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FOREWORD

A high quality geochemical database is pertinent to a wide range of investigations in the earth and life sciences, and should be considered as an essential component of environmental knowledge. Natural radioactive elements associated with radioactive raw materials, the radiation environment and their health impact, form part of such a comprehensive geochemical database.

Databases on radioelement mapping have been increasingly used and updated in several countries for the exploration of uranium and thorium raw materials for nuclear fuels, environmental geochemical studies and the assessment of the radiation environment. The demand for radioelement databases is expected to grow over the next decade as new applications for them are foreseen. To this end, the IAEA invited a group of experts to investigate the issues and draft a report on the current state of radioelement mapping and the development of a global radioelement baseline.

In the past, based on gamma surveys for uranium exploration and field gamma spectrometry, the IAEA took a leading role in facilitating the development of methodologies and standards for the quantitative estimation of radioelement concentrations and for the geochemical mapping of radioelements.. The need for approved methodologies and standards for radioelement mapping was identified at an IAEA panel meeting in 1972. This led to IAEA technical meetings in 1973 and 1974 and the publication of the proceedings of an IAEA symposium entitled Exploration for Uranium Ore Deposits.

In subsequent years, calibration standards and procedures were developed for radiometric field equipment. The standards were based on geological reference materials for laboratory gamma ray spectrometers issued by the IAEA. The information on the standards and the equipment has been documented in detail in IAEA technical reports: Preparation and Certification of IAEA Gamma ray Spectrometry Reference Materials RGU-1, RGTh-1 and RGK-1, report IAEA/RL/148 (1987); and Construction and Use of Calibration Facilities for Radiometric Field Equipment, Technical Reports Series No. 309 (1989).

This report should be read in combination with other IAEA reports which describe the use of uranium exploration data and techniques applied to the preparation of radioelement maps and the establishment of guidelines for radioelement mapping using gamma ray spectrometry. It is also recommended that this report be read in combination with the UNESCO Final Report of the International Geological Correlation Programme Project 259. That report analysed methods and inconsistencies in geochemical mapping and specified the requirements for a global geochemical database. Specifically, the report recommended the establishment of a global geochemical database for environmental and resource management. In addition, gamma ray spectrometry was introduced as a fundamental method for radioelement mapping.

The IAEA expresses its thanks to all who have contributed to the worldwide gamma survey coverage map and the details presented in Appendix II of this report. The abstracts and papers (where provided by authors) of presentations made at the Technical Meeting on Radioelement Mapping and Status of the Global Radioelement Baseline and Maps held in Golden, Colorado, USA, in 2003 are included in the annex on the CD-ROM attached to the back cover of this report.

The IAEA officers responsible for this report were J. Slezak and K. Wenrich of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

Geochemical and gamma ray surveys have been used for many years by those exploring for uranium. However, with the development of spectrometers in the 1960s, the scope of the gamma ray method was expanded to include geological and environmental mapping. As national coverage of gamma ray spectrometric data grew, it soon became evident that unless the acquisition, calibration and data processing procedures were standardized, it would be difficult to either merge data from different surveys, or make meaningful comparisons between surveys. Similar problems affect sample based geochemical surveys. A lack of standards has lead to inconsistencies between surveys. The IAEA has been instrumental in the establishment of gamma ray spectrometric standards over several decades. Modern surveys complying with these standards are referenced to a global radioelement baseline. Darnley et al. described standards for the development of a global geochemical database [1].

The variety of sampling techniques, methods of detection and analysis, and reference standards that have been applied to radioelement mapping over the past fifty years have complicated comparison of local, national and international data sets and their application to mineral resources prospecting and environmental issues. Airborne and ground gamma ray spectrometry surveys are powerful techniques for K, U and Th analysis in rocks, and already cover large areas of the earth's surface. Many national and regional radiometric maps have been compiled and published. Geochemical mapping, performed under international and local research programmes, represents a long term effort that has resulted in valuable databases. The need for unification of these data and maps became evident some years ago. In 2002, the IAEA evaluated past and contemporary procedures of radioelement mapping and recommended the establishment of a global radioelement baseline. Benefits of a global radioelement baseline are: identification of uranium provinces; detection of uranium deposits; uranium resource evaluation; and the estimation of the radiation environment and contamination caused by uranium cycle activities and human made sources. Globally standardized radioelement data would lead to a more accurate appraisal of uranium potential on a global scale.

Radioelement baseline data sets are essential components for many research applications in earth and life sciences. The benefits of radioelement baselines include the effective use of radioelement data for uranium exploration and mining, geological mapping, and mineral (including hydrocarbon exploration) and regolith mapping. Radioelement baselines also benefit land use mapping, and are used in health and environmental applications, for both natural and anthropogenic sources. Also, the regulatory framework surrounding radioactive materials cannot be effectively established without knowledge of the natural variability of radioelements on the Earth's surface. Radioelement baseline data sets are thus crucial for the setting of good public policy in relation to uranium resources discovery and development.

A global baseline requires the establishment of a global network of radioelement standards that can be used for the calibration of gamma radiation instruments, and a set of standard procedures for the acquisition and processing of radioelement data. All radioelement standards should be related to IAEA primary geological reference materials for laboratory gamma spectrometry, which were issued by the IAEA in 1987. Older survey data can be adjusted to conform to the global baseline through the application of suitable 'back-calibration' procedures. Also, the establishment of radioelement baselines for geochemical surveys requires standardization of media types (e.g. water, soil), field sampling and laboratory analyses, and data set calibration.

1.1. BACKGROUND

1.1.1. Gamma ray spectrometric surveys

Many radiometric instruments convert gamma ray energy into electrical pulses that are modified, recorded and displayed as counts (c) or count rate (counts/s). Both these quantities are relative measures of radiation because they depend on the sensitivity and efficiency of the equipment used, the sampling time, and the geometry of measurement. However, relative measures of radiation are unsatisfactory from the point of view that measurements from one instrument are not easily compared to measurements from other instruments. Survey data are thus not easily merged and are also not amenable to quantitative interpretation, leading to estimates of the strength of

radiation sources and fields. The data should therefore be standardized and reported in internationally accepted units.

Since the 1950s, intensive prospecting for uranium has led to an effort to relate the response of radiometric instruments to geological sources or physical units. However, it took several decades to develop and establish systems for radiometric equipment calibration, the standardization of radiometric data and maps, and to recognize the importance of uniform global radioelement baselines. Over the same period, uniform units and terminology for radiation mapping were adopted.

Baranov reviewed the problems associated with interpreting the response of total count (TC) gamma ray instruments to the natural occurrence of K, U and Th in rocks and soils [3]. He noted that TC surveys do not strictly measure the 'intensity' of gamma rays. A compromise solution was to calibrate TC radiometric instruments by means of a ^{226}Ra point source, and report the results in units of exposure rate (μR/h (1 μR/h in SI units is 2.58×10^{-10} C kg^{-1} h^{-1})). Baranov's book also used the term 'sensitivity' of a radiometric instrument expressed as a count rate per unit of exposure rate (counts/s per μR/h).

Novikov recognized the limitations of calibrating a TC instrument using a ^{226}Ra point source [4]. The gamma energy spectrum of K, U and Th in rock is quite different to that of a ^{226}Ra point source in air. The scattering of gamma rays in rock results in a substantial lowering of gamma ray energies. This, coupled with the high detection efficiency of scintillation counters at lower energies, results in a substantial overestimation of reported exposure rate (μR/h). With the introduction of airborne spectrometers, it was therefore recommended that the airborne response to K, U, and Th concentration in rocks should be established by flying over three natural calibration strips with known average radioelement abundances. In addition, radiation sources (of approximately 10 kg mass), derived from K, U and Th ores, were recommended for estimating the parameters required for separating the K, U, and Th contributions to the observed radiation field (the 'stripping ratios' — see Section 3.1.4).

Kogan also recommended flying over natural calibration sites, or the use of medium mass K, U, and Th reference sources [5]. He noted that for energies above 1.2 MeV, the gamma ray spectra from these sources are similar to those observed in the natural environment. He also noted that the vertical inhomogeneity of natural calibration sites could result in the derivation of incorrect sensitivities for airborne and ground gamma ray spectrometers.

A series of scientifically valuable contributions to the theory and application of gamma ray spectrometry in geoscience were presented at a symposium on Nuclear Techniques and Mineral Resources held in 1968 [6]. In the symposium proceedings, Darnley et al. described the use of airborne gamma ray spectrometers in experiments over the Canadian Shield [7]. The data were background corrected, stripped, and reported as elemental count rates (counts/min). In order to improve the data processing, five calibration pads of dimensions 7.6 m × 7.6 m × 0.5 m were designed and manufactured at Uplands Airport, Ottawa. Foote reported on a high sensitivity airborne gamma ray spectrometer equipped with six 292 mm × 102 mm NaI(Tl) scintillation detectors, and an additional detector for airborne radon correction [8]. Data were recorded as count rate (counts/min). Adams stressed the need for instrument calibration to convert the data to meaningful geological radioelement units [9]. Løvborg indirectly calibrated a portable gamma ray spectrometer and determined its sensitivities through statistical analysis and a regression of field data and the radioelement concentrations of rock samples derived from laboratory analysis [10]. Killeen et al. applied a similar indirect calibration procedure to a portable gamma ray spectrometer [11].

Substantial progress was made in field gamma ray methods and data standardization during the 1970s. Much of this work was summarized in IAEA publications [12–13]. The basic considerations necessary for the application of natural and humanmade calibration facilities to gamma ray methods were discussed by Matolin [14]. Airborne and ground gamma ray spectrometers became widely available, and calibration facilities were established in several countries. The terms 'instrument sensitivities' (count rate per unit radioelement concentration for a specified detection geometry), 'stripping ratios' (ratios of sensitivities), 'background' (and its components), and K, U, Th reporting units were universally adopted. Field and data reduction procedures for gamma ray spectrometry were thus standardized.

Recognizing the importance of radiometric methods in uranium exploration, the IAEA has taken a leading role in the development of standardized methods for measurement and calibration in this field. Relevant topics have included radiometric instrumentation and the sensitivity of field radiometric instruments for surface and borehole measurement geometry [15], and data standardization [13]. Suitable calibration facilities are crucial for correct data standardization. For portable gamma ray spectrometry, the IAEA recommended the use of 4 cylindrical concrete calibration pads for estimating instrument stripping ratios and energy window sensitivities [13]. These should have

minimum dimensions of 2 m × 0.6 m. Each of the three of the pads is enriched in one of the radioelements (K, U or Th), with the fourth, low radioactivity pad, serving as a background pad. For airborne spectrometers, three (U, Th and low radioactivity) cylindrical concrete pads (8 m × 0.5 m) were suggested for the estimation of stripping ratios, and a calibration strip was recommended for the estimation of instrument sensitivity and the linear attenuation coefficients of gamma rays in air. This would facilitate the reporting of the concentrations of the natural radioelements in percent K, ppm eU, and ppm eTh. In recognition of the complexity of the response of TC instruments to terrestrial radiation, a new 'unit of radioelement concentration' (abbreviation 'ur') was recommended, as a compromise, for the reporting of TC survey data. A rock with concentration 1 ur is equivalent, in terms of the amount of gamma radiation, to a geological source with concentration 1 ppm uranium in radioactive equilibrium. However, it was later shown that this approach to the reporting of TC results was not entirely satisfactory [16]. The IAEA emphasized the advantages of standardizing radiometric measurements through the construction of calibration facilities, the adoption of standard reporting units, and the design, manufacture and supply of geological reference materials to be used as laboratory standards [17]. Valuable contributions to data processing and standardization were also presented in an OECD Nuclear Energy Agency publication [18].

As the number of available calibration facilities grew, problems began to emerge. These included:

— Loss of radon from uranium calibration pads;
— Temporal variation in radiation output due to varying moisture content in the pads;
— Difficulties in estimating the true radioelement concentrations of the pads because of heterogeneities within the pads, and a lack of primary radioelement reference materials;
— Lack of primary radioelement reference materials.

In an attempt to solve these problems, the IAEA, in collaboration with the Risø National Laboratory, Denmark, carried out an intercomparison experiment of 12 established calibration facilities in ten countries (Argentina, Australia, Brazil, Canada, Denmark, Finland, Israel, South Africa, Sweden and the USA), between 1980 and 1984. The report comprehensively reviewed field gamma ray spectrometry and the calibration of instruments, and analysed the problems associated with calibration facilities [19].

A major difficulty at this time was the assignment of true radioelement grades to calibration facilities because of a lack of accurate standards for the calibration of laboratory gamma ray spectrometers. In 1983, the IAEA convened a consultants meeting to prepare specifications for an appropriate set of primary geological reference materials that could be used for such calibrations. This ultimately resulted in the IAEA's Analytical Quality Ccontrol Services, in collaboration with CANMET, Canada, preparing a set of three reference materials (RGK-1, RGU-1 and RGTh-1), called the RG-set, for the calibration of laboratory gamma ray spectrometers for K, U and Th analyses. The RG-set is available from the IAEA and serves as the primary reference standard for gamma ray spectrometric applications [2].

The issues involved in the construction and use of calibration pads is comprehensively reviewed in an IAEA publication [20]. This covers the theory, design and construction of calibration pads. Four pads (8 m × 0.5 m) were recommended for airborne instruments, while smaller calibration pads (3 m × 0.5 m) were recommended for the calibration of portable gamma ray spectrometers. In the early nineties, smaller transportable calibration pads (1 m × 1 m× 0.3 m) were introduced for the calibration of both ground and airborne gamma ray spectrometers [21]. The pads can be used for the estimation of stripping ratios for both portable and airborne gamma ray spectrometers. The pads are also used for the estimation of sensitivity constants for portable spectrometers. However, a geometric correction factor must be applied to the estimated portable spectrometer sensitivities because of the limited size of the pads.

In the last three decades, more than 40 calibration facilities have been constructed in several countries. Portable spectrometers calibrated on these facilities can be used to back calibrate older surveys (expressed in count rate or other relative units) to absolute concentrations of the radioelements. The back calibration is based on a comparison of the uncalibrated radiometric data with absolute field concentrations established using a calibrated portable gamma ray spectrometer [16], [22–23]. Modern approaches to instrument calibration and the compilation of radiometric maps can be found in recent IAEA publications [24–25]. Air absorbed dose rate, expressed in nGy/h, is now the preferred unit for total terrestrial radiation [26].

The IAEA has been instrumental in the development of field radiometric methods. This has resulted in standardized procedures for radioelement mapping which are now being adopted globally. Standardization has

resulted in high quality radiometric data that can be used more widely. A high quality geochemical database is pertinent to a wide range of investigations in the earth and life sciences, and should be considered an essential component of environmental knowledge.

1.1.2. Geochemical surveys

Geochemical surveys were reported in literature nearly 450 years ago with the publication of Georgius Agricola's De Re Metallica [27]. He noted that mineral deposits could be found by their association with vapours being released and seen by their action to create frost free areas [28]. Such empirical information from surface observations led the way for geochemical prospecting. Understanding of elemental associations through chemistry, such as behaviour of elements in oxidized or reduced environments and chemical groups of similar elemental behaviour, was a major breakthrough in exploration geochemistry; because the primary element of interest may be found by its association with another element, for example, the uranium, radium, and vanadium association.

The central problem of geochemistry was defined by V. M. Goldschmidt early in the 20th century to be "the determination of the distribution of the elements in materials of the earth and the reasons for this distribution" [29]. This would include all chemical elements, including radioelements and isotopes. This process is ongoing and is the basis of the application of geochemistry to problems of geological mapping, mineral resource exploration, environmental problems, medical geography, crops and livestock yields, and natural hazard identification. Considerable research and experience has been gained in the application of geochemistry to problems of mineral resource discovery, delineation and development. The following summarizes this area in the expectation that this experience will benefit other areas of applied geochemistry [30].

Radiation of elements was discovered by Becquerel in 1896. Within ten years of the discovery of radiation, work by Marie Curie found radiation associated with over 20 elements, including uranium, thorium, and potassium, which were discovered as elements 50 to 100 years earlier. The concept of the isotope was only just being conceived and by the early 1920s, with the invention of the first crude mass spectrometers [31], nearly 200 isotopes had been discovered. Some of the earliest geological calculations using radiation were geological dating using uranium–helium [32], and uranium–lead [33], and in determination of heat production in the Earth from the energy of the decay [34].

Slowly, the concept of the radioactive decay chain from uranium and thorium through to lead emerged. Uranium and thorium are both alpha emitters with long half lives (4.5×10^9 years and 1.4×10^{10} years, respectively), and they do not emit much radiation. Radioactive potassium (^{40}K decaying to ^{40}Ar) is only about 0.01% of naturally occurring potassium, with the stable ^{39}K having 93.3% and stable ^{41}K being 6.7%. Early uses of potassium (potash) involved making soap from animal fat. Uranium was used as a colorant in glasses and paints, and thorium was used in mantles for gas flames, generating extremely bright light as it heated. The fission of uranium, and the large amount of energy released, was discovered in 1939 [35–36]. Physicists recognized the military potential as well as peaceful uses of fission if it could be controlled. With the growing clouds of war, interest in U as a weapon began in earnest. The largest surficial deposits known at that time were in countries whose trade activities were restricted by war; so exploration began in other countries seeking uranium as raw material for war.

The Geiger counter was developed by Hans Geiger, between 1908 and 1912, and improved in 1928 by Walther Mueller. The Geiger–Mueller counter became the primary exploration tool for uranium both before and after World War II. Major exploration projects were undertaken after the war to ensure stockpiles of uranium for the production of nuclear weapons. Thorium was of less interest as a fissionable element but interest in its use in breeder reactors grew later.

As surficial deposits were discovered, through the use of surface gamma ray detection, other methods were developed to explore for hidden deposits. These methods followed closely those of exploration geochemistry. The use of uranium expanded from war materials to energy production with the construction of commercial nuclear reactors. A uranium boom occurred in the 1970s, when a worldwide energy crisis (driven by low oil production and subsequently higher prices for consumer oil and gas consumption) coincided with a shortage of non-nuclear fuels. As a result of that crisis, nuclear-fuel raw materials gained worldwide interest and large programmes, such as the National Uranium Resource Evaluation (NURE) programme, began in the USA. As part of that programme, an airborne gamma ray spectrometric survey and a ground sample based analytical survey were designed for the

country. Many countries followed with similar programmes, but there was little coordination of methods or data reporting.

Information gleaned from such programmes proved to be very valuable, not only for exploration but especially as environmental concerns increased. This information provided insight into the distribution and mobility of various elements considered to be toxic [37]. It was recognized that regulators and litigators could use this data to determine where, and how much, pollution occurred from anthropomorphic activities. Because environmental responsibility could cost significant amounts of money, it was realized that the data had to be reported responsibly. In 1978, the international geochemical society started a programme focusing on worldwide geochemistry surveys. This is an ongoing activity that, in some countries, has been completed, partially completed, or still to be initiated. But the important point is that guidelines have been issued which, if followed, make the use and interpretation of the surveys possible on a worldwide basis.

1.2. OBJECTIVE

A baseline is a reference for measurements. A radioelement baseline is a set of measurements that conform to some standard, and depict the concentrations of radioelements at the Earth's surface at a given point in time. The term 'baseline' can be used in several different contexts — see Section 1.2 for a discussion of the term, as used in this report.

Airborne gamma ray spectrometry is the preferred method for obtaining comprehensive radioelement baseline data [1]. Large areas of the Earth's surface have been covered by airborne gamma ray spectrometric surveys. However, there are two significant problems that limit the usefulness of much of the data collected in these surveys.

The calibration and data processing of older survey data was inadequate by modern standards. In particular, poor background estimation has resulted in poor accuracy of the estimated radioelement concentrations.

In addition, much of the older data are in units of counts/sec, and the data values are therefore dependent on the instrument detector volumes, the survey height and the window energy limits used to measure the gamma radiation. Thus, data values on adjacent surveys are often, but not necessarily, directly comparable.

These problems limit the usefulness of radioelement data derived from airborne and ground gamma ray surveys. Similar problems also affect radioelement data derived from geochemical surveys. The sample site and the methods of sample collection, preparation, and analysis can affect the estimate of radioelement concentrations. Radioelement survey data need to be both internally consistent and comparable between surveys if they are to be useful in activities such as environmental management, establishing regulatory requirements and the sustainable development of the earth's resources.

Two essential needs underline the successful preparation of global radioelement baseline for gamma ray spectrometric data:

— A global network of radioelement standards that can be used for the calibration of gamma radiaton measuring instruments;
— International standards for the acquisition and processing of radioelement data.

If a mapping organization complies with these standards, then their data can be referenced to the global baseline. A global radioelement baseline for sample based geochemical data requires the collection of representative samples in a standardized manner, and consistency in the preparation and analysis of geochemical samples [1].

This report:

— Reviews the global status of radioelement mapping for both gamma ray spectrometric surveys and sample based geochemical surveys;
— Reviews the benefits and uses of a global radioelement baseline and their implications for a variety of environmental and geoscience issues;
— Facilitates the use of international standards and procedures for the establishment of a global radioelement baseline;
— Recommends procedures for adjusting existing data to conform to the global baseline.

The material contained in this report has been deemed essential for the formulation of sound environmental policies. The intended audience for this report includes: policy makers and regulatory agencies; scientists conducting geochemical surveys and analyzing geochemical data; scientists acquiring and processing airborne and ground gamma ray spectrometric data; and data custodians tasked with archiving these data.

1.3. SCOPE

1.3.1. Gamma ray spectrometric surveys

The term ‘baseline’ can have different meanings depending on the context in which it is used. For gamma ray spectrometric survey data, the term has the following meanings:

— In its broadest sense, the global radioelement baseline refers to reference standards for gamma ray measurements and a set of procedures which, when followed, will ensure that survey data are tied to (or are consistent with) the reference standards. The primary reference standards are the geological reference materials for laboratory gamma ray spectrometry issued by the IAEA [2].
— The global radioelement baseline also refers to all gamma ray spectrometric measurements acquired at specified times and processed according to IAEA specifications (Section 3). These estimates of radioelement concentrations are thus registered to the IAEA laboratory standards.
— At any survey scale, a radioelement baseline refers to the distribution and level of radioelement sources at a particular point in time, and against which temporal changes in radioelement concentrations, due to both natural causes and human activity, can be monitored. In this case an exact definition will depend on the geological environmental or regulatory context in which the baseline is used and the time of the new measurement.

The term ‘background’ can have three distinct meanings in the context of gamma ray surveys:

— For gamma ray surveys applied to the measurement of terrestrial sources of radiation in geoscience, background refers to that radiation not emanating directly from the earth’s surface. There are 3 components to this background:(1) the radioactivity of the instrument, (2) radiation of cosmic origin, and (3) radioactivity due to atmospheric radon and its progeny products. These background components are removed as part of the data reduction procedures.
— For geological applications, background radiation often refers to the average terrestrial component of the gamma ray field for a specified region or geological unit. In this case, the background could be used as a reference for estimating the anomalous values of radioelement concentrations in the area.
— For environmental applications concerned with dose rates, the background would include average cosmic and atmospheric contributions to the total dose.

1.3.2. Geochemical surveys

As opposed to the gathering of radioelement data by gamma ray spectrometry, many geochemical surveys require the collection and chemical analysis of physical samples of geological material. These surveys are referred to in this report as ‘sample based’ surveys. A geochemical baseline in the context of a sample based geochemical survey differs to some extent from the term baseline as defined for gamma ray surveys. A geochemical baseline is the concentration, or the range of concentrations, of a specific chemical parameter in a given sample of geologic material at a given point in time. The chemical parameter may be a chemical element, compound, or species, either inorganic or organic. A wide variety of media has been collected for sample based geochemical surveys. Soils, stream sediments, water and the atmosphere are the most common media, but biological material such as certain species of vegetation, and animals, have been used.

The establishment of a sample based geochemical baseline is dependent on many variables. Each is important and must be carefully considered in the design of any sample based geochemical survey. Some of the more significant variables include the following:

— *Sample medium.* The geochemical baseline is dependent on the type of material collected and chemically analysed. For example, the concentration of a given element in stream sediment is generally not the same as the concentration measured in soil. The concentration of an element in soil or sediment is likely to be very different to that measured in water.
— *Sample collection.* Varying the collection protocols for a given sample medium can change the geochemical baseline. For example, the baseline measured on A-horizon soils is likely to be quite different from the baseline measured on B- or C-horizon soils.
— *Sample preparation.* This is a variable that is often overlooked. Often, a mineral sample, such as stream sediment, is sieved to a specific size fraction (e.g. <150 μm) before being chemically analysed. Wide ranges of size fractions may have been chosen for analysis for various reasons. Consequently, the geochemical baseline may vary depending on which size fraction is selected. Preparation of water samples may include filtration and acidification. The baseline may then vary depending on the nominal aperture size of the filter used, strength or type of acid used.
— *Sample dissolution.* Many analytical techniques require dissolving the sample before introducing it to the analytical instrument. The chemicals used to dissolve the sample vary from distilled water (used to extract only the water-soluble fraction of a sample) to the use of nitric, perchloric, hydrofluoric, and hydrochloric acids (used to dissolve the 'total' sample). Many environmental studies are now using aqua regia as the extractant of choice. Each of these different dissolution methods can give very different geochemical baselines.
— *Analytical methods.* Analytical methods have varying lower limits of detection. While the more modern methods such as ICP-MS (inductively coupled plasma in combination with a mass spectrometer) have limits generally at or below crustal abundance for most of the elements. Some of the older techniques may have detection limits considerably above these crustal abundances, particularly for minor and trace elements. For this reason, some older surveys chose not to analyse for some potentially important elements. Those surveys that did analyse for these elements often produced data sets with an abundance of censored data (i.e. many values recorded only as 'lower than the detection limit'). A geochemical baseline cannot be quantified from such a data set.

In order to produce a global scale geochemical baseline using sample based geochemical surveys, a standardized procedure must be developed in which the above mentioned variables are considered. Changing any of these variables for different parts of the land surface of the Earth may result in a mixture of geochemical baselines that cannot be successfully merged. Such a patchwork picture of the geochemical landscape of the Earth minimizes the usefullness of the final database. Darnley et al. [1] provides a comprehensive discussion of the above mentioned variables and estimates that only 19% of the Earth has been covered by sample based geochemical surveys. Unfortunately, most of these surveys were not conducted using standardized protocols and cannot be successfully combined.

1.4. STRUCTURE

This report provides a comprehensive review of the status of radioelement mapping and the development of global radioelement baselines. The review covers the use of both gamma spectrometry and geochemical methods for the estimation of baseline radioelement concentrations.

Section 1 provides the purpose and scope of the report, definitions and a historical review.

Section 2 reviews the benefits and uses of global radioelement baselines. These include the effective use of radioelement data for uranium exploration and mining, geological mapping, mineral (including hydrocarbon exploration) and regolith mapping. Section 3 describes the methodology used to establish a radioelement baseline using gamma spectrometry. Section 4 describes the methodology for the establishment of radioelement baselines for geochemical surveys. Section 5 reviews the global status of radioelement mapping using gamma spectrometry and sample based geochemical surveys. The extent and quality of the global coverage are discussed.

Section 6 is dedicated to the application of radioelement baselines to uranium exploration, mining, milling and remediation.

Section 7 lists the major conclusions arising from this report. If followed up, these should lead to greater consistency in the development of radioelement data sets. This would improve the utility of these data for environmental and geoscience applications.

Appendix I indexes the worldwide coverage of gamma radiation spectrometry surveys, which illustrates that the major part of the world's land mass has been the subject of radiometric measurements. National coverage of public domain data, and contacts for each country where data is known by IAEA, are provided. Bibliographical listing of the worldwide coverage is provided in this report after the references.

Appendix II is a list of more than 40 calibration facilities for gamma ray spectrometers located in 22 countries on five continents.

This report builds on the contributions made at the 2003 IAEA Technical Meeting on Radioelement Mapping and Status of the Global Radioelement Baseline and Maps, Golden, USA, in 2003, which focused on standardization of radioelement data.

2. BENEFITS AND USES OF A GLOBAL RADIOELEMENT BASELINE DATABASE

2.1. URANIUM EXPLORATION

Historically, the development of gamma ray spectrometry methodology and instrumentation, particularly airborne methods, was driven by uranium exploration in the years following World War II. Initially, detection of anomalies was sufficient to locate deposits that possessed some kind of surface expression. As the 'easy' deposits were located, and the applications of gamma ray spectrometry to mapping or locating a broad spectrum of natural and anthropogenic (man-made) sources were realized, the technology gradually became more sophisticated. This, in turn, has led to uranium exploration applications that extend well beyond the location of primary anomalies. Radioelement mapping has continued to play a critical role in uranium exploration.

