carbonatite are also the host rocks of the majority of thorium resources in Finland, Sweden and Norway. Greenland is known for its mineralisation of thorium, uranium, REEs and other minerals in a nepheline syenite (quartz undersaturated peralkaline intrusion). The same rock type hosts deposits of Lovozerov on the Kola Peninsula in the Russian Federation.

Due to some uncertainties in the description of deposit types or lacking of details in some countries, it is difficult to break down the estimates on resources (as in Table 15 below) according to deposit types. However, to the best judgment, Table 15 gives the following rounded percentages for a break down on the world thorium resources according to deposit type.

TABLE 15. PERCENTAGE DISTRIBUTION OF THORIUM RESOURCES ACCORDING TO MAJOR DEPOSIT TYPES

Carbonatites	29%
Placer	35%
Vein	25%
Peralkaline rocks	9%
Others	2%

As shown in the chapter on deposit description (Chapter 4), there are some important events in the formation of thorium deposits. There is a distinct tendency for some of the deposits to be associated with processes of crystal fractionation during which accumulation of thorium occurs in rocks in the upper parts of peralkaline complexes, e.g. Kvanefjeld/Greenland. Peralkalinity is described as enrichment of the alkali elements over aluminum (Na+K>Al) in silicate melts [5; 8]. Peralkalinity can be understood as one of the major parameters controlling the solubility of incompatible elements (e.g. Th, U, REE, Zr,

Nb and others) in the melts [19]. Another process resulting in enrichment of thorium can be observed in deposits resulting from partial melting in deep settings with a high degree of metamorphism.
Another example of thorium enrichment is seen in high temperature vein-type mineralisations of the uranothorite type (Lemhi Pass/United States of America, Nolans Bore/Australia, Kizilcaören/Turkey) were thorium is associated to Ca-P-REE-U-F-CO_2 rich fluids [5, 45, 101, 108]. The composition of the veins and close spatial relation suggests influences of carbonatitic rocks and monazite veins as shown in the example of Steenkampskraal/South Africa [69] in which thorium occurs with apatite, iron ore and base metals.

No regularities could be found in respect to ages of the thorium mineralisation associated to the igneous cycle. In contrast, placers occur in younger shorelines, ancient shorelines (inland) and fossil placers (e.g. quartz pebble conglomerates).

7.4. THORIUM SUPPLY

Despite the rather high resource amounts for various categories of thorium resources, short term availability of thorium resources is mainly based on the availability of thorium as a by-product. Because of the current low demand for thorium, there is no great incentive for the industry to acquire thorium resource data as well as theoretical production figures for thorium at operating deposits in which thorium occurs as a constituent. Exploitation of thorium deposits as a single commodity presently seems unfeasible because it is not economical. Extraction of thorium as a by-product during the extraction of REEs from monazite and other Th-bearing minerals seems at present the most likely path [109].

To obtain a general view on the theoretical availability of thorium production from monazite, mining monazite production may be taken as a measure. Estimates for cumulative world monazite production arrive to a total of ~700 000–800 000 t. A maximum of more than 30 000 t annually was reached in the mid-1980s.

The leading producer of monazite was Australia with an estimated total of 165 000 t of monazite [105], mostly extracted as a by-product of heavy mineral sand mining in Western Australia. In peak periods a total of six companies were extracting monazite. The majority of monazite was exported to France where monazite was used for the extraction of REEs. Due to problems related to radiotoxicity of the resulting waste the monazite extraction plant was closed [105].

Other large-scale producers were India, Brazil, Malaysia and Thailand. No information was obtained from China and the former Soviet Union.

India has a long history of monazite extraction from its heavy mineral sands. Production occurs in plants located in the states of Kerala, Tamil Nadu and Orissa The estimated total capacity of the plants is ~5000 t of monazite annually. India extracts thorium from monazite for its use in nuclear power plants.

In Brazil, separation of monazite from beach sands (heavy mineral sands) was carried out between 1886 and 1950 and ~95 000 t of monazite have been exported [52]. In Brazil, extraction of monazite from beach sands was undertaken in heavy mineral operations in the states of Rio de Janeiro, Bahia and Espirito Santo. During the restoration phase of the Pocos de Caldas uranium deposit in Brazil, thorium concentrates were stored, resulting as a by-product of rare earth production. [51].