2.1.1. Identification of uranium provinces

There are two main applications of radioelement mapping for regional exploration:

— When integrated with other geological, geophysical and geochemical data, radioelement data are used to map the geology, and locate lithology and structure that are conducive to hosting uranium deposits, or source rocks from which uranium may have been mobilized.
— Radioelement data are used to assess lithologic units, or sub-units, for elevated (i.e. anomalous) levels of uranium in order to prioritize detailed exploration.

The assembly of baselines on a regional and global scale, where the concentrations of the radioelements are well calibrated, plays a critical role in recognizing uranium provinces.

Tassinari et al. describe a geochemical analysis of uranium distribution in granites (including migmatites and gneisses) for all of Brazil, which was used to locate uranium provinces [38]. The age, tectonic environment, lithology, Rb content and $^{87}Sr/^{86}Sr$ ratio were also studied to determine what correlations existed with uranium content.

2.1.2. Detection of uranium deposits

Uranium deposits types are classified as follows [39]:

— Sandstone deposits (45% of world total);

— Quartz-pebble conglomerate (and other placer) deposits (20%);
— Proterozoic unconformity-related deposits (16%);
— Other e.g. ultra metamorphic, breccia-hosted, calcrete (8%);
— Disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks (6%);
— Vein deposits (5%);
— Volcanogenic deposits (minor);
— Proterozoic strata bound and remobilized deposits in continental sedimentary environments (minor);
— Uranium in carbonatites (minor).

Deposits that outcrop can be directly detected by radioelement mapping. Their footprint may be small, of the order of hundreds of square metres, but they typically show a highly anomalous response above background. They may also be characterized by an alteration halo or eroded sediments with elevated radioelement responses.

Arkimaa used a classification of airborne gamma ray spectrometric data to explore for uranium and gold in the Kuusamo Schist Belt of northeast Finland [40]. Using the signature of known U and Au–Co–U mineralization, several targets were located despite extensive glacial overburden.

Numerous uranium deposits are buried and often at significant depths (Athabasca Basin, Saskatchewan, Canada). In such situations, radioelement mapping still plays an important role (radon content in groundwater, locating radioactive boulders, mapping alteration halos) but the anomalies may be quite subtle (Fig. 1). Other methods, such as electromagnetic surveys, to locate graphite associated with uranium deposits usually play a primary role [41].

Some of the iron oxide–copper–gold deposits contain significant uranium content, possibly at economic levels (Olympic Dam, Australia). These deposits are of particular exploration interest as they are frequently both large and rich in metals. Magnetic and gravity surveys are the primary exploration tools, but radioelement surveys locate the surface expression of alteration and uranium mineralization.

Radioelement mapping is extremely useful in locating a wide variety of mineral deposits, to map lithology and in particular, to locate alteration zones that have distinct radioelement signatures (e.g. preferential enrichment of potassium) that may be related to mineralization [22].

2.1.3. Description of uranium deposits

Once a deposit has been located, it is typically systematically drilled. Killeen [42] provides a summary of both passive (gamma ray spectrometry) and active (gamma-gamma, X ray fluorescence, neutron) borehole techniques that can be used to estimate ore grades for a variety of deposit types [42]. These can be used to characterize deposits based on related physical properties, such as uranium content or density. The method can also be used to locate alteration zones as a pathfinder to uranium or other types of mineralization.

Løvborg describes an analysis of borehole gamma ray spectrometry to estimate tonnage for a uranium-thorium deposit in Greenland [43]. The thorium results matched the drill core assays very closely. The uranium results were somewhat less accurate due to variable levels of radon in the boreholes.

A gamma ray spectrometer mounted on a conveyor system can be used to estimate uranium content in ore at various stages of crushing, sorting and milling.

2.1.4. Detection of rare earth and exotic mineral deposits

Certain types of exotic mineral deposits exhibit elevated radioelement content. These include intrusions such as carbonatite and syenite hosted rare earths, and deposits related to pegmatites (e.g. tantalum and caesium). Diamond-bearing kimberlites may be differentiated by their radioelement content from host rock with similar magnetic and conductive properties. Mineral sands may contain concentrations of radioelements that can be mapped.

Barthel et al. provide a comprehensive review of thorium deposits, including the various deposit types and examples [44]. Most thorium production results from monazite recovered as a by-product from placer deposits mined for other elements.

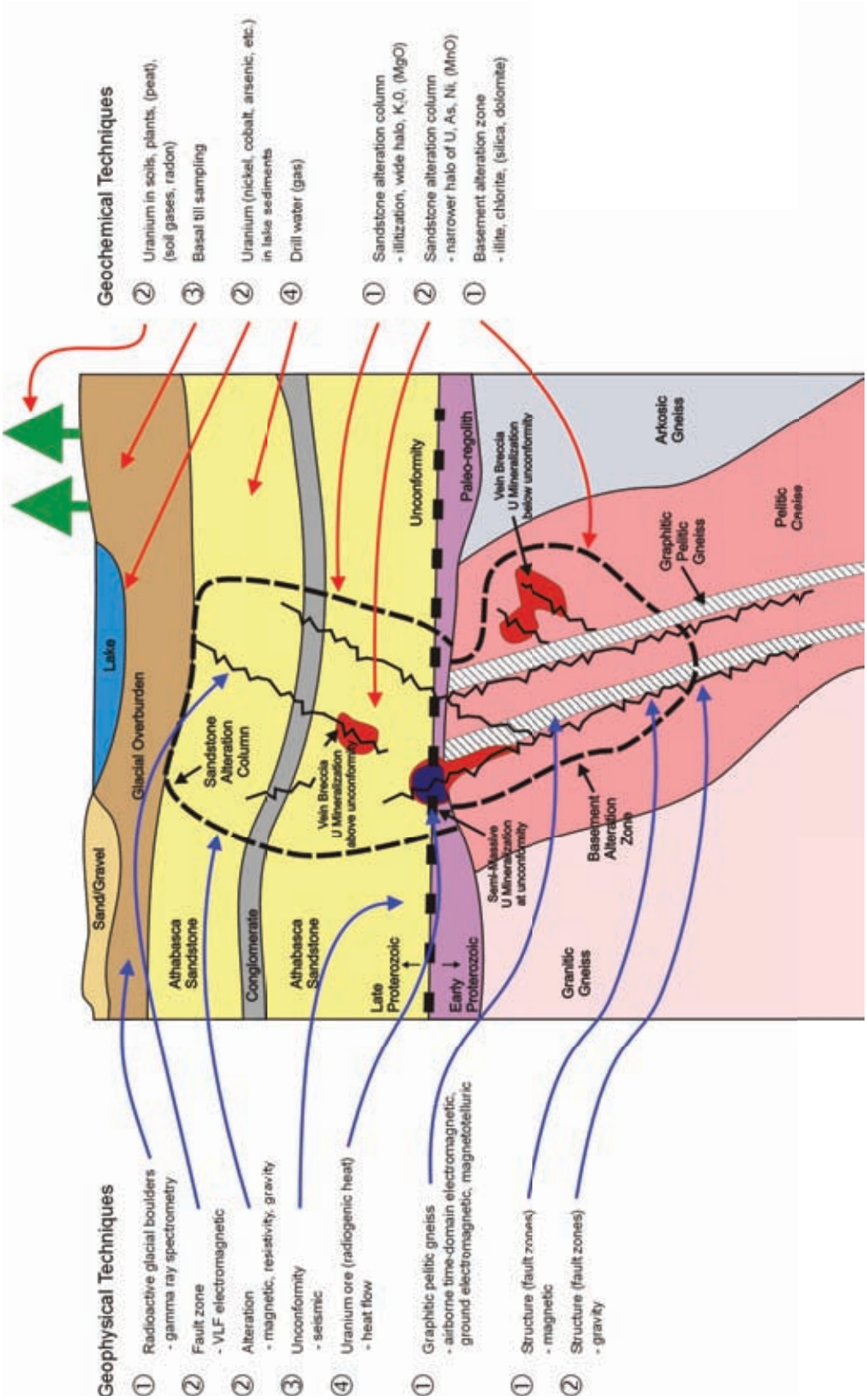

FIG. 1. Exploration techniques for deeply buried unconformity uranium deposits, Athabasca Basin, Saskatchewan, Canada, rated 1: excellent; 2: good; 3: fair; and 4: poor. (Courtesy of Hornby Bay Exploration Ltd and Cameco Corporation.)

2.1.5. Planning and levelling of geochemical surveys

Airborne gamma ray spectrometry has application to the planning of geochemical surveys. Presentation of the radioelement data (and possibly satellite imagery) together with a digital elevation model in 3-D is particularly useful for analysing the responses with respect to geomorphology. Radioelement distributions are used to:

— Map drainage systems and catchment areas;
— Interpret the presence and nature of weathering profiles;
— Map transported overburden and assess soil types.

This information is used for locating the optimum positions for geochemical sample sites for a particular application.

Darnley et al. suggest that gamma ray spectrometer data, particularly Th, K and Th/K, can be used to level corresponding geochemical surveys where Th and/or K data were determined from soils [1]. The soil should not be abnormally wet or dry during collection of gamma ray spectrometer data.

2.2. URANIUM MINE AND MILL WASTE

A comprehensive overview of the uranium production cycle and the environment is provided in Ref. [25]. It focuses on the guiding principle for radiation protection that, while taking economic and social factors into account, radiation exposures should be kept 'as low as reasonably achievable' (ALARA). ALARA was developed as a common sense approach such that radiation doses for both workers and the public are typically kept lower than their regulatory limits. It is also being applied to the environment by the uranium mining industry.

Radioelement baseline studies play a critical role throughout the uranium production cycle to determine the background levels of radiation, monitor changes in radiation over time and to verify site remediation (see Section 5).

2.2.1. Baselines of the natural background

Prior to development of a uranium mine, mill or waste disposal site (or any mining complex where the ore contains significant concentrations of radioactive material), a comprehensive baseline study of the natural background is recommended. It would form part of an environmental assessment required by regulators. In the case of a mine (and a mill if it is located at the mine site), the surrounding area may show high radioelement content if the surficial material is related to the uranium mineralization and host rock. The surface water and groundwater should be incorporated in the study as they may come in contact with radioactive material, even if it is not located at the surface. The study should also include any transportation corridors between the mine and mill. This study would form the basis for comparison of monitoring studies through the life of the mine and mill.

The IAEA provides a safety guide for waste disposal at uranium mine and mill sites [45]. It emphasizes the need for baseline studies of radioelements and other elements prior to construction of the site to provide a reference for monitoring throughout the life of the site. The baseline is important as the reference for post-closure assessment, particularly if the regulatory body has stipulated closure requirements in terms of incremental changes permitted in parameters rather than by setting absolute limits. A complementary publication gives a comprehensive review of the components of a baseline study for sites used to store the residues of uranium and thorium mining, as well as the monitoring procedures [46]. It discusses the processes that may result from the storage of the wastes, and the preferential methods of measuring them.

2.2.2. Site contamination

A continual programme of monitoring the ground, air, water (surface and underground), waste material and transportation corridors, and comparison to the baseline data, will alert the site owners and regulatory authorities to any contamination episode. Repeated baseline studies are needed to assess the short and long term impact of the contamination and verify that satisfactory remediation has been achieved.

2.3. NUCLEAR EMERGENCY PREPAREDNESS

Fission or activation products, which can be transported by atmospheric processes over large areas, are usually characterized by short half-lives (Section 3.6). An exception is ^{137}Cs, which has a half-life of approximately 30 years. Caesium contamination produced during the atmospheric nuclear weapons testing programmes of the 1950s and 1960s can still be found in soils worldwide. The caesium contamination deposited after the Chernobyl accident can still be observed, for example, in Scandinavia and central Europe.

A major benefit of a global radioelement baseline database is the ability to measure the extent of any further caesium contamination from possible future nuclear plant accidents. Several countries have used airborne gamma ray surveys to establish local radioelement baselines in the vicinity of operating nuclear plants [47–50].

2.3.1. Nuclear plant accidents

Since the Chernobyl nuclear power plant accident in 1986, public opinion has been alerted to issues concerning the safety of nuclear plants — particularly in Europe. An extensive literature search [51] produced information on approximately 150 nuclear incidents. In 38 of these, radioactive material was released beyond the installation's site boundary. As the number of incidents with off-site release of radioactive material has been constant over the years [51], there is a need to be prepared for possible future incidents, and to be able to measure the extent of any future contamination.

2.3.2. Lost radioactive sources

On average, three incidents involving radioactive sources or radioactive material per year have been reported to the IAEA since the early 1990s [52]. Because the hazards in these cases are localized, a global baseline is not that useful in these situations. However, where radioactive material is accidentally distributed over larger areas, as happened during the Cosmos 954 satellite incident when more than 100 000 km^2 in Canada were contaminated [53], a global radioelement baseline is useful for estimating the extent of the contamination.

2.4. GEOSCIENCE APPLICATIONS

There are two main benefits of a global radioelement baseline for geoscience applications. First, broad-scale, continuous coverage of radioelement data facilitates the recognition and interpretation of regional features in the data. Second, where continuous coverage is not available, and surveys are referenced to a global baseline, lessons learned in one area can be applied to the interpretation of data elsewhere. A comprehensive review of the application of radioelement mapping data to geoscience can be found in Ref. [22].

2.4.1. Geological mapping

Radioelement data are used for the mapping of lithological units and is a very common down-hole technique. Although there is significant overlap between the range of radioelement concentrations found in common rock types, some general associations can be made. Igneous rocks are generally more radioactive than sedimentary rocks, although some slates and shales can have high concentrations of U and Th. Radioelement concentrations in igneous rocks tend to increase with increasing Si content, with the highest concentrations found in pegmatites. Felsic intrusions are the most radioactive. Mafic intrusions and volcanics tend to have lower concentrations of radioactive minerals.

Interpretation of radioelement data should take into consideration factors such as the extent of outcrop, the distribution of in situ and transported soils, and the degree and nature of weathering of rocks and soils. If extensive radioelement coverage is available, then large scale regional distributions and patterns in the data may emerge.

2.4.2. Regolith and soil mapping

Weathering modifies the concentration and distribution of the radioelements, and the degree of weathering depends on the climate to which the rocks and soils have been exposed. Differences in radioelement concentrations between fresh bedrock, weathered regolith, and transported material can be expected. Uranium can be leached from rocks and soils and deposited in sediments some distance away. Thorium is less soluble but can be differentiated from the parent material through transport in solid mineral grains. Even where soils are in situ, radioelement concentrations can vary throughout the profile.

Because weathering modifies the concentration and distribution of the radioelements, radioelement data can provide information on geomorphic processes and soil/regolith properties [54]. If the radioelement data are registered to a global baseline, then associations made in one survey area may be useful for the interpretation of radioelement data elsewhere.

2.4.3. Mineral and hydrocarbon exploration

Early gamma ray spectrometric surveys were used almost exclusively for the direct detection of U and Th orebodies. But radioelement data can also be used for the indirect detection of a number of metal deposits. Porphyry Cu-Au deposits may be detected through potassium alteration, and gold through Au-U associations. The interpretation of K alteration from radioelement data has led to several mineral discoveries [55–56]. Further examples are given in other IAEA publications.

Hydrocarbon accumulations at depth can result in measurable geochemical anomalies at the surface. Hydrocarbon microseepage is due to the vertical migration of gas above hydrocarbon deposits. Through a chemical reduction process [22][57], K and U concentrations can be reduced relative to Th. Alternatively, the signature of reduction-oxidation electrochemical cells above reduced bodies has been applied to both hydrocarbon and mineral exploration [58]. Both types of alterations can be inferred from variations in radioelement concentrations.

2.4.4. Heat flow studies

Baseline radioelement data sets have application to heat flow studies. In areas of solid rock outcrop, knowledge of the distribution of K, U and Th (in absolute concentrations) can be used for estimating radiogenic heat production and modelling heat flow within the Earth. This is useful for estimating the bulk chemical composition of the crust and for predicting the mechanical behaviour of the crust during the geological past. For example, heat flow controls the thermal regime and hence mechanical strength of the crust. This has a bearing on the behaviour of the crust during orogenesis, with implications for tectonic evolution and mineral system/ore formation studies.

2.4.5. Geochemical baselines

Geochemical data are widely used in the earth and environmental sciences. Baseline geochemical data are essential for informed decision making on issues related to mineral exploration, the environment, agriculture, and public health. Radioelement data are just one component of comprehensive geochemical databases. If the radioelement data are registered to a global datum, then they can be directly compared with other geochemical data. For example, a global Th datum could assist in the levelling of geochemical surveys worldwide. Radioelement data also have applications for the planning of geochemical surveys. For example, K, U and Th radioelement data derived from airborne gamma ray surveys can be used to infer the provenance of surficial materials — thus assisting in the selection of geochemical sample sites.

2.4.6. Land use applications

Baseline radioelement data are increasingly being used in decision making processes relating to land use. These issues include areas such as trace element pollution, water quality, metal contents in foods, and natural levels of radiation — including the health risks associated with high levels of atmospheric radon.

2.5. HEALTH AND ENVIRONMENTAL APPLICATIONS

The 1986 Chernobyl incident served as a catalyst in the mapping and detection of anthropogenic radioelements. It proved the effectiveness of tracking the spread of radioelements using gamma ray spectrometry and other methods in near real time, and also the requirement for well-designed and tested response methodologies to nuclear emergencies. The importance of the establishment and maintenance of radioelement baselines, not only of the naturally-occurring isotopes, but also the anthropogenic isotopes, is critical to measuring short and long term effects. Proper calibration of the data is required if they are to have lasting value. The IAEA provides a number of case histories for mapping of anthropogenic radioelements and radon risk mapping.

In recent years, security and environmental concerns have driven developments in gamma ray spectrometry instrumentation and their application. A wide array of hand-held, portable and stationary devices has been developed to detect isotopes of interest, requiring several types of detectors (e.g. thallium-activated sodium iodide, germanium, cadmium zinc telluride, neutron, Geiger-Mueller, plastic). Car-borne systems for nuclear emergency preparedness, and detection of lost sources, have become increasingly sophisticated.

There is a wide variety of anthropogenic isotopes that may be produced as a product of a nuclear process. Table I lists these isotopes and their measurement characteristics. The instrumentation and methodology best suited to map and monitor these isotopes vary with the measurement characteristics. Mapping often requires a staged process, for example an airborne gamma ray spectrometer survey to locate sources of radioactivity, followed by ground-based measurements with different sensors to identify and locate the specific isotopes. There are economic implications of the different survey methods and instrumentation, and a cost/benefit analysis is usually necessary to determine the best approach to achieve the desired objectives at a particular site.

Baseline studies of both the natural and anthropogenic radioelements should be incorporated in epidemiological studies where the incidence rates of disease and illness are correlated with environmental effects. Analysis of spatial and temporal variations in the radioelements can help to determine the root cause of a corresponding increase or decrease in the incidence rate of a certain health characteristic, and lead to improved policy. Darnley provides an example extracted from the Atlas of Endemic Diseases and their Environments in the Peoples Republic of China, (1989) [1]. It shows a direct correlation between regions of deficient Se in the natural environment and two, sometimes fatal diseases.

The Scottish Universities Research & Reactor Centre (SURCC) undertook a comprehensive airborne gamma ray spectrometer campaign between 1988 and 1993 across 16 areas in the United Kingdom [59]. The applications of the surveys included mapping of aged nuclear fallout, Chernobyl derived activity, dynamic signals in the estuarine and coastal environment, and technologically enhanced natural signals at nuclear and industrial sites. SURCC developed instrumentation that incorporated two NaI and two Ge detectors that could be mounted in a helicopter or vehicle, and also techniques to calibrate and process the gamma spectra to recognize the signals due to

TABLE I. SIGNIFICANT NUCLEAR FALLOUT RADIONUCLIDES EMITTING GAMMA RAYS

Isotope	Half-life	Energy of gamma rays (keV)
^{95}Nb	35,15 d	766
^{95}Zr	65,60 d	724, 757
^{103}Ru	39,50 d	497, 610
^{106}Ru	368,2 d	512
^{131}I	8,05 d	364
^{132}I	2,38 h	668, 773
^{132}Te	78,33 h	228
^{134}Cs	2,06 y	605, 796
^{137}Cs	30,12 y	662
^{140}Ba/La	12,78 d	487,1596

anthropogenic radioelements. Their studies showed the effects of geomorphology and climate on the deposition and preservation of fallout from Chernobyl and previous activities, providing guidelines for mapping activities for future incidents. They were also able to map the control due to tidal and estuarine movement on the distribution of fallout and waterborne emissions from nuclear sites. The collection of case histories demonstrates the applicability of airborne gamma ray spectrometry to a range of problems resulting from human activity, as well as studying the natural radioactive background.

Parslow provides an excellent example of a radioelement baseline data set that was available, but not used, in the exploitation of groundwater in the Kadugli region, central Sudan [60]. UNICEF established a small dam and hundreds of wells in the area throughout the 1970s and 1980s where minimal fresh water was available. At the same time, a geological mapping campaign located four nearby uranium occurrences. Subsequent studies showed high radioelement contents in the groundwater. The net result was that the water supply, though adequate for the local population, was considerably contaminated. If the radioelement data had been acquired and utilized properly in the water development, the contamination could have been avoided.

2.5.1. Nuclear site evaluation

Nuclear facilities include nuclear power plants, waste treatment plants and waste disposal sites. All require baseline studies and ongoing monitoring to ensure that the air, water and soil are not contaminated by leakage of nuclear material, whether by a sudden event or long term, low level activity. Baseline studies proximal to nuclear sites are useful to familiarize the public with the existing levels of both natural and man-made radiation from all sources.

A recent example of a baseline study is the helicopter gamma ray spectrometer surveys undertaken over two operating Canadian nuclear power plants (Pickering and Darlington, Ontario) in 1999, and a nuclear waste disposal research facility slated for decommissioning in 2000 [61]. The objectives were to examine the radiation signatures of the facilities, and determine the background radiation levels in the surrounding areas. The data processing was configured to determine the levels of ^{137}Cs, ^{60}Co, ^{16}N and ^{41}Ar, in addition to K, U and Th (Fig. 2). Normal levels for all elements were found within and outside the facilities, and particular signatures for each site explained by known sources. The survey results provide a baseline for the nuclear facilities and surrounding region, should any contamination occur. Grasty describes a ground follow-up study at the Darlington site where fourteen ^{60}Co sources were located on the grounds [62]. This report provides an excellent overview of various types of ground-based instrumentation and survey techniques needed to properly evaluate a nuclear site.

The geological disposal of radioactive wastes is summarized in Ref. [63], with particular emphasis on the safety case, and safety/performance assessments in the development process. It mentions the need for a baseline study prior to construction of the waste disposal repository, focused on characterization of the geological environment. In most cases, this will include the hydrogeology to determine the potential effects on groundwater.

2.5.2. Industrial site evaluation

Industrial sites and military installations that use radioactive materials are in a similar situation to nuclear sites and uranium mines/mills, although the volume and perhaps the lethality of the material are less. Consequently, monitoring is required in and around the areas where the radioactive material is utilized and stored. A baseline study of the complete site and neighbouring area may be in order, depending on the potential impact of an incident. Storage sites require studies of the surface and groundwater, in addition to the soil, to monitor for any leakage.

The largest sources of radioactivity dispersed from industrial (non-nuclear) activity are fly ash or bottom ash from coal-burning electricity generation plants, and phosphate fertilizers used in agriculture [64]. In the former case, radioelements are concentrated through the coal burning process. Baseline studies help determine the incremental increase in radiation dose on the affected population and environment.

2.5.3. Nuclear material transportation corridors

The establishment of radioelement baselines along transportation corridors used for nuclear material is recommended. It is particularly relevant to roads and railways that are used regularly. Reference [65] provides guidelines for response to transportation accidents, but does not address the issue of baselines. Baseline data

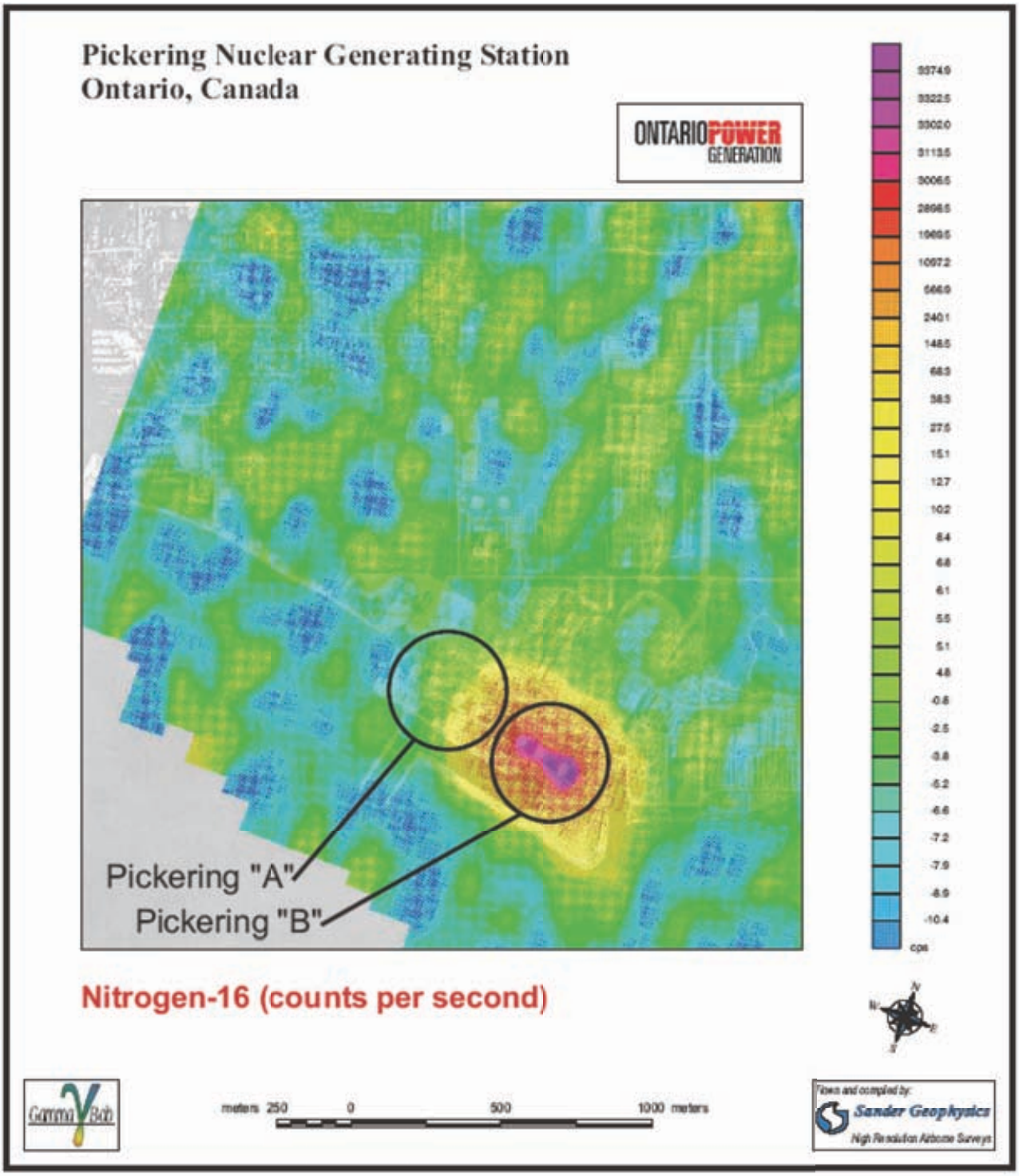

FIG. 2. Image of ^{16}N concentrations in the vicinity of the Pickering Nuclear Generating Station, Ontario, Canada, showing elevated levels over the operating Pickering B reactor and background levels over the shutdown Pickering A reactor, and the remainder of the complex and surrounding residential area. (Courtesy of Sander Geophysics Limited.)

proves most useful for locating a source lost during transport, locating contamination due to leakage, or evaluation of the impact of ongoing use of the corridor (e.g. accumulation of radioactive material over an extended period of time).

2.5.4. Building materials

Building materials require evaluation for excessive radioelement content if it is possible they were derived from radioactive material. This includes recycled steel that may have been irradiated and uranium tailings used in road or building construction. It also applies to naturally-occurring rocks (e.g. radiogenic granites) that are mined for aggregate or ornamental stone. It is becoming standard practice in certain industries (e.g. steel manufacturing, garbage disposal) that the material is passed through a purpose-built gamma ray spectrometer to ensure that radioactive material does not place the public at risk. Cox describes the development of large scale plastic detectors to monitor vehicles loaded with scrap steel, to locate shielded sources and other radioactive material [66]. The implementation of these systems was in response to a series of incidents worldwide where ^{60}Co and ^{137}Ce sources were melted and incorporated into steel, resulting in expensive decontamination of the plants, and destruction of the buildings where the contaminated steel had been used in construction.

2.5.5. Security

Purpose-built systems and hand-held devices that scan for radioelements are used at border crossings, ports and other sensitive entryways for security purposes. Much of the current and future development in instrumentation is driven by security issues. In particular the need to be able to monitor, locate and characterize radioactive material.

2.5.6. Radon risk mapping

Radioelement baseline studies make an important contribution to radon risk mapping. ^{222}Rn is a colourless, inert gas and is a progeny product of ^{226}Ra in the ^{238}U decay series, with a half-life of 3.82 days. The gas migrates through soil and rocks over tens of meters by diffusion and convection. The exposure to high concentrations of radon in buildings for extended periods of time poses a definite lung cancer risk to humans. Therefore, mapping the concentration of uranium in rocks and soils is the best method for determining radon risk on a regional scale. The class of igneous rocks known as alkali intermediate intrusives and extrusives possess particularly high concentrations of uranium. Locally, radon distribution is significantly affected by soil/rock permeability and soil moisture, and direct measurement of radon concentrations below ground surface provides a more accurate assessment of the risk because it takes these modifying factors into account [67]. This is emphasized by a radon study in southern England, where geochemical and spectrometer data were compared to indoor radon levels [68]. The three main controls were found to be the source mineralogy, the uranium concentration and the permeability of the soil and rock. A good example of radioelement baselines applied to regional radon risk mapping is provided by Barnet, which assesses the issue across the Czech Republic [69]. Ford addresses a study over radiogenic geology for planning of a housing development [70]. The mode of construction, materials used and ventilation play a large role in the volume of indoor radon that collects in a building. In the USA, the airborne gamma spectrometric component of the National Uranium Resource Evaluation (NURE) study was compared with a large data set on indoor radon measurements. It was found that the airborne gamma spectrometric component had a 70% correlation in identifying areas of higher radon risk (http://eetd.lbl.gov/IEP/high-radon/hr.html). Similarly, ground based sampling for soil gas radon could identify, on a large scale, high risk areas [71].

2.5.7. Temporal variations in anthropogenic radioelements

The naturally-occurring radioisotopes measured by gamma spectrometry are generally in equilibrium, with half-lives of the U and Th progenitors on the order of 10^9 to 10^{10} years (except the radioisotopes of uranium decay series under certain weathering and ground conditions). Anthropogenic radioisotopes are generally temporally unstable. Table I shows that several have a half-life of ten days or less, and only ^{134}Cs and ^{137}Cs have half-lives that exceed two years. Consequently the concentrations of these radioisotopes in the natural environment rise and fall as a result of new incidents, natural decay and mobilization. The implication, particularly for the longer lasting isotopes, is that regular baseline studies are required to monitor these changes, and differentiate between natural decay and other temporal variations.

2.5.8. Policy and regulatory issues

The regulatory framework surrounding radioactive materials is steadily being refined on the national and global levels. It is critical that the establishment and maintenance of radioelement baselines be legislated as a key component for managing man's nuclear endeavours and to provide security to the general populace and the natural environment. The IAEA is the primary global agency for determining protocols related to radioactive materials, and assists its Member States in drafting appropriate legislation.

Regulatory agencies at the national, state/provincial and municipal levels determine acceptable limits for the content of radioelements in air, water and soil. These levels should be determined in the context of baseline studies, particularly of the natural environment, so that the limits are realistic in a local context. There are numerous cases where the upper limit for emission of a particular element exceeds the local value of the natural background, making it impossible for the regulated activity to meet the standard. Figure 8 (Section 4.3.3.1) shows the uranium levels across the USA measured using regional scale, airborne gamma spectrometer surveys. The concentrations depicted on the map are almost entirely due to uranium that occurs naturally in the rocks and soils. While regulating the uranium limit in a particular area is desirable, this type of data may be determined relative to the natural background.

Government agencies and international institutions regularly sponsor the collection of new radioelement data, and the recovery of archived data. It would be extremely useful if the guidelines provided in this report were followed, so that the data inherently formed part of the global radioelement baseline.

3. METHODOLOGY TO ESTABLISH A RADIOELEMENT BASELINE USING GAMMA SPECTROMETRY

As indicated in the introduction to this report, the establishment of a global radioelement baseline based on gamma ray spectrometric measurements has, as its foundation, two essential elements. First, there needs to be an easily accessible global network of radioelement standards that can be used for the calibration of gamma ray instruments. Second, there needs to be a set of standard procedures for the acquisition and processing of radioelement data. If a gamma survey complies with both of these, then the radioelement data will be referenced to the global baseline.

The principles of gamma spectrometry are reviewed in the next section. This is followed by a description of the calibration facilities and procedures required for the establishment of a global radioelement baseline. The discussion is pertinent to airborne, ground (portable), car-borne, borehole logging, and laboratory spectrometry, as each of these methods share common principles and methodology.

3.1. PRINCIPLES OF GAMMA RAY SPECTROMETRY

Only a brief description of the gamma spectrometric method is given here. Comprehensive accounts of the method can be found in Ref. [72].

3.1.1. Theory

Potassium, U and Th are the only naturally-occurring elements with radioisotopes that are readily detectable using the large NaI detectors commonly used in both ground and airborne gamma surveys. Potassium is measured via gamma emissions from ^{40}K, the only radioactive isotope of K, which occurs as 0.012% of natural K. ^{238}U and ^{232}Th are unstable and give rise to decay series that terminate in stable isotopes. The gamma method uses gamma

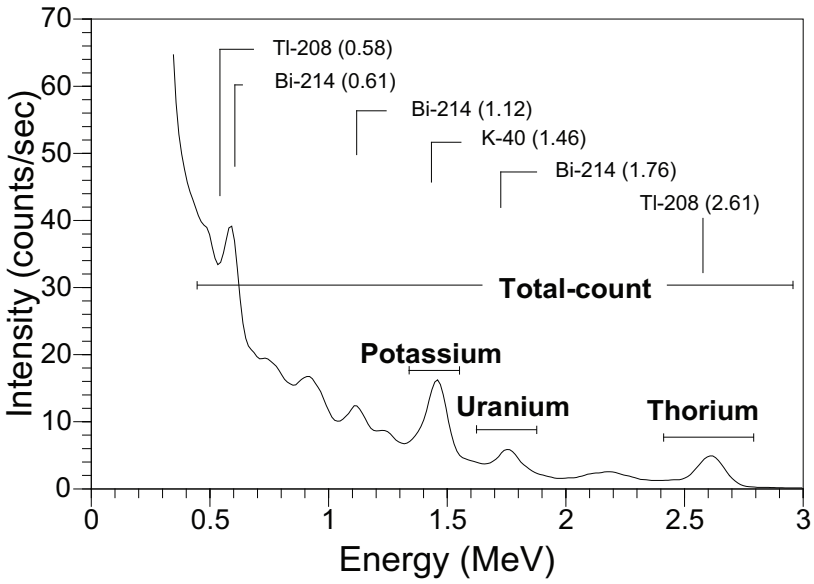

FIG. 3. A typical gamma ray spectrum recorded at 60 m height above the ground using a 33 L NaI(Tl) detector and a long integration time.

emitting daughter products in this decay series to indirectly estimate the concentrations of U and Th. Gamma rays have associated energies that are measured in electron volts. The main emissions commonly monitored in field gamma spectrometry are at 1.46 MeV for K (^{40}K), 1.76 MeV for U (^{214}Bi), and 2.62 MeV for Th (^{208}Tl). Estimation of U and Th concentrations is thus based on the assumption that their respective decay series are in radioactive equilibrium. This is not usually the case with the ^{238}U decay series, and this is a significant source of error in the estimation of U.

Figure 3 shows a typical gamma spectrum measured with a long sampling period using a thallium-activated sodium iodide NaI (Tl) detector. These detectors have the property that the absorption of a gamma ray in the detector is accompanied by a scintillation of a light photon whose intensity is proportional to the energy of the incident gamma ray. Each gamma ray (or 'count') has its energy estimated, and the numbers of gamma rays as functions of energy are recorded as a spectrum such as that shown in Fig. 3. The conventional energy windows centred on the ^{40}K, ^{214}Bi and ^{208}Tl photopeaks used to detect the presence of K, U and Th are also shown in the figure. The heights of these photopeaks are proportional to the concentrations of the respective radioelements. The exponential rise in the channel count rates towards lower energies is due to the Compton scattering of gamma rays from the higher energy emissions. The Compton scattering occurs either in the source, in the air between the source and the detector, or in the detector itself. Scattered gamma rays suffer a partial loss of energy and appear as counts in lower-energy channels. Thus, some of the counts in the U window are due to Th, and some of the counts in the K window are due to both U and Th. These scattered gamma rays are removed from the window count rates as part of the data processing procedure described later.

3.1.2. Data acquisition

NaI(Tl) detectors are the most common detectors used for both ground (portable or vehicle-borne) and airborne gamma surveys. Incident gamma rays interact with the detector crystal to produce scintillations. These photons of visible light are measured using a photomultiplier, with the voltage pulse output of the photomultiplier proportional to the energy of the incident gamma ray. The output pulse amplitudes are analysed, and the output of the detector is an energy spectrum. Most modern spectrometers are multichannel (256, 512 or 1024) differential spectrometers. They record the number of gamma rays with energies falling within specified energy ranges. For example, typical airborne gamma ray spectrometers record 256 channels between 0 and 3.0 MeV. Each energy channel therefore records the number of gamma rays absorbed by the detector that have energy within an 11.7 keV range.

The sampling integration time (sample interval) depends on the purpose of the survey — the longer the sample interval, the greater the precision of the measurement. Fixed-wing airborne surveys flown at nominal survey heights greater than 40 m would use a sample interval of 1s. For lower flying heights, or for helicopter surveys, there may be an advantage in using a 0.5 s sample interval. For measurements with portable spectrometers at specific sites, sample intervals of several hundred seconds are typically used.

3.1.3. Survey design

The survey design depends on the purpose of the survey. Airborne gamma spectrometric surveys are usually flown on a regular grid of parallel lines spaced between 50 m and 400 m apart. Flying heights of between 20 m and 100 m are common. The line spacing represents a trade-off between the required spatial resolution of the data and the cost of the survey. Regional geochemical baseline surveys might have a line spacing of 1 km or greater.

Portable spectrometer surveys range from spot readings for mineral exploration to airborne surveys for detailed soil mapping. For moving detectors there is also a trade-off between spatial resolution and the precision of the measurements. Large sample intervals give good precision but poor spatial resolution. Precision can be improved by reducing the speed of the detector, by increasing the detector volume, or in the case of airborne surveys, by flying closer to the ground.

3.1.4. Calibration and data processing

Comprehensive descriptions of the standards and procedures for the calibration of both airborne and portable spectrometers, and the processing of these data, can be found in Refs [22], [72]. Only brief descriptions of the procedures are given here. The corrections that need to be applied to gamma ray spectrometric data are as follows.

- *Spectral noise reduction*. Where a large number of raw gamma ray spectra are available (typically more than 10 000), principal component (PC) type methods can be used to remove noise. These methods exploit the fact that the signal tends to correlate highly between spectrum channels whereas the noise is random. After suitable normalization of the raw spectra, PC type analysis can extract the dominant signal components in the data. These components are used to reconstruct noise reduced spectra. There are no calibration requirements for this stage of the data processing.
- *Live time correction*. Spectrometers require a finite time to process each recorded gamma ray count, and this reduces the total counting time available. Modern portable spectrometers automatically correct for live time. Modern airborne spectrometers measure the sample live time and this is output with the data stream. The live time correction adjusts channel count rates to the count rates that would have been observed had the spectrometer counted for the full sample period.
- *Energy calibration*. Spectrometers are affected by energy drift in the measured spectra. This is not a significant source of error for modern spectrometers that automatically correct for drift. But drift can be a significant problem with older spectrometers. Spectra are corrected by using the positions of prominent photopeaks to re-sample each spectrum channel to its correct energy range.
- *Background corrections*. There are three components to the background correction: The instrument background (called ‘aircraft background’ in airborne gamma spectrometry), cosmic background, and the effect of atmospheric radon. In portable or car-borne gamma ray surveys, the background component is usually small relative to the signal from the ground. The background is then measured once — typically over a large body of water at least several hundred metres from shore. In airborne gamma surveys, the radon background component, in particular, comprises a large proportion of measured gamma rays, and more sophisticated means are used for estimating the background radiation. Aircraft background is constant, and is derived from a series of high-altitude calibration flights over water. The shape of the cosmic spectrum is estimated from the same calibration flight data. By monitoring a cosmic window (energies greater than 3.0 MeV) the cosmic contribution to any channel can be estimated. There are two approaches to the estimation of atmospheric radon background in airborne gamma spectrometry. Upward looking detectors can give airborne spectrometers a directional sensitivity and the means to discriminate between atmospheric radon and terrestrial sources of radiation. Alternatively, a spectral method that uses the shape of measured gamma spectra to estimate the relative contributions of terrestrial sources and atmospheric radon can be used.

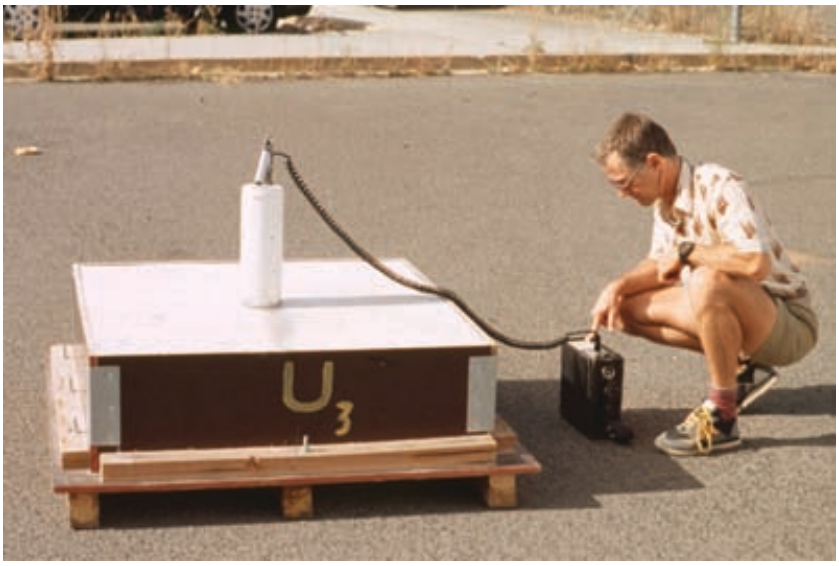

FIG. 4. Calibration of a portable spectrometer on transportable concrete calibration pads.

Complete descriptions of these methods, and the calibration procedures required for their implementation, can be found in Ref. [22]. Background estimation is a significant source of error in airborne gamma spectrometry which will be discussed later.

— *Stripping corrections*. The stripping correction removes ('strips') counts from each of the K, U and Th energy windows that do not originate from their associated radioelement or decay series. As indicated earlier, thorium series gamma rays appear in both the U and K windows, and U series gamma rays appear in both the K and Th windows. 'Stripping ratios' are constants that relate the number of counts in an ancillary window to the number of counts in the radioelement window for a pure source of the relevant radioelement. They are used in equations to affect the stripping corrections. For example, the stripping ratio 'alpha' is the count in the U window per unit count in the Th window for a pure Th source. Similar ratios 'beta', 'gamma' and 'a') apply to the other radioelements and windows. The stripping ratios are derived from calibration experiments over specially constructed radioactive concrete pad sources (Fig. 4). Stripping ratios vary with the height of the detector above the ground, so a correction based on the height of the aircraft has to be applied for airborne gamma surveys. Full details on the stripping correction and the derivation of stripping ratios can be found in Ref. [22].

— *Height correction.* Height corrections only apply to airborne gamma spectrometric data. Gamma radiation falls off approximately exponentially with the height of the aircraft. Because the height of the aircraft changes continuously, the window count rates must be corrected to a nominal survey height above the ground. The rate of attenuation of gamma-radiation with height depends on the energy of the radiation. The relevant attenuation coefficient for each of the radioelement energy windows is determined empirically from data acquired through a calibration range. This is an easily navigated strip of land with approximately uniform distribution of the radioelements. The calibration range is flown at several heights, and the window attenuation coefficients are derived from an exponential regression of the background-corrected and stripped window count rates against detector height.

— *Reduction to elemental concentrations*. While the corrected window count rates are proportional to the concentrations of the radioelements in the ground, they are also dependent on the equipment used (detector volume and efficiency, window widths) and, in the case of airborne surveys, the nominal survey height. Corrected window count rates are therefore converted to equivalent concentrations of the radioelements by dividing each count rate by a 'sensitivity' coefficient. Window sensitivities for portable spectrometers are derived directly from the calibration data acquired over the concrete calibration pads used for the estimation of stripping ratios. Corrections to the sensitivity coefficients for the finite dimensions of the pad must, however, be made [22]. Because airborne survey sensitivities are a function of the height of the detector, they

can not be determined from measurements on the calibration pads. Instead, they are estimated indirectly through the use of a calibration range as follows. The calibration range is flown at the nominal survey height. At the same time as the calibration range is flown, a calibrated portable spectrometer is used to measure the concentrations of the radioelements along the calibration range. Sensitivity coefficients are derived from the ratio of the average background-corrected and stripped airborne window count rates along the calibration range and the corresponding average concentrations measured with the portable spectrometer.

3.1.5. Error sources, accuracy and precision

Most of the errors in gamma spectrometry derive from the statistical nature of radioactive decay. Each radioactive decay is a random event. This means that the frequency of observed gamma rays associated with radioactive decay follow a Poisson statistical distribution. A special property of this distribution is that the variance is equal to the mean. As a consequence, if two measurements are taken over the same source, then the sum of the two measurements will have a smaller fractional error than that of the individual measurements. For example, for Poisson distributed window countrates with a mean of n, the standard deviation of a single 1-s measurement will be $\sqrt{n}$, and the fractional error thus $1/\sqrt{n}$. However, if two 1-s measurements (that sample the same source) are summed, the fractional error in this channel is reduced by $\sqrt{2}$.

Increasing the sample integration time can thus increase the precision of portable gamma measuring measurements taken at discrete sites. Alternatively, count rates, and hence the precision of measurements, can be improved by increasing the detector volume. For airborne measurements and moving detectors, the sample time is usually fixed, as it defines the spatial resolution of the measurements. Precision can only be increased by increasing the detector volume, or in the case of airborne surveys, increasing the count rates by flying closer to the ground.

Sources of inaccuracy in gamma ray surveys include the following.

— Disequilibrium in the ^{238}U decay series.
— Source geometry. Sensitivity and height attenuation coefficients are derived using a source geometry approximating a radioactive half-space. Rugged terrain can lead to significant errors in both portable and airborne gamma surveys.
— Vegetation and other absorbers such as leaf litter on forest floors can significantly attenuate radiation. Where the vegetation cover in the survey area is different from that on the calibration range, airborne survey data can be in error. Soil moisture has a similar effect.
— Inadequate calibration and data processing procedures.

Of most concern to radioelement baseline mapping is the introduction of systematic biases into processed data. Inadequate atmospheric radon background removal can be a major source of error for airborne gamma data. The atmospheric radon contribution to the U window count rate can be many times the contribution from U decay series radioelements in the ground. So, even small errors in radon background estimation can translate into large biases in the background-corrected U window count rate. Another source of bias in airborne data is through inaccurate estimation of the window sensitivity coefficients during calibration. Again, the presence of atmospheric radon is often the source of the problem. For example, sensitivity coefficients are derived from the average background-corrected and stripped window count rates obtained over a calibration range. The background is usually measured over a nearby body of water. If the background over the water is not the same as the background over the calibration range, errors will be introduced into the estimation of the sensitivity coefficients.

Finally, the calibration procedures for the estimation of sensitivity coefficients for both airborne and ground surveys rely ultimately on the use of concrete calibration slabs. Obviously, if the concentrations of these slabs are in error, then processed airborne and ground survey data tied to these calibration pads will be in error as well.

3.2. ESTABLISHMENT OF GAMMA RAY SPECTROMETER CALIBRATION FACILITIES

The approach taken to the calibration of gamma spectrometers is empirical. The calibration constants are derived by measuring the instrument response to calibration sources that simulate the source-detector geometry likely to be encountered during field surveys.

3.2.1. Calibration overview

Gamma ray spectrometers record both the number of gamma rays interacting with a detector within a specified sample interval and the energy lost by each gamma ray to the detector. Measured count rates are relative measures of a radiation field. Both count rates and measured energies depend on the response of the detector. The detector response includes such factors as detector volume and detection efficiency. In order to convert the measured count rates and energies to physical units, such as radioelement concentrations or air-absorbed dose rate, the instrument must be calibrated.

The calibration requirements for portable, airborne and laboratory gamma spectrometers are described in detail in [22][72]. The essential requirement for all calibrations is access to suitable radioactive sources with known concentrations of the radioelements. These reference sources are used to estimate the response of gamma ray spectrometers to pure K, U and Th sources for a specific source-detector geometry. The main gamma ray spectrometers calibration factors that require specialized calibration facilities are:

— *Stripping ratios.* These are used to convert background-corrected window count rates to elemental count rates.
— *Sensitivity coefficients.* These are used to convert elemental count rates to elemental concentrations.

For portable and laboratory spectrometers, the stripping and sensitivity corrections are usually combined into a single correction to convert background corrected window counts to elemental concentrations using a matrix method of enumeration [22].

3.2.2. Laboratory calibration sources

Laboratory spectrometers are calibrated using calibration sources (cylindrical canisters) that have identical geometries to the samples used in routine analyses. The accuracy of laboratory analyses depends on the accuracy to which the concentrations of the radioelements in the calibration sources are known. In 1987, the IAEA, in collaboration with the Canada Centre for Mineral and Energy Technology (CANMET), introduced a set of three certified geological reference materials (called the RG-set) for laboratory gamma ray spectrometry analysis [2].

— RGK-1 is a potassium-rich material (44.8% K) prepared from potassium sulphate.
— RGU-1 is a U+Ra-rich material with 400 ppm U and 392 ppm eU (Ra) prepared by dilution of uranium ore with floated silica powder of similar grain size distribution. The ore is in radioactive equilibrium.
— RGTh-1 is a Th-rich material with 800 ppm Th and 6.3 ppm U prepared by dilution of thorium ore (a rare earth phosphate) with a floated silica powder of similar grain size distribution.

The assignment of K, U and Th concentrations to these geological reference materials was based on analytical assays performed in 29 renowned laboratories in nine countries. These reference materials have been available from the IAEA since 1987. The certified RG set has been adopted as the primary standards for all laboratory gamma ray spectrometry analyses. Because calibrated laboratory spectrometers are used for estimating the radioelement concentrations in calibration sources used for portable and airborne spectrometers, the RG set is the ultimate radioelement baseline for all gamma ray spectrometric studies.

3.2.3. Stationary (fixed) calibration pads

The construction and use of calibration facilities for radiometric instruments are described in Ref. [20]. Portable gamma spectrometers may be calibrated over four cylindrical concrete pads with dimensions of 3 m diameter and 0.5 m thickness. For a detector placed centrally on the pad's surface, the pads generate approximately 96% of the gamma radiation that would be observed from an infinite source Ref. [22]. Consequently, geometrical correction factors must be applied to instrument sensitivities derived from measurements on these pads.

Each of three of the pads is enriched in either K, U or Th. Recommended concentrations are 8% K in the K-pad, 50 ppm U in the U pad, and 125 ppm Th in the Th-pad. The fourth pad is manufactured from selected low-radioactivity rock material, and serves as a 'background' pad. The site for the construction of a calibration facility should be flat and easily accessible, and of low and uniform radioactivity. The four concrete pads should be

positioned in line and spaced about 5 m apart. Uranium ore used for the enrichment of the U pad should ideally be in radioactive equilibrium, have low radon emanation power, high U/Th ratio and grain stability. For the Th pad, the ore should have a high Th/U ratio. The pads are used for estimating stripping ratios and sensitivities for portable gamma ray spectrometers.

Stationary (fixed) concrete calibration pads for airborne gamma spectrometers are generally cylindrical with dimensions 9 m diameter and 0.5 m thickness. For practical construction reasons, a square concrete pad of dimensions 8 m × 8 m is of equivalent area and serves the same purpose. These pads generate approximately 80% of the gamma radiation of an infinite half-space source for a detector at 1 m height. Ideal concentrations for the pads are 8% K in the K pad, 20 ppm U in the U-pad, 40 ppm Th in the Th pad and low radioactivity material in the background pad. The pads are located in a line with a distance of 15 m between their closest edges. The pads should be situated in a flat area with low and homogeneous concentrations of the radioelements. Obviously, the pads should also allow easy access for both aircraft and vehicles. The pads are used for estimating stripping ratios for airborne and vehicle borne spectrometer systems. Because sensitivity coefficients for airborne systems depend on the height of the aircraft, these are estimated by flying over a calibration range (Section 3.2.5). A similar procedure is usually applied to the estimation of sensitivities for roof-mounted vehicle-borne detectors.

Calibration facility for logging gamma spectrometers consists of vertical concrete cylinders (1.2–1.6 m in diameter) with a centric hole at their vertical axis. Horizontal layers within the cylinders are selectively enriched in the radioelements. A typical sequence of layers might be: a 1 m thick non-radioactive layer at the top; a radioactive layer enriched in K, U or Th; and a basal layer of low-activity concrete material 0.6–1.5 m thick. The radioactive layer could be between 0.1–1 m thick, and depends on the geometry being modelled. The radioactive layers might be enriched with K, U or Th separately for lithological logging, or several layers might be enriched with various grades of U for uranium exploration and resource evaluation purposes. The cylindrical sources are usually inclined slightly from the vertical to ensure contact between the source material and the logging probe. Also, calibration models using high grade U layers are kept saturated with water to prevent radon loss, and thus better simulate the geological environment. Further information on calibration logging models, the concentrations of calibration sources, and procedures for their use can be found in Refs. [13][42].

3.2.4. Transportable calibration pads

Large stationary pads are expensive to build and maintain. Grasty et al. showed that smaller calibration pads of 1 m × 1 m × 0.3 m can be effectively used for the calibration of both portable and airborne spectrometer systems [21]. These are much cheaper to build than the larger stationary pads, and with a mass of approximately 675 kg (approximately 1488 lbs) they are transportable. The recommended concentrations are adapted from those recommended by the IAEA [20]. These are 8% K, 50 ppm U, and 125 ppm Th for the K, U and Th pads, respectively. The fourth pad has low concentrations of each of the radioelements, and serves as a background pad.

Tests have shown that the gamma energy spectrum generated by transportable pads is identical to that from larger calibration sources for energies in the geological range of interest. The transportable pads may thus be used for estimating the stripping ratios for airborne spectrometer systems, and both stripping ratios and sensitivity coefficients for portable gamma spectrometers. However, because of the small dimensions of the pads, geometrical correction factors must be applied to the estimated sensitivities. These are in the range 16–19%, depending on the energy of the gamma rays. There are several advantages to the use of transportable calibration pads as opposed to the larger stationary pads.

- They are cheaper and easier to manufacture.
- The moisture content of the pads is not an issue — the pads are easily stored under cover and their moisture concentrations kept stable.
- Background radiation is easily accommodated during calibration. Each pad is placed at the same position during calibration, and background is removed by subtracting the radiation measured over the background pad [22].

A disadvantage of the smaller pads is that the geometry correction for the estimation of sensitivity coefficients for portable spectrometers is necessarily higher than that for the larger stationary pads. Also, for some aircraft types it may be necessary to raise the aircraft to allow placement of the pads for the estimation of stripping ratios.