Monazite was extracted as a by-product of tin mining in Malaysia, Thailand and possibly in Indonesia.

TABLE 16. MONAZITE PRODUCTION FOR 2000–2008 [93, 110]

Country	2000*	2001*	2002*	2003*	2004**	2005**	2006**	2007**	2008**
Brazil	200	200	200	200	731	958	958	1 173	1 200
India	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
Malaysia	818	643	509	450	1 683	320	894	682	700
Total	6 018	5 843	5 709	5 650	7 414	6 278	6 852	6 855	6 900

* from [110]
** from [93]

Published production figures for monazite in 2008 were estimated for the three countries shown in Table 16 at 6 900 t with a content of 6–8% Th, which equals to about 400–550 t Th contained.

Monazite production during the years 1990–1994 is published in [10]. The report shows that during that period the largest producer of monazite was Australia (>17 000 t in 1993), followed by India (>5000 t) and China (2 620 t in 1990).

In the 1970s–1980s, Australia produced REE minerals as a by-product of mining heavy mineral sands (50 t and 12 000 t of monazite of xenotime every year). Currently, in Australia, the monazite being extracted together with valuable heavy minerals from beach sand deposits is dispersed back to the original sand [83] because of the radioactivity of monazite. Estimated production during 1980–1995 amounted to ~165 000 t of monazite, of which ~160 000 t was derived from mining of heavy mineral sands in Western Australia. Majority of the monazite was exported to France for REE extraction, but the monazite plant in France was shut, as its operators were not able to acquire a permit for the radioactive and toxic disposal site.

7.5. PRINCIPAL PRODUCING COUNTRIES

World cumulative thorium production until 1988 was estimated to more than 20 000 t Th, however in many cases estimates are based on non-official information. Principal producing countries are shown in Table 17.

TABLE 17. PRODUCTION OF THORIUM (CUMULATIVE UNTIL 1988)

United States of America	>71 t
Australia	~ 8 000
China	~ 6 000
India	~ 4 000
Germany	~ 2 000
France*	2 000 t as Th-nitrate

* Thorium produced from U–Th concentrates from Madagascar.

Estimated thorium production, calculated from thorium grades in monazite, for Brazil may be 70–100 t Th annually and for India 300–400 t Th annually. Some production was reported in Canada, Malaysia and Turkey. Production also occurred in Indonesia, Nigeria, both Koreas, and from countries of the FSU. Recent details are not available. No thorium is produced in Australia presently. Monazite has been produced in the past, mainly for export; however, production of monazite ceased in 1995.

Reported figures for world production of thorium were given in [111] for the years 1960–1977 amounting to 12 401 t Th; however, no information is given for individual countries. Annual production during this period has fluctuated between 363 and 1 140 t Th. Further details on the production of other years could not be obtained.

In the United States of America, ashes from coal fired power plants contain annually 700 tU and 1 700 t Th, however these are not recovered separately. In the United States of America, the rare earth Mountain Pass Mine was closed in 2002, but reopened in late 2010. The products of Mountain Pass Mine had thorium, which was, as an unwanted commodity, removed and stored in the tailings.

7.6. PRICES

The trade of thorium and its compounds is limited to small transactions only, due to limitations of its commercial application. Its trade is not comparable to the trade of uranium. No international market was established due to limited quantities needed. Prices for spot or long–term contracts do not exist. Sales transactions were undertaken bilaterally between producer and consumer.

Prices for various thorium compounds were formerly published by the U.S. Bureau of Mines, and since its dissolution, by the U.S. Geological Survey in its annual Mineral Commodity Summaries. According to [28], during the 1970s prices for various thorium compounds remained rather stable. Thorium nitrate, used for the fabrication of gas mantles, quoted in the 1970s around 2.50–3.00 US$ per pound contained $Th0_2$. During the 1980s the price increased steadily to ~14 US$ per kg contained $Th0_2$ (US$ 6.35 per pound contained $Th0_2$). In the years from 2000 to recent, the price for mantle grade thorium nitrate remained stable at US$ 27 per kg (US$ 12.25 per pound contained $Th0_2$) [28].

Thorium nitrate used for welding was quoted during the last decade stable at US$ 5.46 per kg. Depending on the purity thorium oxide was quoted by commercial companies at US$ 82.50 per kg at 99.9% purity at the early 2000s until 2006; after that, sales of purity 99.9% ceased.