3.2.5. Calibration ranges and natural calibration strips

Sensitivity coefficients and height attenuation coefficients for airborne spectrometer systems are obtained by flying calibration flights over an airborne calibration range. This is an easily navigated strip of land with uniform concentrations of the radioelements. Selection criteria for suitable calibration ranges are given in Ref. [72].

Where concrete calibration pads are not available, it is possible to derive stripping ratios for airborne spectrometer systems using calibration flights over three specially selected calibration ranges. These natural calibration strips are selected on the basis that each of the calibration strips has an elevated concentration of one of K, U or Th. Otherwise the selection criteria for the calibration strips are similar to that for calibration ranges. The ground concentrations of K, U, and Th are determined by a calibrated portable gamma spectrometer in a relatively dense grid that may amount to hundreds of measurements.

3.2.6. Temporal variations in calibration facilities

Long term repeat measurements of concrete calibration facilities have revealed temporal variations in radiation output. The variations are caused by changes in the moisture content of the pads and the escape of radon. The presence of water in rock pore spaces results in an increased attenuation of gamma rays within the rock medium. The gamma ray fluence rate from a dry rock, Φ_d, is related to the fluence rate from a wet rock, $\Phi_{w,}$ by [19]:

$$\Phi_d = \Phi_w (1+1.11\ w) \quad (1)$$

where w is the pore moisture content. An increase in soil moisture of 10% will decrease the measured gamma fluence rate by about the same amount.

However, increased moisture content can actually lead to an increase in U radiation output [73]. The major sources of gamma radiation in the ^{238}U decay series (^{214}Bi and ^{214}Pb) are disintegration products of radon gas (^{222}Rn). Consequently, the escape of radon from concrete calibration pads or soil will affect the radiation output. If radon has escaped, then the radiation output at the surface will be lower. Radon escapes more freely from a dry soil than from a wet soil. However, the presence of water in pads or soil can prevent the escape of radon resulting in an increased U radiation output.

A temporal change in gamma radiation output from calibration pads has been observed in several countries. Barretto ascribed a 10% change in radiation output over a 3-year period from calibration pads in Brazil to climatic changes [74]. Experiments over concrete pads at Walker Field, Grand Junction, Colorado, USA, showed a 5% increase in radiation over the U pad and a 2% decrease in radiation over the K and Th pads during the wet winter period. Almost identical variations were observed at calibration concrete pads at Risø National Laboratory, Denmark [75]. Similar effects can be expected over natural calibration strips. Note, however, that estimates of airborne spectrometer sensitivities using a calibration range are not affected by soil moisture and radon effects if the concentrations of the radioelements along the calibration range are measured using a calibrated portable spectrometer at the same time as the calibration range is flown [76]. The sensitivities are derived as the ratio between the airborne and ground measurements. Because changes in soil moisture and radon escape effect the airborne and ground measurements equally, the sensitivities are unaffected.

3.3. STANDARDIZATION AMONG GAMMA RAY SPECTROMETER CALIBRATION FACILITIES

As indicated earlier, the accuracy of both stripping ratios and sensitivity coefficients are tied directly to the accuracy of the concentrations of the radioactive calibration pads. Thus, where a spectrometer is calibrated on a set of pads that have a systematic bias in their elemental concentrations, this will translate into a similar bias in survey data acquired with this spectrometer. A global network of spectrometer calibration facilities tied to the same global datum is thus an essential pre-requisite for a global radioelement baseline.

3.3.1. Inter-pad calibrations

The grades assigned to calibration pads depend on the procedure used to analyse the samples of pad material taken during their construction. For example, the moisture content of laboratory spectrometer samples can affect the assigned grade by up to 20%. Also, moisture absorption and radon exhalation by pads can offset apparent pad concentrations from their reference values [19]. The effect of radon exhalation can be large.Seasonal monitoring of the Risø U pad [77] showed a variation of ±20%. The effect of soil moisture in concrete pads can be expected to affect estimated concentrations between 2% and 10% [19]. There are practical solutions to minimize these problems.

The source material for the U pad should be carefully chosen to minimize radon exhalation [20]. Pads can also be sealed using special plastic or other coatings to mitigate against radon loss.

The moisture content of pads should be kept constant. Pads can either be kept constantly wet, or if transportable, they should be kept dry. Care must be taken that the moisture content of the pads during use is the same as the moisture content of the pad samples used to assign the pad reference grades through laboratory analysis.

Under a research contract with the IAEA, Løvborg [19], compared calibration facilities across ten countries. Twelve calibration sites were included in the experiment. He showed that a well calibrated portable gamma spectrometer could be used to re-assign the reference K, U and Th grades to calibration pads to make them internationally consistent.

Ideally, all calibration pads should be tied to the global IAEA standard based on the reference materials for laboratory gamma spectrometry issued by the IAEA [2]. If calibration pad samples are measured using laboratory spectrometers calibrated using the Seibersdorf laboratory standards, then irrespective of which set of pads is used to calibrate a particular gamma spectrometer, the results should be consistent.

Alternatively, an inter-pad calibration exercise can be used to incorporate new calibration pads into the global network as follows.

— Calibrate a portable spectrometer using a set of calibration pads that are tied into the global network and thus calibrated to the Seibersdorf standards.
— Take portable spectrometer measurements on the new K, U, Th and background pads that are to be incorporated into the global network.
— Subtract the background pad measurements from each of the K, U, and Th pad measurements.
— Estimate the concentrations of the K, U, and Th pads using the background-corrected measurements.
— Apply a reverse density/geometric correction to estimate the final K, U, and Th concentrations of the new pads.
— Assign zero concentrations of the radioelements to the background pad.

Note that the above procedure establishes the concentrations of the K, U and Th pads relative to the background pad. The concentration of the radioelements in the background pad is unknown, but this is irrelevant, as the background pad measurements are subtracted from the K, U and Th pad measurements during spectrometer calibration.

3.3.2. The global calibration network

Appendix II is a worldwide directory of all known gamma ray spectrometric calibration sites. The distribution of these sites is shown in Fig. 5. Most of these sites have been tied to the global gamma spectrometric radioelement baseline. For further information on these sites, potential users should contact the lead agencies responsible for the distribution of public domain gamma spectrometric data for the relevant countries listed in Appendix I. These agencies should be able to provide information on location, access, radioelement concentrations, and whether the facility is tied to the global baseline.

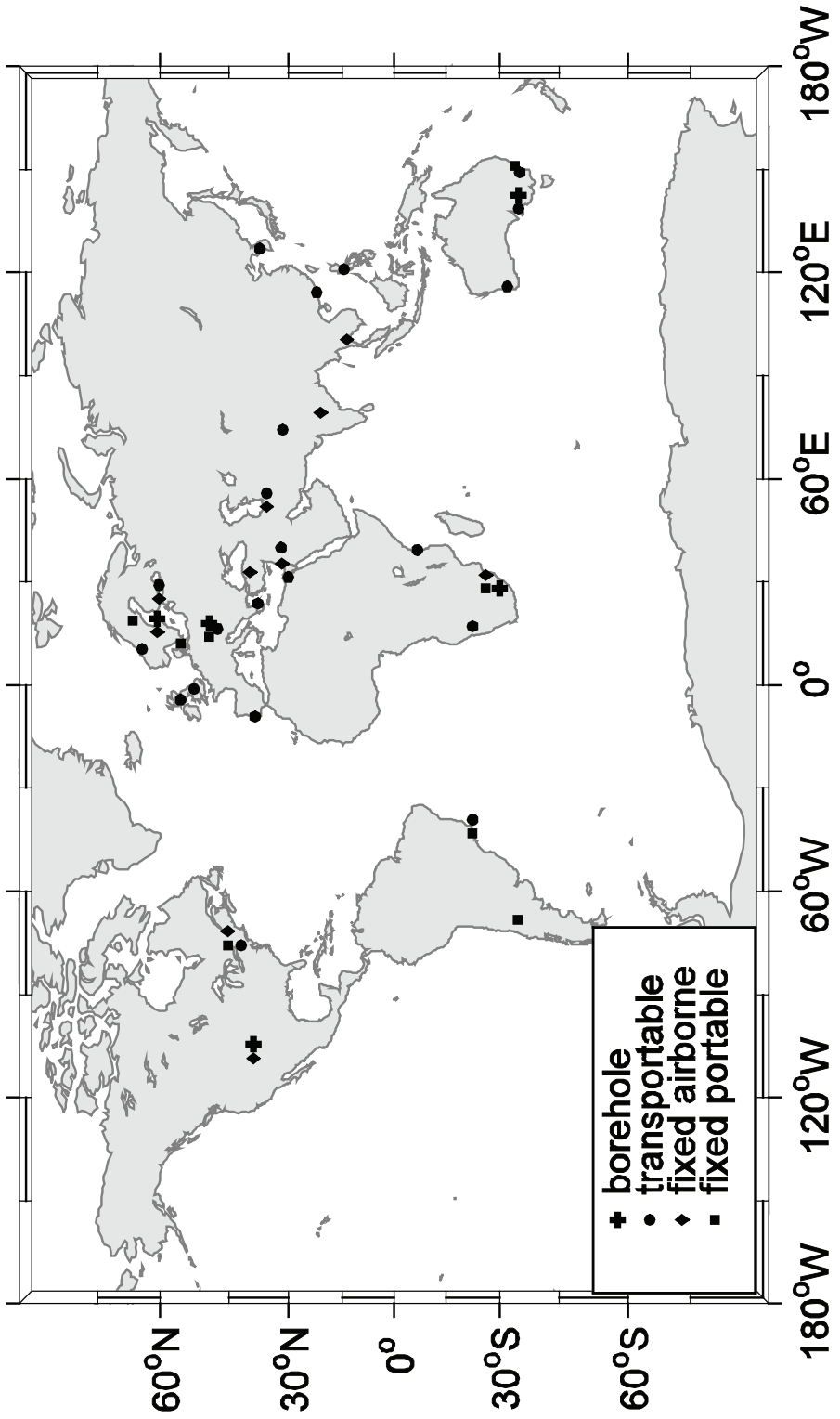

FIG. 5. Worldwide distribution of gamma ray spectrometric calibration facilities.

3.4. BACK CALIBRATION OF EXISTING SURVEYS

Early radiometric surveys using uncalibrated or inadequately calibrated instruments provided only relative measures of radioactivity. Standardization refers to the process of converting gamma survey data to standard units - i.e. dose rate (nGy/h) in the case of TC data, or radioelement concentrations (% K, ppm eU, ppm eTh) in the case of spectrometer data. The general procedure includes quality checking of the original radiometric data, ensuring that the data are levelled, and their conversion to gamma dose rate in air, or radioelement abundances in rocks. The conversion is either direct, if suitable conversion factors are available, or through back calibration. Back calibration refers to the conversion of older data through comparison with ground measurements made with a calibrated portable gamma spectrometer.

3.4.1. Assessment of data quality

Data standardization requires knowledge of the survey parameters and the quality of survey data. An important prerequisite is an acceptable accuracy of the geographical positioning of the survey data points. Adequate documentation of the field procedures and data processing procedures includes:

— Scale, type and extent of the survey;
— Instrument type, detector type and volume, and instrument sensitivity;
— Calibration procedure and calibration sources;
— Background estimation procedure;
— Data processing and map compilation procedures;
— Reporting units.

Attention should be paid to topography, vegetation and any indication of nuclear fallout in the area since the survey was conducted. The quoted errors of the original survey results are also important information.

3.4.2. Recovery and reprocessing of existing surveys

Older survey data are often in analogue form, and it is necessary to digitize the data prior to reprocessing. In many cases a choice must be made as to whether the original analogue records should be digitized (the raw data), or whether the compiled map information should be digitized. Analogue airborne gamma spectrometric data is usually present in one of three formats:

— The annotation of individual anomalies along flight lines, sometimes with annotated response levels;
— Profiles of total count and the three radioelement energy window count rates, plotted by chart recorder on the aircraft;
— Contour maps of total count and the K, U and Th energy window count rates.

Digitizing techniques for large volumes of analogue data rely on scanned images of the original hard copy. Typically, the process requires separate recovery of the flight path and gamma data. The positional information is then merged with the radiometric data using a common fiducial system. Care must be taken in the digitizing of profile data to ensure that the radioelement channel count rates are correctly positioned, as even slight offsets along a survey line can result in significant false anomalies in computed radioelement ratios.

The recovery of analogue data from contour maps is typically accomplished by digitizing the contour values where they intersect the flight path.

Where the raw data have been digitized, the data are then reprocessed using the calibration constants documented at the time of the survey. If sensitivities are not available, the reprocessed survey data will have to be back calibrated (Section 3.4.3).

3.4.3. Back calibration of gamma spectrometry surveys

The standard procedure for calibrating airborne gamma spectrometers includes flying over a calibration range at the same time as the ground concentrations of the radioelements along the calibration range are measured with a calibrated portable gamma spectrometer. The sensitivity coefficients (that convert window count rates at survey height to elemental concentrations on the ground) are derived as the ratios of the background corrected and stripped airborne window count rates to the concentrations of the radioelements on the ground. Exactly the same principle is used in the back calibration of older airborne radiometric surveys. The concentrations of the radioelements in the ground are estimated beneath selected portions of flight lines. The sensitivity coefficients are then derived as the ratios of the average airborne window count rates to the average concentrations on the ground. This procedure is repeated for several sites - each homogeneously radioactive, but with different radioactivity levels among sites.

The approach taken to the selection of back-calibration sites depends on the radioactive variability, topography and accessibility of the survey area for ground surveys. Grasty et al. selected a 10 km section of an existing flight line as a back-calibration line [78]. Ideally, the back-calibration line should fulfil the main criteria used for selecting a calibration range - topographically flat, reasonably radioactive with uniform concentrations of the radioelements, as well as being easily accessible. Grasty took 4 measurements (10–20 m apart) at each of 19 calibration sites along the line [78]. These were used to compute 19 estimates of the window sensitivities. The final sensitivities were derived as the weighted average of the 19 sites, with each site weighted according to the computed uncertainty in the associated sensitivity.

Duffy et al. used a slightly different approach [79]. They selected 20 calibration sites (for each survey) situated at the intersection of flight lines and roads. Sites were selected based on an elevated but uniform radioelement concentration, and subdued topography. Four measurements were made at each calibration site (two on each side of the road) about 25 m apart. K, U and Th sensitivities were calculated at each site, along with their associated uncertainties. Following Grasty et al., mean sensitivities for each of K, U and Th were derived from a weighted average of the site sensitivities [78].

In principle, if the back calibration sites cover a range of radioelement concentrations, a linear regression of the mean K, U and Th concentrations against measured count rates will yield both a base level adjustment (background-correction) as well as a scaling adjustment (sensitivity) for each energy window. In practice, this is difficult, and only the sensitivities are estimated using mainly high count rate areas of the survey selected for their radioactive uniformity and accessibility.

For the back-calibration of car-borne surveys, traverse segments of about 50 m length are selected for comparison with ground measurements. Segments are measured with a portable gamma ray spectrometer at sites separated 10 m along the traverse with at least three measurements along a line perpendicular to the traverse segment at each site. Similar procedures are applicable for the back-calibration of older ground surveys with portable instruments.

Where survey results are reported as K, U and Th concentrations, they can be converted to dose rate (nGy/h). If the source of radiation can be approximated by an infinite plane surface, then conversion constants 13 .078 nGy/h per 1% K, 5.675 nGy/h per 1 ppm U and 2.494 nGy/h per 1 ppm Th can be used to convert and sum the K, U and Th contributions to the total dose rate [20].

3.4.4. Back calibration of total count surveys

Features that are specific to TC instruments affect the way total count surveys should be standardized. The relationship between the background corrected count rate, n_{TC}, and the concentration of K, U, and Th in the ground is given by:

$$n_{TC} = s_K c_K + s_U c_U + s_{Th} c_{Th} \quad (2)$$

where

n_{TC} = background -corrected total count rate, (counts/s);
s_K, s_U, s_{Th} = K, U, and Th instrument sensitivities (counts/s per unit concentration);
c_K, c_U, c_{Th} = K, U, and Th radioelement concentrations.

Because the K, U, and Th energy spectra are different, the sensitivities s_K, s_U, s_{Th} vary with changes in the instrument parameters (detector type and size) and the energy discrimination threshold. The sensitivities can be estimated by measuring the TC response over three natural geological sources, or calibration pads, that have different K, U and Th concentrations. The ratio s_K/s_U is the uranium equivalent of potassium, and the ratio s_{Th}/s_U is the uranium equivalent of thorium for a given TC instrument. Based on the gamma dose rates of an infinite plane surface with unit concentration of K, U and Th, the gamma dose rate from 2.3 ppm U is equivalent to the dose rate from 1% K, and the gamma dose rate from 0.44 ppm U is equivalent to the dose rate from a rock containing 1 ppm Th. For TC radiometric instruments with $s_K/s_U = 2.3$ and $s_{Th}/s_U = 0.44$, the count rate is proportional to the gamma dose rate. For instruments with other uranium equivalents, the measured count rates do not vary linearly with dose rate. Relative deviation between the true dose rate and that estimated from later TC instruments vary up to 25% and depend on the K/U and Th/U radioelement ratios [16].

TC measurements should preferably be reported as dose rate. TC surveys reported as count rate provide only a relative measure of environmental radioactivity and must be standardized through back-calibration. The total count rates from selected areas are compared to the gamma dose rate estimated by a portable gamma spectrometer or ionization chamber. A linear regression of dose rate on count rate is used to estimate the appropriate conversion constant. Total count surveys reported in equivalent uranium concentration (ppm eU) or ur units can be similarly back calibrated.

3.5. MERGING OF SURVEYS

Gamma spectrometric coverage of most countries consists of a combination of systematic surveys by government agencies to obtain national coverage, and ad-hoc surveys designed to address particular geological or environmental problems. In many countries the survey coverage is now such that surveys can be joined together to form large geological province scale, or greater, compilations. There are several advantages of larger compilations: the data are more amenable for digital enhancement and display; large scale radiometric features can be more reliably mapped; and, comparisons and inferences can be made between spatially remote features.

Unfortunately, there are almost always level differences between surveys. These differences arise mainly because older survey data were often not corrected for the sensitivity of the detector system. However, environmental effects, inadequate background-correction and instrument calibration also introduce level differences. As indicated earlier, system sensitivity is a function of detector volume, detector efficiency, flying height and the window boundaries used for detecting K, U and Th. The sensitivity adjustment is a scaling of the survey data channels. On the other hand, errors in background estimation would need to be corrected by a base level adjustment of the survey data channels. So both a scaling and a base level adjustment may be required to bring survey data to the same level.

Several approaches can be used to facilitate the levelling and merging of disparate surveys. These are discussed further.

3.5.1. Radioelement baselines

All gamma ray spectrometric surveys should be tied to the IAEA global radioelement baseline. This requires that:

- Spectrometers are calibrated using a set of calibration pads tied to the global network as described in Section 3.2;
- The spectrometer calibration and data reduction procedures recommended by the IAEA are followed [20][22][72].

In principle, if all gamma ray spectrometric surveys are tied to the same global baseline, then surveys should be easily merged. In practice, this seldom happens. Even where the same baseline has been used, surveys never match exactly across their common borders because of small errors in the calibration of the spectrometers and the limitations of the data processing procedures (Section 3.1.5). Where there is an inconsistency between surveys, one or more of the methods described in the following sections can be used to register surveys to the same datum.

3.5.2. Control lines and control points

Control lines or control points can be used to back calibrate surveys to bring them to the same level (Section 3.4). A calibrated spectrometer is used to estimate the radioelement concentrations (and/or dose rate) either along control lines, or at discrete control points within the survey area. A comparison between the control data and the survey data is used to estimate scaling factors and level shifts (for each channel) that will restore the data to the global datum.

3.5.3. Grid stitching

Where two surveys overlap, the differences in data values in the region of overlap can be used to estimate the base level shifts and scaling factors which, when applied to one of the surveys, minimises the differences in the region of overlap. The procedure is very similar to that used in back-calibration. Let grid A be the uncalibrated survey grid and B be a survey grid registered to the global baseline. Then a linear regression of the overlapping data points of grid A against grid B yield the level shift (y-intercept) and scaling factor (slope of regression line) required to register grid A to the global baseline.

A similar technique has been used for the merging of magnetic field surveys [80]. For gamma spectrometry, the data in the overlap region must have a reasonable dynamic range — otherwise there will not be sufficient information to estimate both a level shift and scale factor for each channel.

There is a range of additional techniques [16] that can be used to bring two surveys to approximately the same level, although these will not be as accurate as back calibration or grid stitching. For example, where two adjacent surveys do not overlap, a statistical analysis of channel data in the vicinity of their common borders can sometimes be used to level the surveys. Adjusting one of the surveys so that for each channel the mean and standard deviations of the data within the border region are the same for each survey will bring the surveys to approximately the same level. Again, this technique can only be used when the data have a reasonable dynamic range within the survey border areas.

Along similar lines, where two uncalibrated surveys (survey data reported in counts/s) were flown at the same nominal flying height but with different detector volumes, then it may be possible to scale one of the surveys by the ratio of the detector volumes to bring the surveys to approximately the same level. This transformation is based on the assumption that the surveys were flown at the same nominal survey height and used the same window boundaries.

3.5.4. Automatic grid merging

The grid stitching methodology works well for a small number of survey grids. Grids are joined sequentially to form larger compilations. However, the sequential levelling of grids is a time consuming task, and the levelling sequence must be chosen carefully. For example, for a circular sequence, a large mismatch between grids can result at the loop closure. Also, joining errors tend to accumulate, and for a large number of grids the sequential levelling can introduce significant long-wavelength errors (warps) into the merged dataset.

Minty described a method for the automatic merging of gridded gamma spectrometric surveys that minimize these problems [81]. Instead of merging grids sequentially, the joining of a large number of grids is considered as a single inverse problem. The method calculates the best shift and scale for each survey grid such that the grids join together optimally. The method seeks to minimize the amount of back-calibration required for the merging of older surveys not registered to the global baseline. An example of the application of the method is shown in Fig. 6.

Figure 6(a) shows a gradient enhanced pseudocolour image of TC channel data for part of north Queensland, Australia. The image is a mosaic of ten different airborne survey grids. Most of the grids are in units of counts per second, and since the detector volumes and flying heights vary between surveys, it is not surprising that the TC data are at different levels.

Using one of the grids as a base grid, all of the other grids are brought to the same level using the automatic grid levelling procedure. Figure 6(b) shows the same data after levelling. The surveys have been effectively levelled. If the base grid used was registered to the IAEA global baseline as air absorbed dose rate (nGy/h), then the automatic grid levelling procedure would bring all grids to the global baseline.

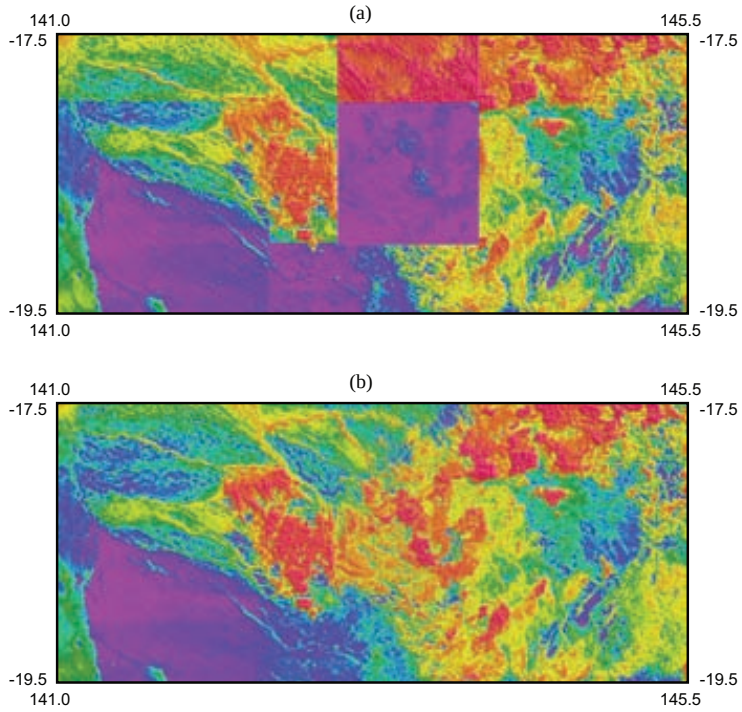

FIG. 6. Automatic grid levelling of total count airborne gamma ray spectrometric data from North Queensland, Australia: (a) composite grid before levelling, and (b) after levelling.

Of course, the method still requires that the data in the overlap areas have sufficient dynamic range to enable the required conversion factors to be reliably estimated. However, for many surveys, particularly for eU estimates where signal to noise ratios can be poor, this condition is not met. In these circumstances the only option is back-calibration using a well calibrated portable spectrometer.

3.5.5. Feathering grid edges

After adjusting survey grids to the same level, there may still be some residual differences along some parts of the boundaries between grids. 'Feathering' is a cosmetic procedure to near-seamlessly smooth over these residual differences. Cheesman et al. used a Fourier analysis of the residuals along the suture line to calculate corrections that are propagated smoothly into the grids by distances proportional to their wavelengths [80]. Minty achieved a similar effect using spatial convolution filtering [81].

3.6. RESPONSES OF ANTHROPOGENIC RADIOELEMENTS

Natural radioactive nuclides are distributed through long term, geological and environmental processes. This can lead to homogeneous distributions over areas ranging from several square metres to much wider spread distributions.

Anthropogenic radioelements are produced by fission or activation in nuclear power plants, from reprocessing plants, research reactors, or from other sources such as nuclear activation products used for medical applications. Where anthropogenic nuclides are accidentally released into the environment, their distribution may be complex, depending on their origin, transport mechanisms and migration processes after deposition.

The activity and chemical properties of the radioelement, such as its half-life and possible paths for inhalation, ingestion or external irradiation, determine the hazard from the point of view of radiation protection.

To get an idea of possible contamination, radionuclides can be classified by their size and behaviour:

- Due to activation of air, several radioactive gases such as ^{41}Ar, ^{85}Kr, ^{133}Xe, different volatile I- isotopes (^{131}I, ^{132}I, ^{133}I) and ^{3}H can be found in the emissions of nuclear power plants and represent a high hazard for inhalation near their source. They are usually diluted and dispersed within a short time (several days), but can also be transported over long distances by atmospheric processes.
- Radionuclides attached to aerosols can travel large distances through the atmosphere until they are finally deposited as fallout, leading to a quite homogenous, usually large scale initial surface distribution. This distribution will subsequently change to a more complicated pattern, both laterally and with depth, due to transport mechanisms like migration into soil and washout effects. The degree and velocity of migration is influenced by the nuclides' chemistry, and the texture characteristics and chemistry of the soil, vegetation (roots) and precipitation. Due to the complexity of influencing factors, it is not possible to make an exact forecast for the probability of appearance and behaviour of radioelements at a certain location. However, the velocity of migration in depth is usually less than 1 cm/year in unfarmed soils. ^{137}Cs fallout from the nuclear weapons tests of the 1950s and 1960s is now at a depth of not much more than 20 cm in unfarmed areas.
- Radioactive dust and particles with small diameters will normally not travel far. However, depending on their weight, in turbulent conditions they can be transported over hundreds of kilometres.
- Larger sources are not influenced by transport mechanisms, but they can still be spread over larger areas. An example would be the distribution of wreckage from the crash of a nuclear powered satellite.

In addition to transport mechanisms, the different half-lives of the observed isotopes must be considered. Within the first days and weeks after accidental release of fission and activation products, many short lived radionuclides, such as ^{132}Te ($T_{1/2}$ = 78 h) or the gases ^{133}I ($T_{1/2}$ = 20.8 h) and ^{131}I ($T_{1/2}$ = 8.02 d) dominate. After a few weeks, the remaining activity is represented more by isotopes with longer half-lives, such as ^{95}Zr ($T_{1/2}$ = 65.5 d), ^{144}Ce ($T_{1/2}$ = 284 d), ^{106}Ru ($T_{1/2}$ = 1.0 y), ^{134}Cs ($T_{1/2}$ = 2.1 y), ^{90}Sr ($T_{1/2}$ = 28.5 y) or ^{137}Cs ($T_{1/2}$ = 30.17 y).

The composition and activity of radionuclides differ strongly depending on the distance to their source, and the type of event that caused the release of the radioactivity. Fortunately, almost all anthropogenic radioelements emit characteristic gamma lines or possess gamma emitting daughter products. Therefore, gamma spectroscopy with scintillation or semiconductor detectors, either in laboratory or in situ, can be used to detect these radioelements. An exception is ^{90}Sr and its daughter ^{90}Y, which do not have measurable gamma emissions. In this case, a beta-sensitive detector must be used.

3.6.1. Calibration for ^{137}Cs mapping

^{137}Cs emits gamma rays at 662 keV, and has a half-life of 30.2 years. This makes it one of the main long term contributors to radiation dosage after a nuclear accident.

Several methods can be applied to the measurement of ^{137}Cs distribution, depending on the size of the area and the desired accuracy.

- The most costly and time consuming method is to take samples in different positions and depths for measurements in a laboratory, thus obtaining very detailed and accurate 3D information on the distribution.
- Detailed information about the distribution in larger areas can be gathered by the use of in situ gamma ray spectrometry with scintillation or/and germanium detectors. The reliability of the measurements depends on good system calibration, and knowledge of the depth distribution of the radioelements. Nevertheless, the procedure is still time consuming.
- Areas accessible by car can be surveyed by vehicle-borne spectrometers. Very large areas, particularly where the topography is rugged, are best surveyed using airborne gamma spectrometry. In this case, the detector volume and survey height will limit the spatial resolution and detection sensitivity for low activities.

For all methods, suitable calibration procedures must be carried out to relate the specific detector output to the activity concentration of ^{137}Cs in soil (Bq/kg) or at the surface (kBq/m^2). Usually, these procedures will be based on calibration relative to measurements in standardized laboratories.

While soil samples are measured directly in laboratories, in situ, vehicle borne and airborne measurements need calibration sources or test sites of suitable size, as well as information on ^{137}Cs distribution with depth in the soil profile. In general, the calibration of a detector system for a certain distribution would only be valid within a limited area, leading to over or under estimation in other areas due to differing buildup effects and absorption processes.

3.6.2. Measurement and mapping of ^{137}Cs response

While the same processing methods for measuring radionuclides with Ge detectors can be used for ^{137}Cs estimation, some changes must be considered where other scintillation detectors are used.

For detectors with low energy resolution, such as NaI detectors, the window stripping method is used to correct for the Compton continuum and overlapping peaks. The stripping factors are derived from calibration facilities, such as calibration pads or test sites, with well known concentrations of the radionuclides. The use of stripping factors requires a knowledge and consideration of all peaks with energies higher than that of the peak under consideration. These requirements are usually easily fulfilled where the high energy peaks are those due to the naturally occurring radionuclides. However, where the photopeak energy of a target radionuclide is low, and a large number of anthropogenic nuclides are present, the window method is difficult to use. This may be the case immediately after a nuclear accident, where there is either no knowledge of which radionuclides are present, or the relevant stripping ratios are not known.

A number of different approaches to this problem have been investigated in recent years:

— The Compton background can be reliably estimated to derive net peak counts in a way similar to the trapezoid methods used with high resolution detectors [82].
— The use of filtering techniques coupled with a study of the derivates [83].
— The use of a statistical analysis of spectra to derive spectral components using noise adjusted singular value decomposition (NASVD) [84]; this is a method that has been successfully implemented for an increasing number of measurement systems in recent years.

For airborne gamma systems, there is a trend towards using a combination of NaI (Tl) and germanium detectors in an integrated system. These combine the high energy resolution of semi-conductor detectors and the high detection efficiency of scintillation detectors [49].

Mapping of ^{137}Cs response is done in units of activity concentration. Soon after deposition, almost all ^{137}Cs activity is at the surface and can be represented as surface activity [kBq/m^2]. After migration into the soil it is quite common to represent the concentration as specific activity [Bq/kg]. This can be interpreted as the average activity concentration within the upper layer of soil corresponding to an assumed uniform distribution.

4. METHODOLOGY TO ESTABLISH RADIOELEMENT BASELINES USING GEOCHEMISTRY

4.1. PRINCIPLES OF APPLIED GEOCHEMISTRY

4.1.1. Introduction

Unlike the rapid, wide area coverage provided by airborne or ground based mobile instruments for detecting radioelements, geochemical methods are discrete, sample based surveys. That is, they rely on going to a specific site and collecting or using a discrete sample for analysis. The analysis may be non-destructive in situ; in that it determines the elemental characteristics on-site, or it may be that some material is collected and brought back to a laboratory for analysis. It is this type of expedition that provides ground truth for the remote sensing of

radioelement detection. No doubt, in the future, remote detection for geochemical analyses will be used, perhaps through satellite or airborne spectral reflectivity. This will require providing adequate power sources for the energetic transmitters, microwave or laser that may be used.

A sample based geochemical survey is the determination of the abundance and spatial distribution of an element, or groups of elements, by collection and chemical analysis of discrete samples of geological material. Different media can be collected: soils, water, organics, sediments, rocks. In addition, any of those samples could be collected at different depths to address different problems. For example, very near surface material would be collected to look at anthropogenic influences and deeper materials could be used to seek natural or undisturbed conditions. These are key conditions that need to be described so that a baseline properly identifies what was sampled, and is not misinterpreted to represent something that it was never intended to describe. This is an important issue in the areas of regulation and public policy, particularly for remediation efforts.

The section on geochemistry may be augmented by reference to the Final Report of the IGCP Project 259. That report, A Global Geochemical Database for Environmental and Resource Management [1] by A.G. Darnley et al., presents an excellent discussion on the need for a geochemical database along with methods for sample collection and analysis. It also identifies databases that existed at that time and addresses concerns about their usefulness. It effectively marks the initiation of an effort on a worldwide scale to develop a geochemical database. This would include all chemical elements, including radioelements, and isotopes. This process is ongoing and is the basis of application of geochemistry to problems of geological mapping, mineral resource exploration, environmental issues, medical geography, crop and livestock yields, and natural hazard identification. Considerable research and experience have been gained in the application of geochemistry to problems of mineral resource discovery, delineation and development. The following section summarizes this area in the hope that this experience will be of benefit in addressing other areas of applied geochemistry. The following sections are updated synopses of issues identified in IGCP report 259.

4.1.1.1. Data acquisition

Effective data acquisition starts with a realistic objective and good sample plan. Directed programmes for mineral exploration are different to those used for establishing baselines. The type of sample, the scale of the survey and the handling of the samples from collection, analysis, through to storage are all important considerations. There is a range of sample types and analytical methods available. For example, samples could be rocks, soils, surface sediments, stream sediments, springs, streams (intermittent to major rivers), groundwater or organic materials including plants. Analytical methods can be quite varied and range from very specific and specialized analysers for gases, to multi-element ICP techniques. Some of the latter, such as ICP-MS, are capable of detecting radioelements and isotopes. This broadens the radioelement identification of sample based geochemical surveys, because they can include more radioelements, specifically alpha and beta emitters, than can an airborne gamma survey.

4.1.1.2. Data presentation

There are numerous ways to present data, but perhaps the most common is in a surficial map form. With today's comparison algorithms, a map format can be used to compare geochemical data to other data sets, including topography, placement of surface water flows, vegetation, agriculture, buildings, highways, known mines or oil and gas production sites, and so forth. However, the ease in availability of data presentation should not be without caution. While a map can present a very 'pretty' picture in multiple colours for concentrations, it is important to recognize that most areas are interpolations between sample points. Consider, for example, that flight lines may be 5 km apart or that geochemical sampling density may be just one sample per 100 km^2. In effect, the map should not be over interpreted in areas for which there are insufficient samples.

4.1.1.3. Minimizing errors and merging existing survey data

With sample based data perhaps the greatest source of error can be in sample collection and preparation. The issue is to collect a proper sample and to avoid contamination. For all new surveys, there is a need for standardization of methods and there are excellent guidelines available, such as IGCP 259 and 360. Existing surveys should have enough information provided such that they can be fairly incorporated into new data. One of

the major difficulties is where normally incongruent data have been combined, such as soil analyses and stream sediment analyses, or using different size fractions after sieving the sample, or different extraction techniques if it is not a whole sample analysis. Commonly less error is introduced in varied analytical methods if proper standards and intercalibrations have been used.

4.1.2. Mineral exploration

This activity is made up of a series of discrete stages. Successful results in each stage justifies moving on to the next stage. Each stage of the process concludes with a decision that is one of three options — go forward, put on hold, or terminate the project. Given a specific target type and geographical location, exploration project design consists of selecting a combination of geoscientific techniques that are both technically and economically capable of providing adequate information to support sound exploration decisions. Geochemical techniques are but one of the options available for inclusion in the design of an exploration programme, and their relative effectiveness must be considered against other options for each stage of the project. Sound appreciation of the principles, practice and limitations of geochemistry, as with any other exploration approach, will improve the chances for overall success.

4.1.2.1. Exploration geochemistry

Hawkes provided a working definition of exploration geochemistry or geochemical prospecting which is appropriate to this day [85]:

> "Geochemical prospecting for minerals includes any method of mineral exploration based upon systematic measurement of one or more properties of a natural occurring material. The purpose of the measurements is the discovery of a geochemical "anomaly" or area where the chemical pattern indicates the presence of ore in the vicinity."

The fundamental approach to exploration geochemistry is based upon a few simple assumptions or premises:

- Geological materials can be considered to be composite in nature;
- The challenge is to recognize, isolate and enhance the 'signal' from the component(s) of the sample reflecting both the presence and proximity of mineralization;
- Exploration geochemistry process consists of a series of steps that are both sequential and iterative; the success of the entire process is based upon the weakest link.

The basic questions to be addressed using the survey results are:

- For each sample, is there any of the imprint of a mineralization process in the geological material sampled and chemically analysed;
- For the subset of 'anomalous' samples, are there any trends in the data that indicate a causative mineralization source.

While the concept is straightforward, its execution, involving all the steps in the process, can be challenging.

4.1.2.2. Exploration geochemistry programme design

Geochemical programmes can be considered in terms of five components:

- Design and planning;
- Field sampling;
- Sample preparation;
- Chemical analysis;
- Data presentation and interpretation.

These components are both sequential and iterative. They provide a framework for reviewing new developments and their potential contributions to survey programmes. The ultimate success of a programme is controlled by the weakest link in the chain of these activities that make up a given programme [86].

Design and planning

Information on the mineralogical, lithologic, geochemical, environmental, and geometric characteristics of target deposits is necessary for sound survey design. Improvements in existing mineral deposit models (e.g. deep mineralization in Carlin type gold deposits) and recognition and development of models for new mineral deposit types iron oxide copper–gold deposits) provide the basis for enhanced exploration contributions from geochemistry. Information on the surficial environment obtained from geomorphic literature, or available conceptual models based on landscape geochemistry, also aid in survey design.

Field sampling

This is a part of a geochemical programme whose importance is often overlooked. No analysis can compensate for poor sample collection methodology. The type of media to be collected must be decided, and how to treat it to be representative of natural variability of samples is critical. Training for sampling is necessary and comprehensive note taking is essential. There is a common problem in collecting samples for geochemical analysis called the 'nugget effect'. That is, a single grain of pure metal in a sample can greatly skew the analyses. Another example is stream sediment samples collected downstream of a road culvert where the culverts are made from material that has been zinc-coated for corrosion resistance. Sometimes it is better to collect a set of samples and analyse them independently to see if there are any unusual analytical results.

Sample preparation

Sample preparation should be standardized. While this alone may not eliminate all problems, it does provide a common base for comparison. For example, where samples are sieved to obtain a certain size fraction for analysis, it is important to avoid contamination by using metallic sieves on the materials being studied. For trace element analysis, it is sometimes important to concentrate a particular component of the sample, such as a heavy fraction.

Chemical analysis

Improvements in instrumental analysis have resulted in a broader range of chemical constituents being routinely determined at lower detection levels and at more modest costs. This provides the opportunity to better define the geochemical associations characteristic of any particular mineralization. The rebirth of partial, selective, and sequential chemical analysis (e.g. enzyme leach) provides the opportunity to more fully speciate metal components and provides a greater confidence in characterizing dispersion processes related to mineralization. Quality control monitoring of data is an essential task.

Data presentation and interpretation

The wealth of high quality, low cost, multi-element data available today presents both opportunities and challenges. Computer based technologies are being increasingly employed for both data management and presentation, and data integration and interpretation. It is essential to maintain the connection between the geological environment and computer based tools intended to portray the data better.

A recent publication by the Association of Exploration Geochemists provides sound advice on the appropriate design and documentation of a geochemical survey.

4.1.3. Areas of geochemistry applied to human problems

Geochemical concepts, experience and aspects of programme execution in mineral exploration have applicability in other areas of applied geochemistry. The international geochemical mapping programme is intended

to contribute to all of these and is based, to a large extent, on experience from geochemistry used in resource assessment.

4.2. ANALYTICAL METHODS

4.2.1. Introduction and theory

A technical revolution in analytical chemical techniques has occurred within the last decade. The miniaturization of computer-controlled devices and the proliferation of production instrumentation can provide micro-analysis of micro-samples that are very cost effective. This is particularly relevant to the determination of naturally occurring radioactive nuclides and their associated elements.

In effect, laboratory devices of the past are now available for transport to the field. While traditionally, gamma ray surveys have been classified as a geophysical measurement, today the distinction is somewhat blurred. For direct determination of radioactive nuclides, wide-area surveys related to uranium resource exploration were conducted in the past by airborne instruments typically flown at an altitude of 100 m, with a flight line spacing of 1–10 km. These airborne instruments usually had large crystalline NaI(Tl) gamma detectors and were used for determination of total gamma, potassium, uranium, and thorium. Only the gamma ray specific to ^{40}K was a direct measurement. ^{238}U and ^{232}Th were calculated as equivalents because the gamma radiation detected was from a progeny product and equilibrium was assumed for the equivalency measurement. (see Table II).

Resolution was limited by the separation of the gamma energies. Typically, these airborne detectors could separate the energy spectrum of 0–3 MeV into 256 channels. Laboratory detectors are typically capable of providing resolution over that energy range into 4096 channels, which provided for determination of numerous other radioactive nuclides. The detector can be smaller because it is closer to the source, rather than at an altitude of several hundred meters.

Technological advances, particularly in crystalline detector configuration, now permit portable 4096 channel detectors weighing no more than 5–10 kg, to be taken into the field. Laptop computers may be used in the field and help to determine the radioactive isotopes present.

There are a number of reasons to expand the baseline to include analysis for other elements beyond those that are radioactive. For example, there must be some calibration or ground truth to verify wide-area airborne surveys. Gamma surveys are restricted by self-absorption of the gamma energy to determining what is in the upper decimetres of the surface, whether it be rock, soil, or water. Normally, those surveys do very poorly in recording radioactive nuclides over water. In fact, flying over a body of water is commonly used to determine the background of the instrumentation, i.e. a sample blank. Environmental concerns, particularly in regard to human made radioactive nuclides, should mandate gamma surveys of the greatest resolution possible. Over time, those elements may be physically, biologically, or chemically transported and be at depths not detected by surface radiation surveys. Transportation is important, because there are a number of elements that are associated with uranium and thorium, the detection of which may be an indicator of the presence of the primary target element and an indicator of the local environment (chemical and physical) that impacted the separation of the association.

TABLE II. RADIOELEMENT, ISOTOPE AND GAMMA RAY ENERGY USED IN GAMMA SURVEYS. BISMUTH (Bi) AND THALLIUM (Tl) GAMMA RAY EMITTERS ARE USED TO ESTIMATE THE EQUIVALENT URANIUM AND THORIUM CONCENTRATIONS.

Primary element	Gamma ray isotope	Energy
Potassium-40	^{40}K	1.46 MeV (^{40}K)
Uranium-238	^{214}Bi	1.76 MeV (^{214}Bi)
Thorium-232	^{208}Tl	2.62 MeV (^{208}Tl)

4.2.2. Laboratory methodology

While primary radioactive nuclide maps currently available map the concentrations of naturally-occurring uranium, thorium and potassium, not all radioactive nuclides are gamma emitters. Many are alpha emitters, such as the transuranic elements, as well as radon (Rn) and radon progeny from the U and Th decay series; these elements are a source of environmental concern. There may also be interest in a number of other (non-radioactive) elements that naturally associate with uranium and thorium.

There is commercially available laboratory equipment for the determination of radioactive particle signatures of various radioactive nuclides. For the most part, these can be detected and identified without specific chemical separation. Separations take time and must be performed with various standard tracer isotopes to establish effective yield or efficiency of the separation. Radioactive standards are available from commercial sources and provide internal checks on the specific detector's calibration.

Perhaps the most commonly used instrument today for the analysis for other elements is the ICP (inductively coupled plasma) instrument, in combination with a mass spectrometer (ICP-MS) or an optical emission spectrometer (ICP-OES). This instrument is capable of providing almost simultaneous analysis of up to 60 different elements, down to concentration levels of 1 part in 10^9.

Other elements may require different techniques. Atomic absorption, X ray fluorescence, and chromatography are some of the common methods used. A discussion of various analytical instruments is provided in Skoog et al. [87].

Generally, the analytical technique used is that most easily available to the contractor conducting the survey, unless otherwise specified in the work plan.

Some sample preparation is required (dissolution) and this procedure should be standardized. Radiochemistry is a specialized field that can separate radioactive isotopes so that there is minimal interference during counting of the emitted energies.

4.2.3. Field measurements

As analytical equipment has become more portable, many analyses are now performed in the field. In many cases, this is preferable because of the increasing burden of sample control requirements and transport regulations. This burden occurs mostly with samples from sites already recognized as contaminated, and not for background locations. However, retention of samples for subsequent analyses is important.

The most useful equipment for the field is that which permits direct measurements without sample preparation. Some field site preparation may be needed, such as removing organic materials to get to the surface outcrop in the case of rocks or soils. In certain cases, some digging or drilling might be necessary, particularly if depth profiles are of interest. This procedure should be standardized in order to minimize or avoid contamination of the sample. For example, if a titanium alloy drill bit were used to obtain a sample, any analytical result for titanium would be questionable.

As mentioned in Section 4.2.1, portable gamma detectors are commercially available. They can be used for car-borne surveys or hand held (backpacked) for walking traverses. They are important in calibrating and 'ground-truthing' airborne surveys [88].

Water sampling is conducted where water can be found and there are a great number of sources requiring different collection and storage techniques. Certain measurements in the field are almost mandatory, such as temperature, pH, Eh, and conductivity. These are made with field portable instruments. Collection and treatment for transport usually changes these parameters from the original field values.

4.2.4. Error sources, accuracy and precision

Perhaps the greatest source of random error is the sampling procedure itself. This is also the most difficult error source to identify and for which any correction can be made. Although protocols can be developed to guide sample collectors, there will always be situations in which non-uniform conditions are encountered.

Included in sampling error is that of sample location. The use of GPS locating devices can greatly assist in establishing the sample location accurately. A major source of misinterpretation can stem from how 'less than'

quantities are used in the derivation of a map. It is important to state in any study how these values are treated by the algorithm developing the map.

Laboratory analyses can be calibrated. Blanks, replicates, calibration of instruments by standards traceable to some national institute calibration, and inter-laboratory comparisons are all methods available to obtain the best accuracy and precision. Even if different instrumentation is used for analysis, data inter-comparisons can be made.

4.2.5. Dataset calibration

The issue of data set calibration is discussed in Section 4.3.4 (rock geochemistry). It includes understanding how representative the sample is of the site from which it was collected. The issue of calibration has less impact on large sampling programmes where the same instruments and methods are used. It is of greater concern when many smaller surveys are combined, especially if those surveys use different methods and instrumentation (and sample design as well as survey spacing).

It is important to include, in any survey, some re-survey component of a previously studied area and to have inter-laboratory comparisons that had previously analysed samples from that area.

4.2.6. Re-analysis of archived samples for radioelements

Archiving is important for a number of reasons. Firstly, sample collection is expensive. Secondly, if any question arises as to the soundness of the initial reported results, the sample can be re-analysed. Thirdly, if different analyses are to be performed, the sample is available for that additional analysis.

Naturally, strict sample handling procedures must be in place for archived samples as their integrity should be maintained for future work.

Depending on the nature of the sample, archiving must be done in strict accordance with established protocols. For example, sample storage should avoid the possibility of cross contamination. Storing a suite of soil samples in cloth bags in the same container would raise concern of cross contamination. Furthermore, special considerations should be given to the storage of samples where change in condition during storage could occur. If a soil sample is moist, bacteria could alter the nature of biological or mineral material present. Radioelement analysis offers the least chance for change during storage (with the half-life of various elements of interest being considered).

4.2.7. Previous data collections

It is doubtful if previous data sets can be directly merged. There must be some element of data smoothing incorporated whenever this is attempted. An example of this was the extensive airborne gamma spectrometric survey of the USA conducted in the late 1970s as part of the National Uranium Resource Evaluation Program (NURE). Many different contractors were used for the survey flying, using different aircraft and gamma detector configurations. Flight line spacing varied and certain regions of the country were excluded from overflights.

4.2.8. Survey merging

The entire NURE data set was merged using algorithms developed specifically for this data set. While it can be done, it must be noted that there is always some loss in accuracy, both in the data and within the scale of the measurements. The same techniques could be applied to data collected by other surveys.

Accompanying this data set was a vast database of stream sediment analyses. Many attempts had been made to correlate various elemental analyses of the stream sediment data to the airborne gamma ray spectrometric measurements but generally, it is only in selected geological provinces that there is any correlation. Another consideration for survey merging is the scale of the surveys. It would be improper to merge regionally collected data (roughly defined as 1 km or greater sample spacing) with local or site specific surveys (roughly defined as less than 1 km sample spacing).

4.2.9. Accuracy, precision and sensitivity

Accuracy, precision, and sensitivity of the instruments are important. There are standard methods of dealing with them and they must be carefully followed and explained in any data release. Various analytical techniques have their own idiosyncrasies. Some are better than others for various elements and cost considerations should be considered. Sampling errors can be greater than analytical errors.

Strict procedures should be in place and followed to minimize the introduction of errors in both sampling and the analytical process. This is not straightforward because of the great variability in the sampling environment. In any case, sufficient information should be given to allow proper evaluation and weighting of the accuracy and precision of the results.

4.3. MEDIA TYPES

4.3.1. Drainage sediment geochemistry

4.3.1.1. Theory

Chemical analysis of drainage sediment material is based on the premise that the sediments represent a composite sample of bedrock and overburden up-drainage from the sample site. This is generally true but must be assessed for each individual situation. Drainage is dominantly characterized by stream systems and active stream sediments are most commonly collected. Recently, overbank sediment (floodplain sediment) has been evaluated. In low relief areas that have undergone continental glaciation, the drainage is characterized by lakes connected by short interconnecting streams. In such situations, lake sediment samples have proven useful. This sample medium has been successfully adapted to many variations of drainage systems and purpose worldwide. It is commonly used at the reconnaissance and early follow-up stage of geochemical assessment. Drainage sediment surveys are often conducted in combination with water geochemical surveys.

Hale and Plant [89] edited a volume devoted to drainage geochemistry applied to mineral exploration. It represents the best departure point for information on this topic; individual papers cover topics such as stream sediments in mineral exploration [90], lake sediment sampling in mineral exploration [91] and drainage sediments in uranium exploration [92]. This volume provides information on drainage geochemistry that is applicable for all drainage survey purposes.

4.3.1.2. Survey design

The combination of drainage environments and survey purposes are myriad. Geochemical survey design in general is addressed by Fletcher et al. [93], Closs and Nico [86] and Bloom [94]. Hale [95] specifically discusses strategic choices in drainage geochemistry. While there is a wealth of literature and existing experience in drainage geochemistry survey design, it still may be appropriate to conduct orientation or pilot investigations to establish appropriate survey design criteria for individual programmes.

4.3.1.3. Sampling protocol

Sampling protocols are established to meet the goals of individual projects. For broader purposes, such as the global mapping programme, efforts are being made to introduce standardization to aid future compilations [96]. General considerations for sampling protocol design are presented by Hale [95], and those for individual survey types are addressed by authors in Hale and Plant [89]. Many of the considerations listed under water geochemistry and soil geochemistry are equally applicable for drainage-sediment geochemistry according to Garrett [97]. The challenge is to select a limited number of essential parameters that will actually be used in the interpretation stage.

4.3.1.4. Data acquisition

Sample collection will be customized to the purpose of the survey. The use of specific material in the drainage survey, such as heavy mineral concentrates, requires additional consideration in both field collection and processing [98]. Appreciation of the sample site environment in subsequent survey data interpretation and decision making cannot be underestimated.

4.3.1.5. Dataset calibration

The success of any survey is controlled by the weakest link in the sequence of steps that make up the entire survey process. High quality work in field sampling and standard analytical quality control is essential in supporting data interpretation. Analysis of variance approaches have proven valuable in the design and execution of the components of geochemical surveys [99]. Time and funds required for preparation of reference materials for use in quality control are often underestimated. Establishing these materials for selective extraction analysis is particularly troublesome [1].

4.3.1.6. Survey merging

Due to the great variation in purpose, methods, data quality, and the evolution of concepts and analytical methods over the years, merging of past surveys is extremely difficult. Again, Darnley et al. provides a review of, and recommendations for, this critical issue [1]. Where appropriate, standardization offers the best solution for future work.

4.3.2. Case study

Figures 7 and 8 represent the uranium concentration of the conterminous USA. Figure 7 shows the sample based analytical results for uranium analysis of stream sediments. Figure 8 is the airborne equivalent uranium concentration from the National Uranium Resource Evaluation study conducted in the late 1970s and early 1980s. Flight lines were generally 5–10 km apart and the sediment sampling was at 10 km centres. This is a good example of comparing data sets from different presentations and reflects the caution needed in interpretation. The sediment sampling shows large contiguous areas of high concentrations (red to purple) while the airborne gamma ray map gives the appearance of discrete points (red to purple).

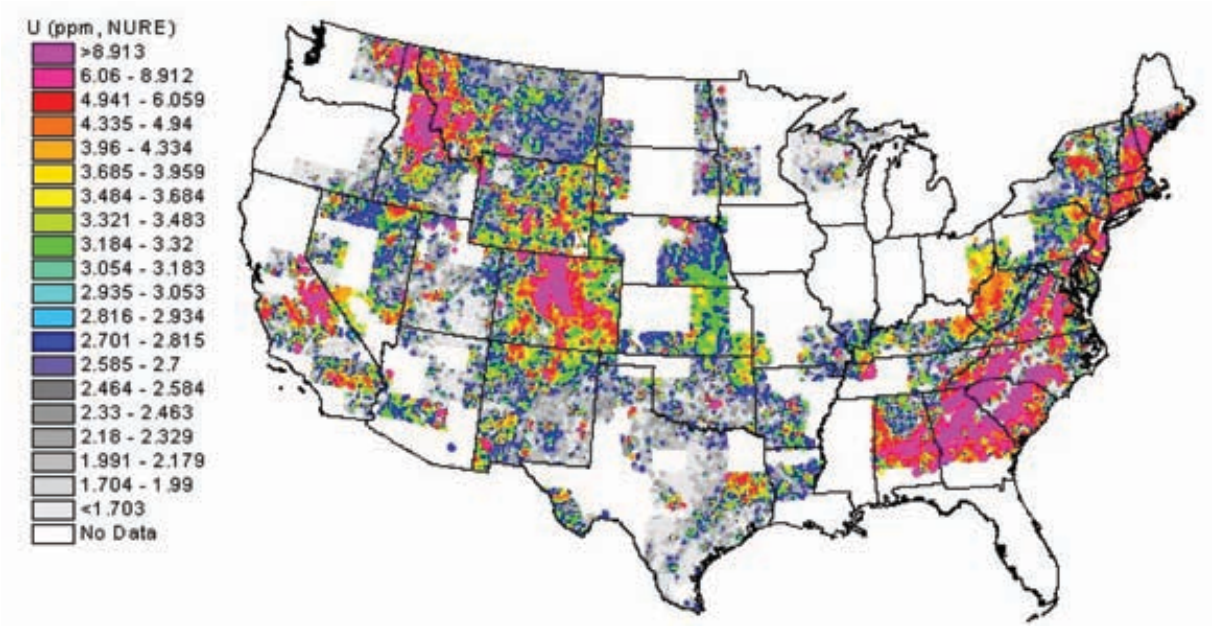

FIG. 7. U concentrations of the conterminous USA based on stream sediment geochemistry.