Thorium oxide of 99.99% purity quoted at US$ 107.25 per kg from 2000–2005, and increased to US$ 300 per kg in 2009 [28].

7.7. APPLICATIONS

7.7.1. Non-nuclear applications

Thorium can be used as an alloy with magnesium (Mag-Thor) for its high strength and creep resistance. Together with tungsten it is used for welding.

Thorium compounds are used as oxide and nitrate. Among all oxides, thorium oxide has the highest melting point and so is used for heat resistant materials, and as catalyst in the chemical industry. Thorium oxide is used in the glass industry for manufacturing glasses with high refractive index and dispersion, to be applied in high quality lenses for cameras and scientific instruments.

Its radioactivity, however, is a limiting factor for its application, and in recent times the use of thorium oxide for non-nuclear application is decreasing.

7.7.2. Nuclear application

Thorium is geochemically about four times more abundant than uranium, although world-wide knowledge on its resources cannot be compared to uranium. Its nuclear properties, however, render its application as a nuclear fuel. During the peak years of nuclear development in the 1960s and 1970s, thorium was regarded as an alternative to uranium fuelled nuclear reactors and a number of thorium fueled reactors have been developed and started operations. As all of the thorium can be utilised it is more interesting than uranium, of which only 0.7% (fissile ^{235}U) can be used. Consequently, specifics on the thorium fuel cycle were developed [111].

Compared to uranium, amounts of thorium needed for nuclear reactors are rather small. Depending on reactor type around 50 t Th is needed per 1000 MWe in the first core and additional reloadings of ~10 t Th annually. Thorium itself is not fissile. The main isotope ^{232}Th has to absorb neutrons in order to produce the fissile isotope ^{233}U. The provider for neutrons is the isotope ^{235}U.

During its development, it was demonstrated that thorium-fueled reactors have advantages and disadvantages. One advantage of the thorium fuel cycle is a higher yield of neutrons. Another positive factor is the absence of plutonium produced in the uranium fuel cycle. Disadvantages include intermediate production of protactinium-233 which diminishes the yield of neutrons, as well as problems related to radiation, the inert nature of thorium oxide and reprocessing of spent thorium fuel. For more details on advantages/disadvantage refer to [1, 2, 112]. To avoid problems with reprocessing, an 'open fuel cycle' is propagated in which no chemical separation of ^{233}U is necessary. In contrast to this, a 'closed fuel cycle' would require chemical reprocessing [111].

Depending on economic and political decisions, in the past a number or reactors using thorium as fuel have been developed. Examples of R&D reactors are AVR in Germany, Dragon in the United Kingdom of Great Britain and Northern Ireland, Peach Bottom in the United States of America, and Kamini in India. Power reactors were run over limited periods in Germany (300 MWe Thorium High Temperature Reactor, 60 MWe Boiling Water Reactor), in the United States of America (330 MWe reactor at Fort St Vrain, Shippingport), and in India (Kakrapar, Pressurised Heavy Water Reactor). Research and development are currently undertaken on several concepts for advanced reactors [1, 2, 112], e.g. Generation IV Nuclear Reactors. Several reactor concepts using advanced technology are currently under development or subject to detailed research, such as:

- High Temperature Gas Cooled Reactor (HTGR);
- Molten Salt Reactor (MSR), Radkowsky;
- Thorium Reactor, Candu-Type Reactor;
- Advanced Heavy Water Reactor (AHWR);
- Fast Breeder Reactor (FBR).

All of the types mentioned above are based on current technology; however, using advanced concepts including various applications of thorium.

India is currently one of the few countries in the world following the concepts utilising thorium in its nuclear planning [88, 113]. Favoured options with thorium fuel are followed by a three-stage concept: Advanced Heavy Water Reactors (AHWR), Fast Breeders (FBR), and Pressurised heavy water reactors (PHWR). The ongoing programs include a 300 MWe AHWR designed to produce 65% of the power from Th-Pu pellets, and a lifetime of 100 years. The Fast Breeder is designed at 1000 MWe using metallic fuel and sodium as coolant. Heavy Water Reactors are using thorium-based fuel bundles. In Fast Breeders thorium is irradiated to produce ^{233}U, e.g. in the research reactor of Kamini.