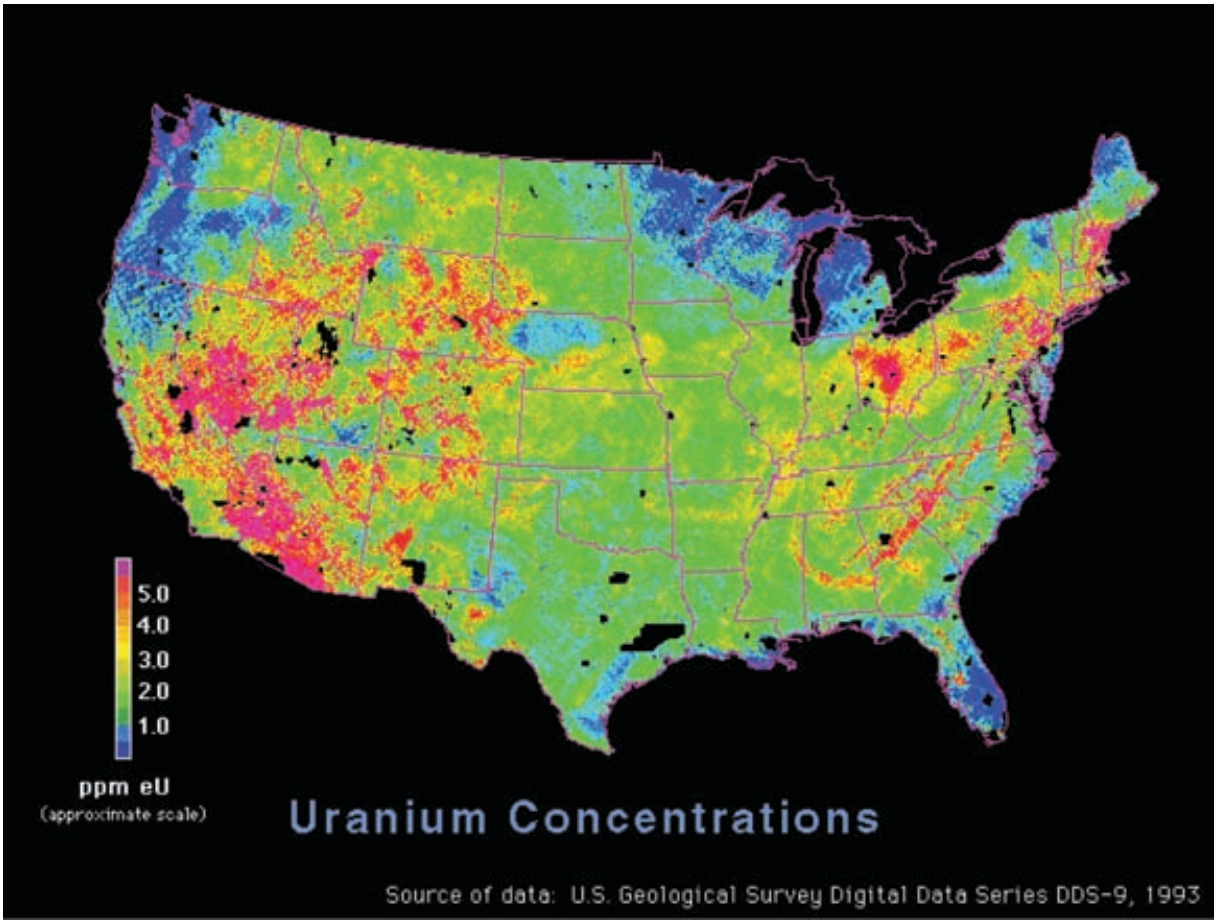

FIG. 8. Equivalent U concentrations of the conterminous USA derived from airborne gamma ray spectrometry.

4.3.3. Water geochemistry

4.3.3.1. Theory

Of all the possible media that can be analysed, water is perhaps the most straightforward. It is the collection and sample preparation that require most careful attention and several sampling protocols are needed depending on the source of the water. Water should be divided and subdivided into several categories: precipitation (snow and rain); surface water (oceans, lakes, ponds, rivers and tributaries); springs (cool or steaming); groundwater (perched or flowing) and interstitial (pore fluids). Many of those sources are either permanent or ephemeral with a great dependence on season. Each of those sources will have a different sampling protocol. Standardized survey methods are available in the United States Geological Survey (USGS) National Field Manual for the Collection of Water-Quality Data [100].

4.3.3.2. Survey design

When water is the desired medium to be collected, it is important to develop a sample design for each category of water to be collected, and one that effectively uses the analytical capability available. The availability of samples is established in large part where the water is located. Although one could design a sampling programme where groundwater samples could be collected on a regular grid through drilling, the costs would be prohibitive.

4.3.3.3. Sampling protocol

It is important to include the objective of the survey in the sampling protocol [101]. Water samples are straightforward to collect, but difficult to maintain the representativeness of the site during transport, analysis, and storage. Water chemistry is easily changed due to the interaction with the sampling materials, the storage vessels, the suspended materials, and even the gas content. Therefore, it is important to make as many measurements as possible at the sampling site. Examples are:

- Temperature and barometric pressure;
- pH;
- Eh or pE,
- Specific conductance;
- Dissolved oxygen;
- Alkalinity and acid neutralizing potential;
- Turbidity.

It is also vital to note whether or not the sample has been filtered to remove the suspended material.

The overall sampling protocol must identify sampling locations and include all of the equipment and information needed for sampling, such as:

- Types, numbers, and sizes of containers for the appropriate volume (weight) of sample;
- Labels, field logs (notebooks);
- Types of sampling devices;
- Numbers and types of blanks;
- Sample splits, spikes, and composites;
- Preservation materials and instructions;
- Chain of custody procedures and transportation;
- Field preparations such as filtering;
- Field measurements such as pH, specific conductance, etc.;
- Identify other physical, meteorological, hydrological or other site characteristics.

4.3.3.4. Data acquisition

The method of collecting the samples will be specifically related to the type of sample collected. Sampling protocols are written descriptions of the procedures to be followed in the collection, packaging, labelling, preservation, transportation, storage, and documentation of samples. This reduces errors or erroneous assumptions about procedure. The method of collecting samples will be specifically related to the type of sample collected. The chemistry of the soils is dependent in large part on the specific size fraction. Whole sample analyses are possible, but often the surface chemistry of a particular size fraction is highly related to various elements. The data quality objectives (DQOs) must be balanced against the cost, schedule, and manpower available for the project.

4.3.3.5. Data set calibration

The data set can be calibrated for precision and accuracy by comparison of replicate analyses and standards and blanks. These are standard laboratory procedures established by international boards that prescribe various methods.

4.3.3.6. Survey merging

Merging past surveys can be very difficult because there is often little or no information available that relates to variations in analysis. Quite often it will be necessary to treat the data as relative data for a specific survey area.

4.3.4. Soil geochemistry

4.3.4.1. Theory

Chemical analysis of soil samples generally reflects the bedrock from which the soil is derived, but is greatly varied by the mechanisms of soil formation which include climate and biological activity. Soil, where it occurs in thicknesses greater than 0.5 m, is a medium that gives the radiometric signature for various gamma surveys. Soil samples also provide an opportunity to analyse pore water and soil gases. It must be kept in mind that these are ephemeral sources, and equilibrium with a source is hardly ever observed — e.g. the well known pair of radioelements, radium and radon.

4.3.4.2. Survey design

As with other media, sample design can be somewhat standardized for a survey in any area. However, for soil, three dimensional profiles are quite important because the chemical characteristics of the various soil profile layers are highly variable.

4.3.4.3. Sampling protocol

Sampling protocols are written descriptions of the procedures to be followed in the collection, packaging, labelling, preservation, transportation, storage, and documentation of samples. This reduces errors or erroneous assumptions about procedure. It is important to include the objective of the survey in the sampling protocol. Water samples are straightforward to collect, but difficult to maintain the representativeness of the site during transport, analysis, and storage. Soils typically contain a great amount of moisture and organic material that can easily interact with the sample to change its condition from that found at the collection site. As with water, soils are easily changed due to the interaction with the sampling materials, the storage vessels, the suspended materials, and even the gas content. Therefore it is important to make as many measurements as possible at the sampling site, or even initiate sample preparation at the sampling site, if necessary. The overall sampling protocol [101] must identify sampling locations and include all of the equipment and information needed for sampling, such as:

- Types, numbers, and sizes of containers for the appropriate volume (weight) of the sample;
- Labels, field logs (notebooks);
- Types of sampling devices;
- Numbers and types of blanks;
- Sample splits, spikes, and composites;
- Preservation materials and instructions;
- Chain of custody procedures and transportation;
- Field preparations such as filtering;
- Field measurements such as pH, specific conductance, etc.;
- Identification of physical, meteorological, hydrological or other relevant site characteristics.

4.3.4.4. Data acquisition

Sampling protocols are written descriptions of the procedures to be followed in the collection, packaging, labelling, preservation, transportation, storage, and documentation of samples. This reduces errors or erroneous assumptions about procedure. The method of collecting the samples will be specifically related to the type of sample collected. The chemistry of the soils is dependent in large part on the specific size fraction. Whole sample analyses are possible but often the surface chemistry of a particular size fraction is highly related to various elements. The DQOs must be balanced against the cost, schedule, and manpower available for the project.

Soil gases are an important component of soil chemistry [102] yet many radionuclide surveys omit these elements. Radon and helium are products of the radioactive decay series. Simple methods are available for collection of soil gases and the analysis of ^{222}Rn from the ^{238}U decay series, and ^{220}Rn from the thorium decay series [67][103]. Included in the soil gas series is also the measurement of geoaerosols, the product of transport of gases

or elemental products from depth. Many transport mechanisms have been proposed, ranging from buoyancy to quantum displacement of elements [104].

4.3.4.5. Data set calibration

The data set can be calibrated for precision and accuracy through comparison with replicate analyses and standards and blanks. These are standard laboratory procedures as established by international boards that prescribe various methods. Sampling protocols are written descriptions of the procedures to be followed in the collection, packaging, labelling, preservation, transportation, storage, and documentation of samples. This reduces errors or erroneous assumptions about procedure.

4.3.4.6. Survey merging

Merging past surveys can be very difficult because there is often little or no information available related to variations in analysis. Quite often, it will be necessary to treat the data as relative data for a specific survey area.

4.3.5. Rock samples

4.3.5.1. Theory

Although geochemical background studies for uranium (or other elements) in rocks are less common than such studies in water, soils, or stream sediments, background studies of uranium in rocks are, nevertheless, useful for a variety of purposes. These include: understanding geological processes; identifying uranium provinces; exploration for uranium ores; exploration for some other types of ores and possible sites for geothermal heat exploitation; understanding ore-forming processes; and, health impact and environmental restoration. This wide range of purposes requires backgrounds at a variety of scales. Not surprisingly, the analytical methods and procedures used in these studies are as varied as the uses.Techniques are not standardized but customized for the problem being addressed.

Compilations of existing data to form backgrounds on a global scale, such as Turekian and Wedepohl, [105], are useful in understanding some geological processes, such as global heat flow and the concentration of uranium and thorium into crustal rocks, particularly granites. Using existing data has the obvious advantages of economy and speed, but also has limitations. As Turekian and Wedepohl point out, one limitation is that the definition of granite (or any other type of rock) varies somewhat from one researcher to the next. One way to overcome that problem is to use data sets that contain sufficient information on the major oxides (of Si, Al, Ca, Mg, Na, K) that the samples can be shown to fit a consistent definition of granite. Such analytical data are available in the US Geological Survey's RASS (Rock Analysis Storage System) database. This computerized database contains all of the analyses of rocks performed by the USGS, and these data may be retrieved by chemical characteristics, field description of the rock type as well as other factors. In an effort to demonstrate that a granite encountered in a kilometre-long drill core [106] in NW Illinois beneath the Upper Mississippi Valley zinc–lead district was unusually enriched in uranium, a background data set of 147 samples of rock that fit a chemical definition of a granite and were analysed for uranium were retrieved from the RASS database (C.T. Pierson, unpublished data). Uranium contents of the granites in this background data set ranged from 2 ppm to 26 ppm with an average of 7.8 ppm. The contrast between this background and the 45 ppm average of 13 samples from the core in north-west Illinois (which were not analysed by the USGS and therefore not in RASS) shows how unusual the granite is in NW Illinois, and the higher average (7.8 ppm) for uranium in these granites compared to the data quoted by Turekian and Wedepohl, and other averages, points to another limitation of using existing data. Specifically, without knowledge of why samples were collected, backgrounds based on existing data may be misleading; rocks that have been analysed were often collected because they were interesting, not because they were average.

4.3.5.2. Survey design and grid spacing

Because of the variety of purposes for background studies in rocks, and because of the variation in the physical and chemical characteristics of rocks, there is no uniform protocol in sampling. The sample size needed to

acquire to be representative depends on the grain size and texture of the rock. The best approach could be to take multiple samples and do an analysis of variance. The depth for an ideal sample also varies with the purpose of the study and with the depth to which weathering has altered the rocks. This too is highly variable from one rock type to the next.

Uranium province scale

Granites with uranium content well above background values are of interest. Although uranium in ore deposits could theoretically be derived from any uranium-bearing rock, those enriched in uranium place fewer constraints on the hydrology of ore formation, and therefore are more likely ore sources. Thus, one reason for identifying granites anomalously enriched in uranium is that they are potential source rocks for uranium ores; identifying anomalous granites (and arkosic sandstones derived from them and eruptive equivalents of granites) is a way of finding a potential uranium province. Stuckless et al. found that uranium rich granites from Wyoming, USA [107], had been leached of uranium to considerable depths and could have provided uranium for ores in the basins adjacent to the granites. It should be noted that care must be taken in such studies to assure that the drilling process is not leaching uranium from the granite and altering the conclusion. In addition to being a source of uranium, fracturing of granites enriched in uranium, thorium and potassium can increase the permeability of the granites sufficiently to allow convective flow of water to carry radiogenic heat into the overlying rocks and thus provide a source of energy (heat) for the formation of hydrothermal uranium deposits [108]. These radioactive granites might also provide heat for the formation of Mississippi Valley type zinc–lead deposits [109].

Another approach in attempting to identify regions of above background uranium, which may be uranium provinces, involves finding anomalously high equivalent uranium (eU) values on existing radiometric well logs [110]. An advantage of their method is that it uses existing data. However, the distribution of oil wells limits the areas where the method may be applied.

Uranium district scale

Within a uranium province (such as the Colorado Plateau), chemical analyses of rock samples have been used to establish background levels of uranium and other elements; anomalies compared to these backgrounds were then used to attempt identification of uranium districts. Some attempts used statistical programmes to contour geochemical data and thus quickly produce both a background and anomalies. Although a study by Cadigan involved mercury rather than uranium [111], it is an example of the use of such programmes and shows some of the problems in statistical treatment of chemical analyses of rocks. Ideally, data for statistical treatment should be collected in a random fashion, but the distribution of outcrops or drill holes seldom allows rock samples to be randomly collected. Consequently, there is a possibility of a bias in the sample distribution and the statistical results need to be viewed with caution. There is also the problem of obtaining a representative sample. Levinson suggested that in order to obtain a representative sample, larger samples should be taken from rocks that are coarse-grained or have inhomogeneous textures [112]. An alternative is collecting multiple samples at each sample site and doing an analysis of variance, though it is expensive.. The advantage of an analysis of variance is that it places a statistical degree of confidence on the estimates of concentrations of elements at various sites and on the differences among these sites. Cadigan took multiple samples in some sites, not all, but did not do an analysis of variance [111]. Inspection of his data shows that the in-site sample variation is about as large as the variation between the extremes of his sample sites. Therefore it is doubtful that the chemical data from sites with only a single sample are representative of those sites and the use of a statistical contouring program to form backgrounds and anomalies is not justified. Cadigan's approach is valid, but only with the appropriate sampling strategy.

Kukkonen and Lahfinen. analysed one sample for about every 40 km^2 (a total of 1193 samples over an area of 120 km by 500 km) from seven geological units to establish a background of uranium, thorium and potassium for heat flow studies in Finland [113]. Only one sample was collected at each site, but that was all that was needed to accomplish their goal of establishing average values of these elements in each geological unit. Their goal was not to compare the amount of uranium, thorium and potassium among the sites, but to determine the average of these elements in each geologic unit.

Within a district, the contrasts between background rock samples and those in or near ore have been useful in prospecting for these ores directly and in finding uranium ores through an understanding of the genesis of these

deposits. Shoemaker et al. contrasted the chemical characteristics of grab samples of background rocks to ore samples for several uranium mining districts on the Colorado Plateau [114]. Their statistical approach involved a correlation matrix, which (like many statistical tests) requires data sets that approximate a normal distribution. According to Fisher, the logarithms of geochemical data approach a normal distribution more closely than do the untransformed values in ppm or per cent [115]. Consequently, the geometric means (which are based on the logarithms of the data) were used by Shoemaker et al. in their study to identify elements associated with uranium ores [114]. Spirakis et al. also used geometric means of geochemical data from large sets of existing data (National Uranium Resource Evaluation data) to determine the elements associated with ores on the Colorado Plateau [116]. Their statistical treatment of the data was a simple 't' test to contrast the geometric means between background rock samples and ore samples. Even that simple test assumes a near normal distribution of the data in order to be valid. Therefore a normal distribution of the data should be confirmed before other statistical tests are conducted.

In contrast to the dispersion haloes found around ore deposits in soil, stream sediments and water samples, the chemical haloes in rocks around ores are generally a consequence of the mineralizing process and represent low grade mineralization [117]. So finding elevated amounts of uranium compared to background values is a valuable prospecting guide. Also of interest are the elements enriched in the ores relative to their background levels because they give clues to the ore-forming processes; with a knowledge of the processes, geological environments where these processes are likely to occur may be sought. The association of uranium with organic carbon (a reducing agent) and with elements that are precipitated by reduction or as sulphides (which are precipitated by the reduction of sulphate) in various types of uranium deposits has long been used as evidence that reduction is essential to forming many types of uranium ores. Thus, seeking sites where organic matter may have accumulated is an aid to prospecting. A study of elements enriched in roll type ores relative to their background values from drill chip samples showed that although the uranium anomaly was confined to rocks near the ore, some other chemical anomalies, particularly zinc, may occur as far as 2000 m down dip of roll type uranium ores [118].

4.3.5.3. Data acquisition

As with all sampling programmes, the use of sampling protocols, the written descriptions of the procedures to be followed in the collection, packaging, labelling, preservation, transportation, storage, and documentation of the samples, are essential for later evaluation of the methods, and the ability to merge any one individual survey with another. This reduces errors or erroneous assumptions about procedure. The method of collecting the samples will be specifically related to the type of sample collected. The chemistry of the soils is dependent in large part on the specific size fraction. For rock samples, whole sample analyses are possible, but trace elements are often contained in specific mineral fractions. Frequently, but at greater expense, separate analyses are reported for various mineral phases. Rock analyses, including the igneous, metamorphic and sedimentary rocks, reveal important data on the primary host of sediments, waters, and soils, media from which most phases are taken. It reveals a mechanism for chemical separation from the host rock to regimes where transportation of elements is greater.

4.3.5.4. Data set calibration

For rock analyses, major elements (those typically reported as per cent) are generally reported with relatively high accuracy, independent of the type of analytical method used. Minor and trace element accuracy and precision are increasingly dependent on sample collection technique, preparation and storage, purity of reagents, and the accuracy of the standards. The data set can be calibrated for precision and accuracy by comparisons of replicate analyses and standards and blanks. These are standard laboratory procedures as established by international boards that prescribe various methods.

4.3.5.5. Survey merging

Merging rock analyses into those of other sample databases is typically not done because of the absolute differences in the nature of the materials. Particularly, this is due to the very great difference in permeability of the samples, e.g. rocks to soils. Although the low permeability of many rocks protects them from contamination, permeable rocks, such as tuffs, are sometimes contaminated with uranium and require an understanding of background levels of uranium for use in preparing remediation targets. As part of an environmental remediation

project around the Los Alamos National Laboratory, New Mexico, USA, Broxton determined the natural background levels of uranium and other elements in the Bandelier Tuff [119]. They also determined how much of the uranium and other elements could be easily leached from the samples. The leachability of uranium is important because contamination does not produce uranium that is locked up in refractory minerals (monazite, zircon) but instead adds uranium to the tuff in the form of mineral coatings or in exchange sites on clays, or other forms, which may be easily leached. However, an analysis of the whole rock includes the refractory minerals and therefore suggests a background based on whole rock analyses, which masks the severity of contamination. A background based on the leachable uranium gives a better estimate of how much more uranium has been made available to the biosphere from contamination and provides a better target level for restoration. One of the major limitations of existing samples of rocks or soils in large databases is that they almost never include information on the mineral residence of elements, or their leachability, and therefore are of little use in establishing background levels for environmental restoration.

4.4. DATA MANAGEMENT AND INTERPRETATION

4.4.1. Introduction

Preparation of regional geochemical baselines is dependent on consideration of numerous tasks that are considered in this section: data management (including basic documentation and archiving issues), data interpretation, data presentation, and validation. All these tasks contribute, both during and after the survey has been completed, to the ultimate goal of employing geochemistry in defining the regional patterns, recognizing 'anomalous' conditions in nature and directing our efforts to those sources. A more extensive coverage is provided in Darnley et al. [1].

4.4.2. Data management

Data management takes several forms. The many tasks considered under this heading include enumeration and sequencing of the aspects needed to describe the nature of the survey and to complement the quantitative measurements. We are in a period of great opportunity with the availability of cost effective multi-element data. However, the challenge is how to use this information effectively to meet the goals of our surveys. Attention to the details of data management is essential to effectively gain the informational insights resident in our data.

4.4.3. Data interpretation

Data interpretation does not start after all the field work has been completed and the geochemical data have been received from the analytical laboratory. Decisions made during the design and execution of the survey itself often control the direction and extent to which the data interpretation component of the programme can proceed; that is, if you didn't collect the correct sample material, utilize the appropriate chemical digestion, or analyse for the best trace element suite, you may not have the opportunity to detect regional trends and anomalous conditions that exist in the survey area.

Geoscience data have two important aspects: magnitude or intensity of the parameter under investigation; and its position in space and time. It is essential to accurately portray natural regional trends in order to recognize abnormal conditions that may be of significance with respect to mineral resources and environmental considerations.

4.4.3.1. Single element data

It is both appropriate and necessary to look at data related to individual parameters first. Basic statistics and graphical representation in the form of histograms and probability plots provide means for appreciating the distributional form of our data and can serve as a first step in classifying the data into anomalous versus background categories. Data quality, both in terms of the measurements themselves (QA/QC) and the sources of variability in the data (measurement, local or in site, and regional or between site), are essential first steps in data interpretation.

As noted in report writing guidelines [94], we must go beyond simply determining what the QA/QC condition is and consider the implications of that condition on the data interpretation task at hand. Evaluation of data in single element format, in their spatial context, is equally essential. It is difficult to appreciate the results of multi-element data treatment without having first considered single element data presentations.

4.4.3.2. Correlation analysis

Geochemical associations are thought of in terms that characterize various geological entities and processes. It is thus appropriate to look at geochemical data as a whole to identify multi-element relationships that can be used to recognize those geological features and processes that are of significance to the problem at hand. The first step in this process is to look at possible inter-relationships on a pair-wise basis. Computation of correlation coefficients provides that opportunity. The correlation coefficient is a measure of the extent of the linear relationship between the two parameters under consideration. Plotting of the data is now readily accomplished and is essential to test this characteristic of the data. Many pitfalls exist. Correlation relationships are frequently the starting point for more sophisticated multivariate data analysis, therefore full appreciation of the validity of results from correlation analysis is essential groundwork prior to using these advanced techniques.

Finally, strong correlation does not equal cause and effect. It may suggest geologically meaningful associations and/or processes; however, that is an interpretation on the part of the explorer.

4.4.3.3. Multivariate data analysis

The first step in data analysis is to characterize the regional or background variations in the geochemical landscape. This involves the identification of what is 'background'. This activity is particularly challenging in the case of environmental work where accepted methodologies are not well defined or are done by regulatory authorities. That information is then used as a base for identifying anomalous conditions of economic and/or environmental relevance to our survey goals, which will assist us in discovering orebodies.

This leads to the recognition of the basic underlying question we need to focus on in data interpretation — classification. For each sample, is it a member of the anomalous or background population? Data analysis techniques such as multiple regression, discriminate analysis and cluster analysis aid in addressing this question.

We recognize that geological materials are frequently composite in nature. The implication is that frequently our chemical data reflect contributions from more than one of these geological components and confound simple classification. Relying on the concept of geochemical associations and correlation to recognize interrelationships in our data, it may be possible to partition the total response of a given element into its component parts. Once these data have been partitioned in this way, we can focus on the associations related to both regional and local features and return to our basic question of classification. Data analysis techniques such as principal components or factor analysis address this type of situation.

4.4.3.4. Data analysis

Geoscience data are characterized by both magnitude and position. Plotting of data as maps or cross-sections is the traditional means of representing geological data. It is critical to distinguish between the factual or raw data (postings) and derived or interpreted representations of the spatial character of geochemical data. Contouring, colouring and shading can both illuminate and mask relationships in the data.

Geographic Information Systems (GIS) approaches in their elementary form are similar to the old light table approach to spatial data analysis-multiple layers of data viewed when superimposed on each other. Evolving interpretive capabilities suggest that these techniques have the potential to provide considerable aid in spatial data analysis. The old saying of 'garbage in – garbage out' holds for GIS as well, but may be harder to recognize.

4.4.3.5. Merging

This topic was addressed in an earlier section. While there is an obvious desire to make use of previous survey results, both individually and collectively, the task must be approached with great caution if useful products and decisions are to be forthcoming. This situation is discussed in detail by Darnley et al. [1].

5. STATUS OF RADIOELEMENT MAPPING

5.1. AIRBORNE GAMMA RAY SPECTROMETRIC SURVEYS

A country by country review of worldwide gamma spectrometry coverage, gathered from publications and contact with national agencies is provided in Appendix A. It gives an assessment of the quality and status of the coverage, including calibration of the data. Contact details for data sources are provided.

In the last decade, a concerted effort has been made in some quarters to recover analogue (profiles or contours) and digital radioelement data from older surveys in order to preserve their legacy in digital form. There remain several regions in the world where this should be done before the data are irretrievably lost. Once the data are in a modern digital form, they can be back calibrated through field work or using adjacent surveys (Section 3.4.3).

The coverage over previously flown areas can easily be improved by new surveys due to a number of factors. These include:

— Larger crystal volumes (typically 33 L to 50 L);
— Denser line spacing (400 m or less);
— Lower flying height (80 to 100 m above terrain, or less using specialized aircraft);
— Radon monitoring and removal (e.g. upward looking crystals);
— Measurement of the full spectrum (256 or more channels);
— More rigorous sensor and system calibration;
— Noise reduction (e.g. NASVD);
— Improved data reduction and leveling.

The majority of airborne gamma spectrometer data are available from government agencies, typically geological surveys. The trend in recent years was to make this data available at a low cost, as an incentive to invest in mineral exploration. The World Bank, European Commission and associated agencies are funding a number of airborne survey programmes, particularly in Africa, for capacity building of the recipient geological surveys. Gamma spectrometry forms a fundamental component for geological mapping and mineral assessment. There is an increase in the application of gamma spectrometry to petroleum exploration, as its ability to delineate sedimentary units and locate hydrocarbon-related alteration is now well known. Activity in the collection of baseline data around nuclear facilities has continued, although these data are not always accessible.

Data acquired by the private sector and marketed on a multi-client basis, usually in past or present ‘hot areas’ for mineral exploration, tend to be more expensive due to the requirement for cost-recovery. Some government agencies must operate in a cost recovery mode as well. However, Fyon et al. quantifies the economic activity that results from the acquisition and publication of low cost, high quality geoscience data, providing a strong argument against the cost recovery approach for government agencies [120].

Airborne gamma spectrometry is becoming more prevalent across a broader array of geological environments, exploration targets and environmental applications. In particular, it represents a relatively low cost add-on to aeromagnetic surveys, which are providing improved coverage over both virgin territory and previously flown areas. Delivery of published geoscience data over the Internet is making gamma spectrometry data more accessible to a wider audience. A number of mineral exploration jurisdictions are now capturing digital geoscience data acquired by the private sector through mandatory submission or purchase, and these data are often upgraded through calibration and processing prior to publication. These developments contribute to the global radioelement baseline.

5.2. SAMPLE BASED GEOCHEMICAL SURVEYS

With the leadership of the Forum of European Geological Surveys (FOREGS), which includes representatives from 33 countries, substantial progress has been made in accumulating a sample based geochemical database [121].

Major problems with worldwide integration have been addressed and with the publication of International Geological Correlation Programme (IGCP) Project 259 and 360, guidelines are available for countries to follow in developing a sample programme and reporting the results. IGCP is now the International Union of Geological Sciences (IUGS)/International Association of Geochemistry and Cosmochemistry (IAGC) Working Group on Global Geochemical Baselines.

Surveys have been completed in several countries and others are nearly complete. Status updates are available on-line at FOREGS (http://www.gsf.fi/foregs/geochem/). An example of excellent progress in a large country may be found in China where, in the last 10 years, about 50% of the country has been sampled and analysed. The Chinese survey data have been used to successfully locate more than 65% of the country's economic mineral resources over the last 10 years [122]. These data will also be important in addressing environmental concerns [123].

In the USA, a large data base has been available for samples collected over several decades. When necessary, re-analysis of samples is being done and data from sample localities are augmented with new sampling programmes. Several States, such as Georgia, have independent programmes in addition to federal sample programmes. One of the advances that have made geochemical sampling programmes cost effective today has been the introduction of new analytical instrumentation. ICP methods provide simultaneous analyses of 40–60 elements and in some cases, for isotopes as well. About 71% of the country has been covered with over 61 000 samples analysed. Of those samples, just over 70% are stream sediments and 18% are soils. The web site for updated coverage can be found at http://tin.er.usgs.gov/geochem/doc/home.htm.

It is unfortunate that gases are not generally included, as helium and radon are easily measured radiogenic progeny. However, it may be possible to use some indoor radon measurements as a crude surrogate for soil-gas measurements.

Most countries participating in establishing the geochemical baseline will have set deadlines to complete their geochemical sampling and analysis by 2010. This includes the Russian Federation, China, Western Europe, Canada, and the USA.

6. APPLICATION OF RADIOELEMENT BASELINES TO URANIUM EXPLORATION, MINING, MILLING AND REMEDIATION

Radioelement baseline data play a critical role in uranium exploration. They are used to locate prospective geological terrain and potential host rocks, as well as for indirect or direct detection of uranium deposits. They also are used to locate mineral deposits where the radioelements (uranium, potassium, and thorium) are a component of multi-element ore, or reflect mineralized alteration systems. They are extremely useful for mapping the surficial geology, and are utilized to explore for base metals, precious metals, industrial minerals and, to a lesser extent, hydrocarbons.

Radioelement baselines are an important component of the environmental assessment process for the development, operation and remediation of uranium mining and production sites. They should be conducted prior to any development, to determine the natural background, and repeated regularly to monitor the sites (and transportation corridors) for excessive levels of any radioelement related to the production process. These baselines must incorporate studies of any pathway through which the radioelements might travel, including air, soil, rock, surface water, groundwater, flora and fauna. They are required within the site to ensure protection of the workers, and in the surrounding region to monitor the effects on the environment and surrounding population. These studies must continue after closure and remediation, to verify that the mine site and waste material remains a closed system.

The IAEA has prepared numerous publications that are directly relevant to the development and use of radioelement baselines for uranium exploration, mining, milling and remediation. The more recent publications include:

— New developments in uranium exploration, resources, production and demand [124];
— Planning and management of uranium mine and mill closures [125];
— Application of uranium exploration data and techniques in environmental studies [126];
— Uranium exploration data and techniques applied to the preparation of radioelement maps [24];
— Changes and events in uranium deposit development, exploration, resources, production and the world supply-demand relationship [127];
— Environmental impact assessment for uranium mine, mill and in situ leach projects [128];
— Impact of new environmental and safety regulations on uranium exploration, mining, milling and management of its waste [129];
— Assessment of uranium deposit types and resources — a worldwide perspective [130]);
— The uranium production cycle and the environment [25];
— Guidelines for radioelement mapping using gamma ray spectrometry data [22].

Note that these publications can be downloaded from the IAEA's publication website. In addition, there are other relevant publications available from the IAEA relating to regulatory and safety issues for the uranium industry.

Environmental impact assessments (EIAs) for uranium production facilities are described in Frost [131]. Studies of the environmental baseline, including topography, geology, surface hydrology, hydrogeology, and flora and fauna, form an important component of an EIA. They include measurement of the background concentrations of the radionuclides and trace metals in the air, waters, sediments, soils and biota. Such studies should be conducted through at least one full cycle of seasons to obtain some indication of variability related to climate.

6.1. USE OF BASELINES TO AID IN URANIUM EXPLORATION

The application of radioelement geophysics and geochemistry to exploration for roll-front sandstone uranium deposits in China is restricted mainly to the reconnaissance stage, to define prospective basins and target areas. At the prospect scale, radiation damage measurements (proportion of paramagnetic quartz concentration to radiation absorption dose) are used to delineate the transition between reduction and oxidation zones, where the uranium is concentrated in this type of deposit.

Gamma spectrometry data were historically collected to aid uranium exploration. The preparation of these data for radioelement baselines, and their application to environmental assessment, is summarized by Tauchid and Grasty [23]. Examples of national compilations using airborne, car-borne or ground gamma spectrometry are provided. For uranium operations, these compilations provide the regional perspective of the natural background radioactivity.

6.2. BASELINES PRIOR TO MINE OR MILL CONSTRUCTION

The Olympic Dam Mine in Australia derives the majority of its revenues from copper production [132]. It also hosts significant reserves of uranium. A recent expansion in production capacity resulted in a 250% increase in uranium production to 4 500 tonnes of uranium oxide concentrate per year. A comprehensive environmental impact statement, including assessment of any possible radiological effects, was required prior to approval of the expansion. It applied to construction, mining, ore processing, emissions and tailings. Monitoring throughout the mining and milling processes was instituted or upgraded, and showed that dose limits to any single worker were well below acceptable levels.

Mel'nik reviews the geology and hydrogeology of sandstone type uranium deposits in a variety of settings [133]. The work is focused on underground leaching, and its effect on the groundwater, but it is also applicable to other mining methods. There are a number of factors that affect the potential contamination of groundwater by mining, and prior studies of the natural contamination due to the ore-bearing structures are extremely instructive for mine planning.

6.3. MONITORING DURING OPERATIONS

The environmental controls in place at the Ranger Mine in Australia are described by Johnston in Ref. [134]. They include biological, chemical and radiological monitoring of the groundwater, surface water and atmosphere. Water management at the mine and mill site will require different levels of treatment depending on the type and uranium content of material that it comes into contact with. Baseline studies are carried out on a regular basis, and additional studies occur prior to and after the planned release of any effluent. Radon levels are monitored to ensure that the cumulative totals from the mine site and the natural background in the region remain well below the recommended dose limit. Studies of the long term impact of tailings disposal by burial, once the mine has closed, have been undertaken and the environmental risk is considered to be minimal.

Khan describes baseline monitoring of uranium mines and the mill at Jaduguda, India, which include measurement of gamma radiation, atmospheric radon and radioactivity of the surface water, groundwater and soil [135].

The McArthur River Mine in Saskatchewan, Canada is an example of an underground, high grade, uranium mine [136]. Monitoring is required for all stages of the mining process to ensure that radiation exposure for all underground and surface workers remains well below acceptable levels during the normal course of operations and during extraordinary circumstances. Cumulative dose rates from gamma radiation, radon gas, radon progeny and radioactive dust are measured.

In 1982, an airborne gamma spectrometer survey was flown in the vicinity of the Königstein uranium mine in eastern Germany, over the Elbe River Valley [137]. Several anomalous areas were located in the valley, but ground follow-up did not begin until 1991, after the mine closure in 1990. A comprehensive ground study found that the anomalies in the valley sediments had ‘disappeared’ from the surface. Soil analyses showed that uranium was located several centimeters below surface, through a combination of erosion, sedimentation and chemical mobilization. In addition, a post-1982 source of water discharge produced a new anomalous area. An equilibrium study of the radionuclides suggested that most of the anomalous uranium was in its natural state, carried by mine water, rather than waste derived from the uranium treatment process. This case study is a good illustration of temporal variation applicable to radioelement baselines.

6.4. ASSESSMENT OF CONTAMINATION EPISODES

Johnston provides a case study of the environmental and social impacts of the Ranger and Jabiluka uranium mines in Australia [138]. He mentioned a minor incident of an 80 m^3 discharge of tailings water during the wet season that showed no measurable harm downstream. Nevertheless, the local population was extremely alarmed. The incident demonstrated the need to have protective measures in place to avoid any negative perception regardless of the actual danger to the surrounding environment. Needham describes the importance of a formal process of community consultation with all stakeholders in the vicinity of a uranium operation, to report any environmental incident and quantify its impact [134]. This type of process helps to bring the public’s perception of the risks associated with uranium mining and milling closer to reality.

Significant portions of the McArthur River Mine’s host rock are sediments, which also host a large volume of groundwater [136]. Grouting or freezing minimizes water inflows to the mine. Due to the high grade nature of the in situ ore, the nearby groundwater shows high levels of radon. Any water extracted from the mine must be treated to reduce its radioactivity prior to use in the mining process. In April 2003, excess inflow occurred resulting in the suspension of mining activities for several months until the inflow could be reduced and the water in the mine pumped out and treated.

Kerbelov and Rangeloc describe the development of an airborne gamma spectrometer system and software adapted to locate radioactive pollution from uranium production, and other sources (e.g. nuclear power plants), in Bulgaria [139]. The mining activity occurs in areas where much of the geology possesses high uranium content. In the case of radiogenic granites, the uranium and potassium levels are correlated, so a map of U/K is useful to locate the polluted areas, where the U/K values remain relatively constant over the granites, but increase significantly over uranium pollution.

6.5. USE OF BASELINES TO MONITOR THE REMEDIATION PROCESS

An overview of baseline monitoring applied to the remediation of uranium mining and milling sites is provided by the IAEA [140]. Continuous monitoring of the potential transfer pathways for uranium and its daughter products (particularly radium and radon), heavy metals and other elements is necessary. This includes sampling of the water, air and food chain in the site's vicinity. Extensive review of water quality before and after the mining/milling operations is a fundamental indicator of environmental quality.

The mine/mill closure process, and the contribution of baseline studies, is discussed in Refs [141–142]. The methodology to implement these studies has been reviewed [46]. It is recommended that the following be measured:

- Soil sampling for total U, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th and ^{228}Ra, as well as any significant stable elements identified in the ore body, and in a full metal scan of a subset of the baseline samples (e.g. V, As, Ni, Se and Mo), with a coincident ground gamma spectrometer survey;
- Sampling of surface water, groundwater, tailings and waste water for total U, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th and ^{228}Ra, gross alpha activity, non-radiological metals (e.g. Se, V, Mn, Fe, As, Ba, Cd, Cr, Ni and Cu), as well as major ions (e.g. carbonate, ammonium, sulphate, chloride and nitrate);
- Atmospheric sampling for radon, airborne particulates of natural U, ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po (and ^{228}Th, ^{232}Th and ^{228}Ra, if ^{232}Th forms a significant fraction of the ore content);
- Monitoring of the biosphere (e.g. flora and fauna, especially those items in the food chain).

The IAEA classifies an environmental baseline study as one that is undertaken immediately after site selection [46]. Any similar study undertaken, once human activity has commenced, is classified as a characterization study. Should no baseline study be available, then characterization studies may need to incorporate surrounding, unaffected areas to provide an estimate of the natural background conditions.

A status report on the environmental restoration of uranium mining and milling sites, mainly located in Europe, is provided in Ref. [143].

A comprehensive baseline study of the uranium production facilities in the Czech Republic, active from 1946 to 1990, was carried out in the 1990s [144]. The work included assessment of mine sites, mill sites, tailings areas, waste dumps, transportation corridors, downstream drainage and roads constructed from waste material. The radioactivity of the natural background (i.e. geology) was measured for comparison. The effectiveness of previous remediation efforts (e.g. waste dumps covered by non-radioactive rock or soil) was also determined. As a result, areas that posed any danger to human activity were identified so that restrictions and remediation procedures could be implemented and prioritized by the appropriate authorities.

Several uranium mines and mills were active in the Mounana district of Gabon from 1960 to 1999 [145]. The local population lived, travelled, worked, cultivated and fished near, and sometimes on, those sites. A series of baseline studies were carried out before and after remediation, to determine the cumulative radiation doses above the natural background from all possible sources affected by the uranium mining operations. The remediation resulted in the reduction of the additional dose by a factor of 2 to 3, which is within the targeted level. Monitoring will continue to ensure that these levels do not spike upwards in the future.

Csicsak describes the treatment of uranium-bearing groundwater from the Pécs deposit in Hungary [146]. The No. 1 shaft was closed in 1968 but has a direct connection to the aquifer that provides the local drinking water supply. Consequently, water must be pumped from the shaft to maintain levels below the surrounding water table, and the uranium removed by ion exchange. By 2000, 150 t of uranium had been produced as a by-product of this treatment process.

Uranium deposits mined using in situ leach processes require the injection of acids or carbonates into the ore-bearing zone to create the pregnant solution for extraction. Active treatment of the groundwater is required once leaching is completed to restore aquifers to their natural condition [147–148]. The remediation requires baseline studies of the ground and surface water for a range of total dissolved solids to ensure that the residual solutions are attenuated properly.

Uranium production at the Zirovski Mine in Slovenia stopped in 1990. Three scenarios for site selection to remediate the mill tailings were analysed [149], namely improvement of the current site, disposal in the mine openings or disposal at a new site. This was undertaken using the rating matrix of the Uranium Mill Tailings

Remedial Action Project, prepared by the United States Department of Energy. Baseline studies were prepared for 35 parameters categorized in four groups: geotechnical [149], hydrological [150], environmental [33] and economic [68]. Based on the current state, it was judged that keeping the tailings at the current site was the best solution. However, projecting the state of the tailings 1 000 years forward resulted in disposal to the mine openings becoming the preferred solution.

Biehler et al. discusses the remediation of a uranium mine in Germany without adequate baseline studies of the hydrogeology and hydrochemistry [150]. The mine was allowed to flood by discontinuation of pumping. The actual flood level proved to be much higher than had been anticipated, and the water chemistry was markedly different. As the mine was located in an area of high population density, and flooding could contaminate the drinking supply, it proved necessary to pump and treat the mine water.

7. CONCLUSIONS

The items below are major contributions of this report. The background and justification for these conclusions is provided in the report and the accompanying papers. Implementation of actions based upon these conclusions will hopefully lead to data consistency, the proper and widespread use of radioelement data for environmental and geoscience applications, and the development of appropriate regulatory guidelines.

(1) Member States should consider adopting the methodologies and standards for preparation of radioelement baseline data that are referenced in this report.
(2) Government and international agencies need to be made aware of the standards and uses of radioelement baselines referenced in this report, and are encouraged to incorporate them in their activities.
(3) Programmes need to be implemented to educate relevant authorities and the public regarding the presence, type and level of both naturally occurring and anthropogenic radioelements in the environment, and what are, or are not, causes for concern.
(4) Regulatory agencies need to consider the range of natural background when setting limits on radioelements and other elements in the environment and should make use of available baseline data, or acquire new data as needed.
(5) A baseline study of the radioelements and other elements needs to be conducted at any site where human activity has the potential to change the levels of radioactivity in the environment.
(6) Wherever possible, radioelement data need to be collected, processed and analysed according to the standards referenced in this report; these data can then be incorporated into the global radioelement baseline.
(7) A global effort to revitalize historical radioelement data is necessary and work should be carried out in accordance with the radioelement baseline standards referenced in this report.
(8) A comprehensive, worldwide metadata catalogue of the existing radioelement surveys needs to be developed.
(9) Member States should be encouraged to make their radioelement data accessible in a web based format.
(10) A worldwide network of radioelement calibration sites is needed, which should be properly maintained, and preferably be tied directly or indirectly to the IAEA laboratory reference standards.
(11) Numerous archived gamma spectrometer survey data include measured spectra from which the signal due to anthropogenic sources (e.g. ^{137}Cs) should to be extracted.
(12) The status of the global radioelement baseline, and its applications, should be revisited every two years.

Appendix I

WORLDWIDE COVERAGE AND CATALOGUE OF PUBLIC DOMAIN GAMMA SPECTROMETRY SURVEYS

Figure 9 shows the current worldwide coverage of gamma spectrometric data. Figures 10 and 11 show more detailed coverage maps for Mongolia and the Russian Federation, respectively. These are followed by a catalogue of public domain gamma spectrometric surveys.

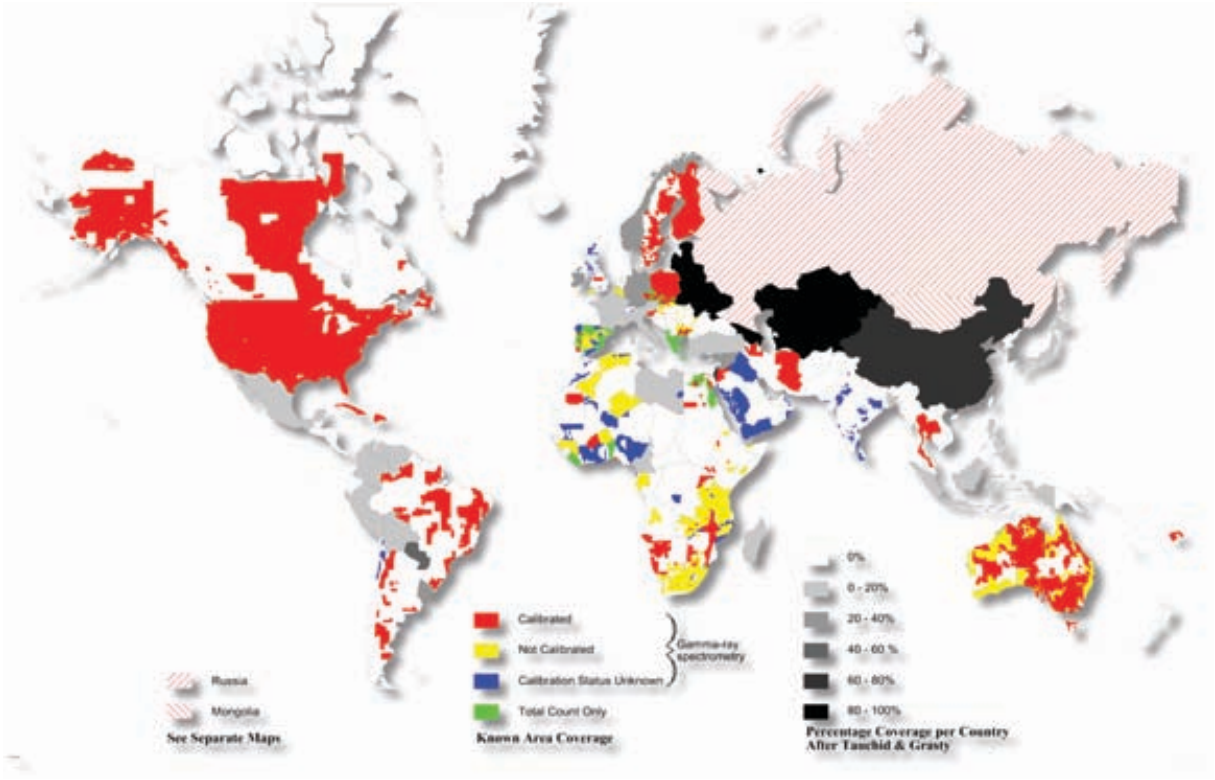

FIG. 9. Worldwide airborne gamma spectrometric coverage.

I.1. WORLDWIDE COVERAGE

The information presented in this appendix was the best available at the time of preparation of this publication and provides only an indication of the extent of gamma coverage in each country. It is not intended as a definitive catalogue. For countries not included in the list below, it was not possible to find the relevant information within the period of preparation of this report. Data acquisition is naturally dynamic and several new surveys may have been conducted during the period between completion and publication. Referenced publications are presented in the bibliography (p. 103).

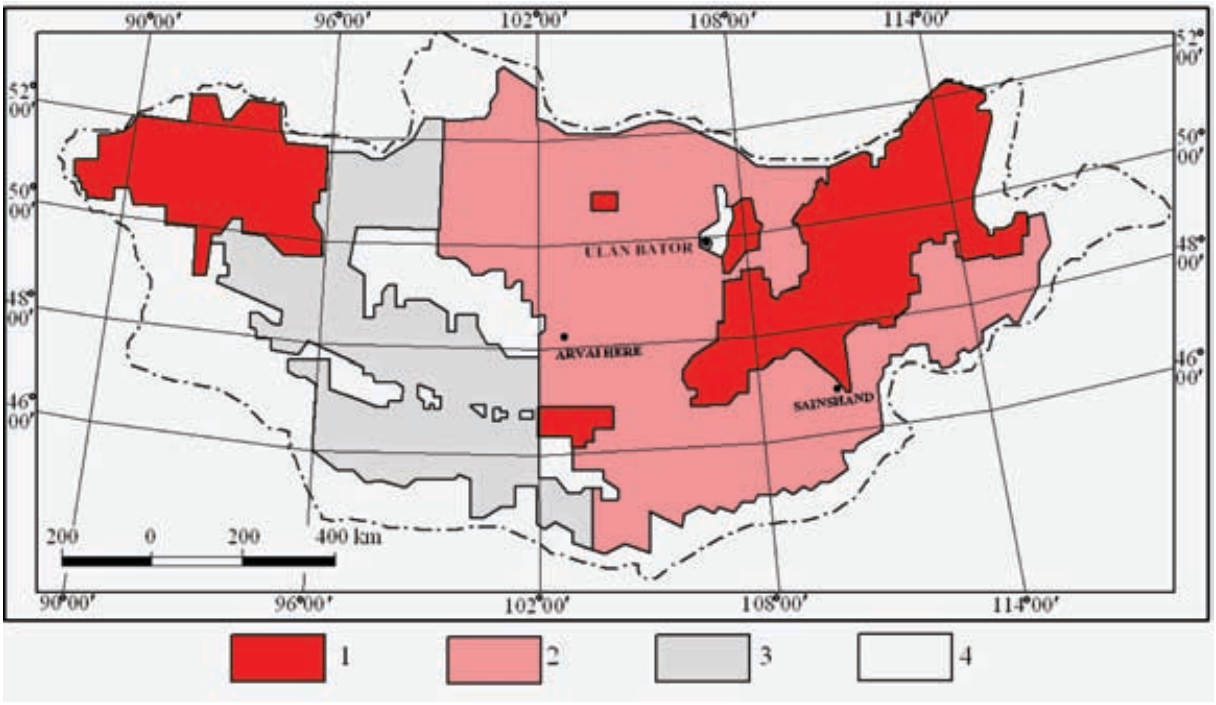

FIG. 10. Airborne gamma spectrometric coverage of Mongolia. Legend: 1 — High quality, detailed (250 m–500m profile separation) AGS performed with airborne gamma spectrometers GSA-77, GSA-75, GSA-80 and 25.2, 37.5 and 75 L NaI(Tl) detectors. 2 — High quality, medium scale (2 km profile separation) AGS performed with airborne gamma spectrometers GSA-77, GSA-75, GSA-80 and 25.2, 37.5 and 75 L NaI(Tl) detectors. 3 — High quality, regional (10 km profile separation) AGS performed with airborne gamma spectrometers GSA-77, GSA-80 and 25.2, 37.5 and 75 litres NaI(Tl) detectors. 4 — Area not covered.

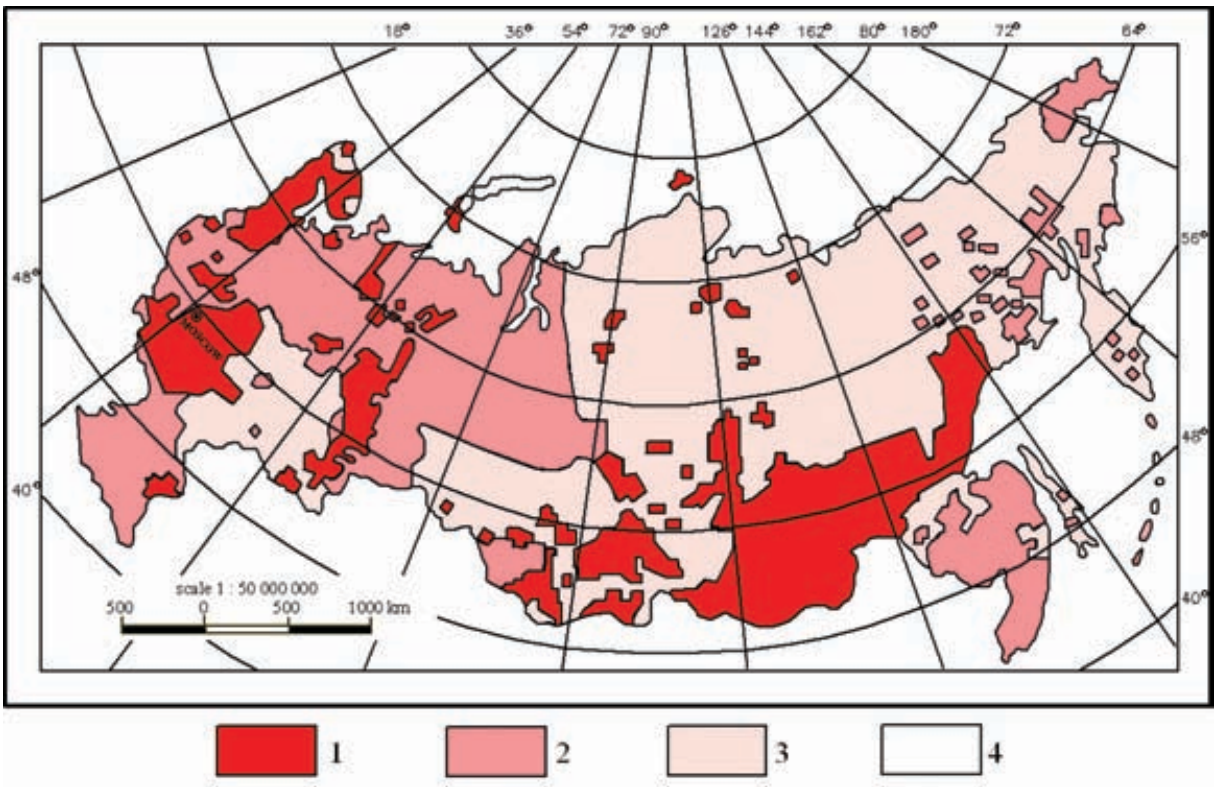

FIG. 11. Airborne gamma spectrometric coverage of the Russian Federation. Legend: 1 — High quality category of AGS. 2 — Medium quality category of AGS. 3 — Low quality category of AGS. 4 — Area not covered.

I.2. CATALOGUE OF PUBLIC DOMAIN GAMMA RAY SPECTROMETRY SURVEYS

I.2.1. Afghanistan

Summary of coverage:

There may be some coverage acquired by the former USSR.

I.2.2. Albania

Contact address:

Geophysical Center of Tirana
L.9, Biloku Vasil Shanto
Tirana
Albania

Summary of coverage:

The entire land area of Albania is covered by a total count ground gamma scintillometry survey, including 37 800 measurements at a density of 1–2 per km^2. The portable ratemeters used were calibrated by means of a ^{226}Ra point source and the measurement results expressed in exposure rate units $\mu R.h^{-1}$. Data records (analogue) and radiometric maps are available at the Geophysical Centre of Tirana. The countrywide measurements range between 2–24 $\mu R.h^{-1}$ with an average of 7 $\mu R.h^{-1}$ (equivalent to 60 $nGyh^{-1}$. Ground gamma spectrometry (4-channel) was only applied to investigate anomalous local zones.

I.2.3. Algeria

Contact address:

Office National de Recherche Géologique et Minière
Cité Ibn Khaldoum
B.P. 102, 35 000 Boumerdès
Algeria

Summary of coverage:

Most of the coverage shown in the map was flown at a 2 km line spacing with four radiometric channels (TC, K, U, Th) being recorded digitally in counts per second only. This older data has not been recompiled or calibrated.