In the case of Molten Salt Reactor (MSR), different options of molten salt are being followed [112]. Molten Salt Reactors are a research subject in China. According to news reports [e.g. 113] a liquid-fluoride thorium reactor (LFTR) got interest by scientist and private companies. The development will be based on a technology developed in the United States of America in the 1950s and 1960s. Media reported on the cooperation of the US Department of Energy with China on the Molten Salt Technology. The China Academy of Science announced in January 2011 a multi-million dollar investment in MSR development [114]. MSR concepts have found interest by state organisations and private companies in a number of countries, e.g. France, Japan and the Russian Federation.

Further recent developments are reported in [102]. Atomic Energy Canada Ltd (AECL) investigates the use of its CANDU reactors to use thorium in Advanced CANDU reactors. Thorium Power Ltd, a US company, has received US Government funding for cooperation with the Russian Moscow Kurchatov Institute on research for Th-U fuel used for the Russian VVER 1000 reactor. The use of thorium is continuously investigated in the United States of America at Shippingport in Pennsylvania, were research is concentrating on the Radkowsky Thorium Reactor. Details are described for example in [86].

8. CONCLUSIONS

Estimates on reported total world thorium resources result in ~6 Mt of thorium in situ. These numbers, however, include several limitations. Considering that recent updates are available only for a limited number of countries world-wide and the estimates of in situ resources do not reflect their availability for recovery nor their economic extraction, the amount of thorium theoretically commercial available is lower by a percentage depending on the geological character of individual deposits. Assuming all limitations are taken into account recoverable resources range from 3.5 to 4.0 Mt of thorium. These estimates are two to three times higher than those reported in recent publications, e.g. Red Book and USGS, which estimate identified resources between 1.3 and 2.2 Mt of thorium.

World-wide thorium resources, regardless of sources of estimation, are by ~60% lower than estimates for uranium resources. Identified uranium resources as of 2014 recoverable at less than US$ 260/kg U are reported to be 7.6 Mt of U. The RAR were reported as of 2014 to 4.6 Mt of uranium recoverable at less than 260 US$/kg U. The estimates of thorium resources include a certain, however presently unknown amount, of undiscovered resources. Thus, it seems to be justified to include into the comparison of thorium and uranium resources at least the PR of uranium which amount world-wide to 1.7 Mt of uranium. The sum of identified and prognosticated uranium resources is ~9.3 Mt. This relates to a total of 6.2 Mt of thorium estimated in the present document.

Comparing the geochemical behavior of thorium and uranium in the upper crust of the earth, available to our observation, thorium is four times more abundant than uranium. This general accepted fact is not reflected in resource estimates, showing higher uranium resources compared to thorium. The reasons for this can be expected by the kind and degree of exploration. There was virtually no specific exploration for thorium per se. Nearly all of thorium resources are a ‘fall out’ of exploration for either uranium or heavy mineral sands (placers). The radioactivity of thorium minerals permits exploration tools using radiometric methods. This certainly is the case for vein-type deposits and a number of carbonatites. In both cases the prime economic targets are for example base metals, uranium, rare metals (e.g. Nb, Ta, etc.), and perhaps REEs and others. Existing thorium concentrations would be recoverable as by-product, for which costs of mining and associated expenditures are borne by the main mineral(s).

In the case of heavy mineral sands (placers) excavation the mining cost and associated expenditures are born by the heavy minerals (ilmenite, rutile, garnet, sillimanite, zircon, monazite) contained in the sands. The heavy minerals are extracted from the sands by specific separation techniques, during which the main thorium mineral, monazite, can be extracted separately. If required thorium can be extracted from monazite and separated from the REEs using specifically developed separation methods.

At present limited amounts of thorium are used industrially. The prime use in the past was its utilisation in gas lamp mantles. This application and other non-nuclear utilisation have limitations due to the radioactivity, and quantities of thorium, mostly in the form of thorium nitrate. During the extraction and separation of heavy minerals in placer deposits, monazite concentrates are regarded as unwanted in Australia and monazite is returned to the sea (see chapter Australia). Unwanted radioactive compounds may be deposited in dispersed form in tailings at the Mountain Pass Mine. Reports mention a Brazilian practice where thorium-rich products after separation from the ores are stored as 4000 t of thorium 'cake' in 20 000 drums [51].

Nuclear application for thorium does not require large amounts of fuel. It has been estimated that, depending on the reactor type, around 50 t of thorium will be needed for the first core for a 1000 MW reactor and additional ~10 t of thorium as annual reloading. Assuming 50 years of operation a 1000 MW reactor needs ~550 t of thorium. Compared to most light water reactor using enriched uranium, thorium operated reactors do not require enrichment. During enrichment process natural uranium (0.7% fissile ^{235}U), the isotopic grade of ^{235}U has to be enriched to 3–6% fissile ^{235}U. In thorium operated reactors, the isotope of natural ^{232}Th has to be irradiated to ^{233}U and does not require enrichment.

Considering estimations for world resources of thorium it is obvious that these resources are beyond theoretical requirements. At the present stage, however, it is too early to estimate future requirements of thorium, only speculations on requirements can be made. Assuming a lowest level of 1 000 000 t of thorium economically recoverable, this amount would be sufficient to supply fuel for ~1 800 reactors at 1000 MWe for 50 years.

The question arises how realistic this speculation might be. An amount of 1 000 000 t of economically recoverable resources seems to be realistic. The document above has indicated that the most probable thorium resources are monazite in placer deposits. According to published material India is presently the only country currently separating monazite in its coastal heavy mineral mining facilities (placer deposits) and is recovering thorium from monazite in the plant at Cochin/Kerala. Recovery costs for thorium are not available. At a rate of 5000 t of monazite produced annually, in India ~400 t of thorium could be produced annually.

In the past, Brazilian companies have extracted thorium. At the deposit of Pocos de Caldas thorium was separated during extraction of REEs and ~4 000 t of thorium 'cake' in drums [94]. Costs of recovery of thorium are not announced. Brazilian production of monazite, ~1 200 t annually, would allow the extraction of ~60 t of thorium.

The only other producer, Malaysia, produces annually ~700 t of monazite with a theoretical content of ~50 t of thorium. No published figures are available on whether and how much thorium is produced in China and in the countries of the Former Soviet Union.

If a commercial demand of thorium as nuclear fuel arises certainly the heavy mineral industry will respond. Australia could then return to a producer of monazite which could be sold for separation of thorium. In the past Australia had produced ~12 000 t of monazite annually for export. Depending on the source of monazite the theoretical content of thorium ranges between ~350 and 700 t of thorium. During the period of monazite extraction, ~165 000 t of monazite have been exported.

In the case of commercial requirements radiological limitations for the use of monazite will be solved as examples in the uranium industry show. At present, in countries of heavy mineral industry the ecological impacts of radiological hazards are carefully studied.

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ABBREVIATIONS

AECL: Atomic Energy of Canada Limited
AHWR: Advanced Heavy Water Reactor
AVR: Arbeitsgemeinschaft Versuchs Reaktor (German prototype pebble bed reactor)
CIM: Canadian Institute of Mining, Metallurgy and Petroleum
CMMI: Council of Mining and Metallurgical Institutes
CRIRSCO: Committee for Mineral Reserves International Reporting Standards
EIA: Environmental Impact Assessment
ESCAP: United Nations Economic and Social Commission for Asia and the Pacific
FBR: Fast Breeder Reactor
HTGR: High Temperature Gas Cooled Reactor
IAEA: International Atomic Energy Agency
INB: Industrias Nucleares do Brasil
IR: Inferred Resources
IRL: India Rare Earth Ltd
JORC: Joint Ore Reserves Committee
LFTR: Liquid-Fluoride Thorium Reactor
MSR: Molten Salt Reactor
MWe: Megawatt electric
NAEN: National Association for subsoil examination. НАЭН: Национальная ассоциация по экспертизе нед
NMA: Nuclear Materials Authority (Egypt)
OECD/NEA: Organisation for Economic Co-operation and Development/Nuclear Energy Agency
PERC: Pan-European Code for Reporting of Exploration Results, Mineral Resources and Reserves
PR: Prognosticated Resources
RAR: Reasonably Assured Resources
REE: Rare Earth Elements
REO: Rare Earth Oxides
SAMREC: South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves
SIA: Social Impact Assessment
SR: Speculative Resources
ThDEPO: World thorium Deposits database
UDEPO: World Uranium Deposits database
UNFC: United Nations Framework Classification
USGS: United States Geological Survey.
VVER/WWER: Water-Water Energetic Reactor (Russian design and name)

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