I.2.4. Angola

Contact address:

Instituto Geologico de Angola
P.O. Box 1260
Luanda
Angola

Summary of coverage:

A large survey, covering 116 950 km^2 of the central highlands of Angola was carried out in 1970, at a 1.5 km line spacing and nominal ground clearance of 152 m. The four-channel survey employed three 15.2 × 10.2 cm NaI crystals, the raw cps data being recorded in analogue format on scaled charts. Pre- and post-sortie flights included 'castle calibration' for correction of aircraft and cosmic background, and a survey altitude test line for monitoring of daily variations due to environmental conditions. No data were collected specifically for the correction of atmospheric radon. Stripping ratios were probably determined from measurements over point sources. The gamma spectrometry data is not calibrated.

I.2.5. Argentina

Contact address:

Comisión Nacional de Energía Atómica
Avenida del Libertador 8250
1429 Buenos Aires
Argentina

El Servicio Geológico-Minero Argentino
(SEGEMAR)

Summary of coverage:

In 1995, SEGEMAR commenced a program of systematic airborne geophysical surveying, including gamma spectrometry, aimed at covering some 1.5 million km^2 in 10 years. The line spacing in most areas is 1 000 m, sometimes reduced to 500m. The nominal flying altitude for these surveys is mainly 120 m mean terrain clearance (mtc), with some flown at 140–150 m. Nominal terrain clearance is maintained except where more extreme topography dictates adjustment for safety purposes.

Data from an older, 1978–79 survey was recently recovered, reprocessed to correct levelling problems, and back calibrated. The National Atomic Energy Commision of Argentina has also calibrated and tested a carborne gamma spectrometry system for use in exploration and environmental monitoring.

I.2.6. Australia

Contact address:

Geoscience Australia
GPO Box 378
Canberra, ACT, 2601
Australia
www.ga.gov.au

Summary of coverage:

Geoscience Australia (the National Australian Geoscience Agency) and the Geological Surveys of Australia's individual states (New South Wales, Victoria, Queensland, Western Australia, South Australia, Northern Territory and Tasmania) have been collecting airborne geophysical data over the Australian continent since the mid 1950's. These data are publicly available — either free of charge or at a nominal cost. Approximately two-thirds of the Australian continent is covered by digital airborne gamma spectrometric surveys. More than half of this coverage consists of data acquired with detector volumes exceeding 32 litres NaI(Tl) detectors and at a line spacing of 500 m or better. Most of these surveys were processed according to IAEA specifications, and the results reported in standardized units tied to the international radiometric baseline. There are several calibration facilities in Australia. All of these are tied to the CSIRO calibration pads at North Ryde, Sydney, which in turn are tied to the IAEA global

calibration network. Most of the earlier surveys were flown with detector volumes of 16 litres, and with a line spacing of 1.6 or 3.2 km. The results from these earlier surveys are generally reported in units of counts per second. However, there are a number of back-calibration programs under way in Australia to ultimately convert the entire national gamma spectrometric database to standardized units.

Metadata on all publicly available gamma ray spectrometric surveys can be found on Geoscience Australia's web site (www.ga.gov.au/oracle/argus). The metadata includes information on data custodianship and availability. Data acquired by Geoscience Australia and the Geological Surveys of New South Wales, Victoria, Queensland, Western Australia and Northern Territory can be downloaded free from the Australian Geoscience Portal (www.ga.gov.au/gadds). Data acquired by the Geological Surveys of South Australia and Tasmania are currently only available from the respective State Geological Survey web sites. These web sites can be accessed through the Australian Geoscience Portal (www.geoscience.gov.au). However, note that data acquired by the South Australian and Tasmanian Geological Surveys is currently being prepared for delivery through the Australian Geoscience Portal.

I.2.7. Bangladesh

Contact address:

Geological Survey of Bangladesh
P.O. Box 720
153 Pioneer Road
Segunbagicha
Dhaka 1000
Bangladesh

Atomic Energy Commission of Bangladesh
4, Kazi Nazrul Islam Avenue
G.P.O. Box 158
Dhaka-1000
Bangladesh

I.2.8. Belgium and Luxembourg

Contact address:

Belgian Geological Survey
Jennerstraat 13
B-1040 Brussels
Belgium

Federaal Agentschap voor Nucleaire Controle
(Agence Fédérale de Controle Nucléaire)
Ravensteinstraat 36, B-1000 Brussels
Belgium

Studiecentrum voor Kernenergie (Centre d'Etude de l'Energie Nucléaire)
Boeretang 200
B-2400 Mol,
Belgium
www.sckcen.be

Summary of coverage:

An airborne survey covering the entire Belgian and Luxembourg territory was carried out in 1994, the data being acquired by Geoterrex Pty Ltd of Australia and processed by Compagne Générale de Géophysique (CGG). Lines were flown N-S and spaced at 1 km except in two selected areas, a large area over the Brabant Massif to the SW of Brussels and a narrow N–S strip across Luxembourg, where the spacing was reduced to 500 m. E–W tie lines were flown at 10 km intervals and the flying height was 120 m mtc.

An Exploranium GR820, 256 channel spectrometer was used, recording counts in the five standard energy windows for TC, K, U, Th and cosmic background. The data were corrected for dead-time, cosmic and aircraft background, Compton scattering and height attenuation. Radon corrections for the uranium channel were carried out by cross-correlation with the corrected thorium data on a line by line basis. Radon corrections for the potassium

and total count channels were then calculated in a similar way using the corrected uranium data. The usual assumptions related to this method of radon removal apply. Full processing details are provided in the survey report.

No calibration line was established for the survey and the data products are in units of counts/s.

I.2.9. Benin

Contact address:

Ministère de L'Energie, des Mines et de l'Hydraulique (MMEH)
04 BP
1412 Cotonou
Benin

Summary of coverage:

A countrywide survey, flown in 1966 by Prakla-Seismos, included a scintillometer. The survey was flown at an altitude of 150 m mtc with a line spacing of 2 km. Contour maps, at scale 1:100 000, of total count were contoured at 25 counts/s.

I.2.10. Botswana

Contact address:

Department of Geological Survey
Private Bag 14
Lobatse
Botswanawww.gov.bw

Summary of coverage:

Airborne gamma spectrometry surveys in Botswana are confined largely to areas of outcropping and sub-cropping Precambrain basement. All surveys were carried out during the period 1996 to 1999 and were conducted to IAEA standards. Full spectrum, 256 channel data were acquired at a flying height of 80 m and a line spacing of 200–250 m. The systems were calibrated using portable pad facilities at Eros airport (Windhoek) and the calibration range established by the Geological Survey of Namibia at Henties Bay.

I.2.11. Brazil

Contact address:

Serviço Geológico do Brasil (CPRM)
SGAN-Quadra 603 — Conjunto J — Parte A - 1º andar
Brasília — DF
CEP: 70830-030
Rio de Janeiro
Brazil
www.cprm.gov.br

I.2.12. Bulgaria

Contact address:

Geology and Geophysics Corporation
23 Sitnyakovo Blvd
Sofia
Bulgaria

Summary of coverage:

The following summary is extracted from a report covering the status of regional gamma data in central and Eastern Europe.

Early airborne gamma surveys recorded total counts only and covered approximately 28% of the country at 250 m line spacing. Contour maps of exposure rate are available for these surveys. Later (1984–1989) 256 channel airborne gamma spectrometry surveys used 50.5 L of downward-looking crystal and covered 20% of the country at a 500 m line spacing and flying altitude of 60–100 m. The measurements were calibrated over three natural test strips in the Czech Republic and on calibration pads in Buhova, near Sofia. Digital data are available and probably require some internal levelling.

Ground gamma surveys conducted (1972–1991) included both total count and four channel spectrometry measurements, using instruments calibrated at the Buhovo facility. These cover 75% of the country at 500 m–1 km spacing.

I.2.13. Burkina Faso

Contact address:

Bureau des Mines et de la Geologie du Burkina Faso (BUMIGEB)
01 BP 601
Ouagadoudou 01
Burkina Faso

Summary of coverage:

A 1976–1977 airborne survey, carried out by Kenting Surveys Ltd, covered the eastern half of Burkina Faso and parts of Niger and Mali, with N–S oriented lines at a spacing of 0.5 km and mean terrain clearance of 150 m. Parts of this area were flown in 1970–1971 by Survair. Profile maps in cps were produced for the four radiometric channels. No calibration to convert the data to ground concentrations was undertaken during the survey operations. In 1984, Paterson, Grant and Watson (PGW) of Toronto carried out ground measurements to back calibrate the airborne data.

In 1978, a small area (200 km × 28 km) around Bobo Dioulasso was flown specifically for uranium exploration. An Exploranium 3001, four channel spectrometer with 3072 cubic inches of crystal was used and channel counts recorded in analogue format on heat sensitive paper. The data were corrected for background, Compton scattering and altitude attenuation and presented as stacked profiles in counts/s. Ground checks using a Scintrex GIS-4 spectrometer were made at 33 locations.

Airborne coverage for the mid-western part of the country was acquired more recently (1998–1999) under SYSMIN Project 480, funded by the European Union on behalf of Bumigeb. The flying contractor was CGG. The 256 channel gamma spectrometry survey employed 33.6 litres of downward-looking and 8.4 L of upward looking crystal. Lines were spaced at 500 m and 1 km and oriented NW-SE. Flying altitude was 100 m mtc and sampling interval 1 s (70–80 m). Fully corrected radioelement data are reported in ground concentrations (K, U, Th) and nGy/h (TC).

I.2.14. Burundi

Contact address:

Royal Museum for Central Africa (RMCA)
Leuvensesteenweg 13
3080 Tervuren
Belgium
www.africamuseum.be

Summary of coverage:

Burundi was covered by two airborne gamma spectrometry surveys (approximately covering 50% of the country each), both of which were older generation, with inherent problems. The earlier of the two, flown in 1974, is not available digitally and is probably of too poor a quality to consider digitising the existing analogue data. The second survey, flown in 1981, used 16.8 L of Na(T1) crystal installed in a helicopter and flown at a terrain clearance of 61 m and line spacing of 0.5–1 km. The data were corrected for background, Compton scattering and flying altitude and the contribution from atmospheric radon removed based on daily flights over Lake Tanganyika. The survey was calibrated and digital results presented as equivalent ground concentrations. The survey was flown and recorded in 11 separate geographical blocks, some of which, due to technical problems during the survey, have not recorded gamma spectrometry data.

I.2.15. Cambodia

Contact address:

Department of Geology and Mines
Ministry of Industry, Mines and Energy
45, Preah Norodom Blvd., Phnom Penh
Cambodia

I.2.16. Cameroon

Contact address:

Institute for Geological and Mining Research
BP 4110
Yaounde
Cameroon

I.2.17. Canada

Contact address:

Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K2H 7M9
Canada

Summary of coverage:

Work in Canada on the development of radiometric instrumentation for the detection of radioactive minerals in the field commenced in the 1930s. Experiments with airborne equipment began in 1946 and the first trial of an airborne gamma spectrometer took place in 1949. During the 1950s many small areas in northern Canada were flown with total count (TC) devices to assist in uranium exploration, but, in general, results were disappointing because of the inability of the method to separate significant from insignificant anomalies. Apart from a few reconnaissance profiles, results were not published.

Canadian development of high sensitivity gamma spectrometry equipment for ground and airborne use commenced in 1966. In order to construct an effective exploration and mapping system, it was recognized that it was necessary to develop methods of calibrating and standardizing all measurements. The results should be reported in units of radioelement concentration, which were meaningful to earth scientists and could be related to other types of geochemical measurement. The procedures developed by the Geological Survey of Canada (1967–1971) were reviewed and accepted by an IAEA consultants meeting in 1976 and current international practice is based upon them.

Canadian AGRS data in the latest compilations were collected (1970–1995). All this work has been performed to essentially the same standard. Data collection began with the Geological Survey of Canada's then newly developed, high sensitivity AGRS system carried in a Skyvan aircraft. With successive refinements to the instrumentation, this system was employed for the following 25 years. Procedures were essentially unchanged throughout this period. Detailed information on instrumentation and procedures was published in 1984.

In the years 1975–1978, three commercial contractors, using instrumentation with specifications compatible with the GSC system, were employed in order to expedite data collection. Their equipment was calibrated under GSC supervision at the beginning and during each season. The contractors delivered a major part of the present coverage. Compilation of the Canadian coverage has involved the melding of more than 250 separate survey blocks from successive years and various operators. Some adjustment and re-levelling of data has been required during the national compilation, particularly with respect to data collected during the period of maximum effort, 1976–1978, at the time of the Uranium Reconnaissance Program. In total, during the 1970–1995 period, the GSC Skyvan system collected 503 706 line km of data and contractors were responsible for an additional 364 506 line km.

Surveys commenced at the outer margin of the Canadian Shield and extended inwards. For reconnaissance purposes a line spacing of 5 km was accepted as the best compromise between a reasonable probability of recognizing uraniferous zones and the need for rapid, economical coverage. Earlier experiments over known Canadian uranium producing areas (Bancroft and Elliot Lake, Ontario, and Uranium City, Saskatchewan) had shown that their anomalous features, indicative of mineralization, had strike lengths of the order of 15–20 km, and widths >5 km. Therefore, by employing a 5 km reconnaissance line spacing at least one recognizable intersection could be expected over any comparable new occurrences. Although 5 km line spacing was regarded as optimum for reconnaissance purposes, some areas (e.g. in Alberta and NWT) for which there were no pre-existing radiometric information were flown at 25 km or 27.5 km spacing in order to make a rapid preliminary assessment to determine if more detailed surveys might be justified at a later date. As a result of this preliminary work, most of the NWT area was subsequently reflown at 5 km, with 5 km spacing samples 5% of the surface area. Note that the validity of the data provided by each individual flight line is unchanged whatever the line spacing.

Following the demise of the Uranium Reconnaissance Program in 1979, priorities changed, budgets were reduced and national coverage became a distant target. During the 1980s and early 1990s, GSCs Skyvan system was used to fly (or refly) small areas for mineral exploration research projects at line spacings less than 5 km, occasionally as close as 300 m. This provided a very detailed definition of ground features, which greatly facilitated ground follow-up, and produced many examples of the application of AGRS to a variety of mineral exploration situations, but this work added little to the reconnaissance coverage of Canada as a whole. As a result there are AGRS data for only about 33% of the Canadian land area, unfortunately excluding most of the more highly populated areas in SW Ontario, the Prairies and British Columbia.

I.2.18. Chad

Contact address:

Ministry of Mines, Energy, and Petroleum
Directorate of Geological and Mining Research
BP 816
N'Djamena,
Chad

I.2.19. Chile

Contact address:

Servicio Nacional de Geología y Minería
Av. Santa María 0104
Providencia, Santiago
Chile

I.2.20. China

Contact address:

Director of Geological Research Centre
Beijing Research Institute of Uranium Geology (BRIUG)
Beijing
China

Summary of coverage:

The southern part of China is covered but the western part, towards Tibet, is not.

I.2.21. Cuba

Contact address:

Instituto de Geología y Paleontología. Departamento de Geofisica.
Vía Blanca No. 1002 entre Carretera Central y Línea del Ferrocarril.
Municipio San Miguel del Padrón
La Habana,
Cuba. CP. 11000

Summary of coverage:

Systematic ground and airborne gamma radiometric measurements have been conducted for geological mapping and uranium exploration in Cuba, since 1960. The ground surveys only recorded total count for both regional and detailed scales, and cover the most prospective parts of the country (around 20–25%) for mineral exploration. The instruments were calibrated by means of a ^{226}Ra point source and the all measurements are in μr/h.

Regional (1:50 000) and detailed (1:25 000) surveys conducted during the period 1979–1993 used a line spacing of 500 m or 250 m, ground clearance of 65–75 m, and a flying speed of 140–160 km/h. Approximately

105 000 km^2 of airborne gamma spectrometry measurements were conducted over the whole country (90%). 25.4 L Na I(Ta) detectors were employed for the 1979–1993 surveys and the systems calibrated at a facility with K, U, Th and background pads. The spectrometric maps of Cuba at 1:100 000 scale, are based on the 1979–1993 regional airborne gamma ray spectromerty measurements A new series of spectrometric maps for Cuba, at 1:50 000 scale is currently in preparation.

Dedicated airborne gamma spectrometric measurements were conducted for gold and base metal exploration in Cuba. These survey, at detailed scale (1:20 000 and 1:10 000), cover some interesting regions, totaling approximately 3.7% of the country. The systems were not calibrated and measurements are available in TC only. Selected areas, principally in the eastern part of the country, were flown at a lower altitude using a helicopter with 33 L of Na(T1) crystal on board. Back calibration of these detailed surveys has not yet been conducted.

The latest, helicopter-borne, surveys were flown 1994–1995, at line spacings of 200 and 100 m and a 60 m ground clearance, using 16.78 L of crystal (+4.2 L upward looking). The surveys covered small areas and were not calibrated to give ground concentrations.

All airborne spectrometric data, in digital form, are owned by the Geology and Paleontology Institute (IGP), La Habana (igp@igp.minbas.cu).

I.2.22. Cyprus

Contact address:

Geological Survey Department
Levkonos 1
Stovolos
Nicosia
Cyprus

Summary of coverage:

No known coverage.

I.2.23. Czech Republic

Contact Address:

Czech Geological Survey
Klarov 3
110 00 Prague 1
Czech Republic
www.geology.cz

Summary of coverage:

Systematic airborne and ground gamma radiometric measurements have been conducted for geological mapping and uranium exploration in the Czech Republic (78 863 km^2) since 1946. Regional 1:200 000 (1957–1959, profile separation 2 km, flight altitude 100 m, flight speed 150 km/h) and detailed 1:25 000 (1960–1971, profile separation 250 m, flight altitude 80 m, flight speed 100–140 km/h) airborne gamma TC measurements cover the whole area of the country. The TC instruments were calibrated by means of a ^{226}Ra point source. Detailed 1:25 000 airborne gamma spectrometry surveys (from 1976 onward, with NaI(Tl) detectors 14.8 L and since 1988, 33.6 L) were conducted over regions of interest, corresponding to 55% of the area of the country. Airborne gamma spectrometers were calibrated at a calibration facility with K, U, Th and background pads and by

flights over three calibration test strips. Carborne and ground TC and gamma ray spectrometry surveys were conducted in individual areas of U exploration interest over 35% of the area of the country.

The radiometric map of the Czech Republic 1:500 000 is based on regional TC airborne measurements. Back calibration was applied in order to level the radiometric data and to convert them into gamma dose rate. 122 regional ground traverses 1–5 km long, evenly distributed in the area of the Czech Republic were measured with a calibrated and verified portable gamma spectrometer in a dynamic mode. Regression analysis between airborne and ground data, with coefficient of correlation r = 0.993, resulted in an estimate of back calibration multiplication constant of 0.85 for the airborne data. The radiometric map of the Czech Republic, expressed in dose rate, compiled as a map of contours, with the step of contours 10 (20) nGy/h, reflects the interval of regional terrestrial radiation 15–245 nGy/h, with a mean 66 nGy/h. The data and map were verified by a series of international comparisons and tests of the applied measurement technique. Radiometric data in digital form are owned by the Czech Geological Survey, Prague.

Airborne gamma spectrometry maps of separate areas, measured gradually from 1976, are compiled at scale 1:50 000. The maps report concentration of K, U and Th, the dose rate in nGy/h and some of them surface activity of ^{137}Cs nuclear fallout. Primary digital data of airborne measurements and radiometric maps are owned by the Czech Geological Survey.

At least two small areas of high-resolution gamma spectrometry data (100–250 m line spacing, 80–100 m agl, 20 L crystal) were acquired by Picodas Prague during the period 1992–1996.

I.2.24. Democratic Republic of the Congo

Summary of coverage:

Maybe some 1970's coverage in central south of country.

I.2.25. Denmark

Contact address:

GEUS, Geological Survey of Denmark and Greenland
Ø. Voldgade 10,
DK-1350 Cph. K
www.geus.dk

I.2.26. Dominican Republic

Summary of coverage:

In 1996, a non-exclusive airborne magnetic and gamma spectrometry survey was flown over the Dominican Republic by Fugro Airborne Surveys. Approximately 50% of the onshore area was flown with a line spacing of 500 m, with the remainder of the onshore area and offshore areas being flown with a spacing of 1 or 2 km. The flying height was 120 m above ground/sea.

I.2.27. Egypt

Contact address:

Nuclear Materials Authority
P.O. Box
530 El Maadi
Cairo
Egypt

National Authority for Remote Sensing & Space Sciences,
23, Joseph Broz Tito St.
Cairo
Egypt

Summary of coverage:

Three phases of airborne radiometric surveying have been conducted over Egypt:

Phase 1 (1958–1977) measured total count by means of a Russian ARS-2 rate meter with a 1006 cm^3 scintillation detector installed on a Russian biplane, the Antonov-2. The system was calibrated using a point radium source and the results expressed in exposure rate, μR/h. The flying heights were 50–100 m terrain clearance. The line spacing differs according to the survey target; it varies from 250, 500, 1 000, 2 000 and 5 000 m.

During **Phase 2** (1983–1984), a large multi-channel, airborne gamma survey was conducted over the Eastern and Western deserts of Egypt, covering a total area of 83 900 km^2 at a terrain clearance of 120 m and line spacing of 1 500 m. The survey was conducted by Aero Service Division, Western Geophysical Company of America. The survey was designed to provide data, which would assist in identifying and assessing the mineral, petroleum and groundwater resources in Egypt.

Phase 3 commenced in 1996 when the Nuclear Materials Authority of Egypt (NMA) established its own airborne survey capability, employing a Scintrex PGAM-1000 multi-channel gamma spectrometer with 50 liters of downward-looking and 4 L of upward looking crystal installed in a twin-engine, Beechcraft King Air. Stripping ratios for the system are determined over IAEA approved calibration pads in Cairo. Sensitivity calibrations are conducted in Egypt using the Canadian calibration pads owned by NMA. Various areas in Egypt have been flown with this modern system, including the Gulf of Suez and its adjacent areas, the Northern Coast of Egypt on the Mediterranean Sea, the East Owinat mountain area in the south Western part of Egypt and some areas in west Sinai and the Western Desert. The line spacing of these surveys varies according to the survey target, from 250, 500, 1 000 and 10 000 m. The flying heights were 100–120 m terrain clearance.

I.2.28. Equatorial Guinea

Summary of coverage:

A 1981 airborne survey in the eastern part of the country included gamma spectrometry. Details are not known.

I.2.29. Eritrea

Summary of coverage:

A poor quality, 1970 survey covered the Tigre area of southern Eritrea - for details see Ethiopia.

I.2.30. Ethiopia

Contact address:

Ethiopian Institue of Geological Surveys (EIGS)
P.O. Box 2302
Addis Ababa
Ethiopia

Summary of coverage:

Three airborne geophysical surveys were carried out 1970–1971 for mineral exploration over areas of Precambrian rocks in the Wollega and Sidamo provinces and in the Tigre/Begemeder area. All of these surveys were flown at a mean terrain clearance of 150 m and a line spacing of 1 km. 16.7 L (Wollega and Sidamo) and 5.7 L (Tigre) of downward looking Na(T1) crystal were employed. Recordings of the four radiometric channels were on analogue charts only. Navigation difficulties were experienced in the Sidamo and Wollega surveys and parts of the Tigre survey, with data recovery based on uncontrolled mosaics. Data correction procedures map products are total count contours (at 50 counts/s, Tigre only) and individual window anomalies (i.e. counts/s above background, peak value + width) marked along flight-line tracks. Recovery of these data would require digitising of the original analogue record charts and geometric correction, if the poor background monitoring and correction procedures and, in the case of the Tigre survey, the very small detector volume justify the effort.

More recent AGRS data have been acquired over the Adola region of Sidamo (1994), partly overlapping with the earlier survey, and in the Wollega province (1996). Respectively, these surveys were flown at 200 m and 1 km line-spacing using 16.8 and 33.3 L of downward looking crystal at a mean terrain clearance of 60 m. Sensitivity constants for these surveys were determined over calibration sites with ground concentrations of radioelements determined using a portable spectrometer calibrated at the Geological Survey of Canada. For the Adola survey, corrections for atmospheric radon were made using constants determined over lakes. For the Wollega survey radon corrections were not applied.

I.2.31. Estonia

Contact address:

Geological Survey of Estonia (EGK)
80782 Kadaka tee
EE-12618 Tallinn
Estonia
www.egk.ee

I.2.32. Fiji

Contact address:

Mineral Resources Department
Private Mail Bag
GPO, Suva
Fiji Islands
www.mrd.gov.fj

Summary of coverage:

Airborne geophysical data acquired by the Fiji Regional Airborne Geophysics Project in 1997 included full spectrum gamma ray spectrometry using a 33 L NaI(Tl) crystal. The data were recorded using a fixed wing aircraft over offshore areas and low lying islands and helicopter over the rugged terrain of the major islands. The survey elevation was 80 m above land and sea, with a line spacing of 400 m over land and 800 m over water. The gamma ray spectrometry data were processed and calibrated to IAEA standards. The survey data were acquired and processed under the supervision of AGSO (now Geoscience Australia). The results of the geophysical survey are available from the Mineral Resource Department of Fiji and include digital point-located data, grids and images, profiles and interpretations. Further details may be found on the MRD web site.

I.2.33. Finland

Contact address:

Geological Survey of Finland
P.O. Box 96
FIN – 02151 Espoo
Finland
www.gsf.fi

Radiation and Nuclear Safety Authority – STUK
P.O. Box 14
00881 Helsinki
Finland

Summary of coverage:

The Geological Survey of Finland (GTK) began systematic airborne geophysical mapping in 1951, the First National Airborne Geophysical Mapping Program (1951–1972) being based on magnetic (fluxgate) and electromagnetic methods. The Second National Aerogeophysical Mapping Program started in 1972 and is scheduled to run until 2010. This new program is based on multi-sensor equipment and extra high resolution digital aerodata: the flight altitude being 30–40 m and line spacing 200 m. The modern spectrometer includes 2 NaI(T1) crystal packages with downward and upward looking crystals.

I.2.34. France

Contact address:

Bureau de Recherche Géologiques et Minières (BRGM)
BP 6009
45060 Orléans Cedex
France

I.2.35. Gabon

Contact address:

Direction des Mines et de la Geologie (DMG)
Ministere des Mines, de l'Energie et du Petrole
BP 576, Libreville
Gabon

Summary of coverage:

The entire Precambrian basement area of Gabon was surveyed on behalf of the DMG in 1983–84, for geological mapping and uranium exploration. North–south traverse lines were at 1 km spacing and the flying altitude was 120 m. Due to the variable topographical relief, 3 of the 13 blocks were flown using a helicopter while the others employed a fixed-wing platform. 256-channel spectrometers were used with a 2048 cu in Na(T1) crystal on the helicopters and a 3072 cu in crystal on the fixed-wing aircraft. Recordings were both digital and analogue. Measurements were not made to determine sensitivity constants but the final cps values are fully corrected. A 'calibration line' was used in order to adjust for the different installations.

I.2.36. Germany

Contact Address

Bundesanstalt für Geowissenschaften und Federal Institute for Radiation Protection
Rohstoffe (BGR)
Alfred-Bentz-Haus Ad1
Stilleweg 2
D-30655 Hannover
Germany
http://www.bgr.de

Summary of coverage:

Approximately 21% of the country is covered by a combination of airborne and foot-borne gamma ray spectrometry surveys, mainly over the Thuringa and Saxony areas. Details can be found in Refs [I.13, I.14].

I.2.37. Ghana

Contact address:

Geological Survey Department of Ghana
P.O. Box M80
Accra
Ghana

Minerals Commission
Plot # 9, Switchback Road Residential Area
Cantonments, Accra
Ghana
www.mincomgh.org

Summary of coverage:

Early airborne gamma ray spectrometry surveys, carried out in 1960 (Hunting Surveys Ltd.) and 1969 (Prakla Seismos), covered various selected areas of mineral exploration interest, but these areas have since been re-flown by more recent, higher quality surveys. Some of the follow-up car-borne and foot-borne traverses carried out in conjunction with the early surveys may, however, be of interest with respect to analysis and interpretation — these were conducted to verify the airborne results and, in the case of a coastal survey, to establish the gamma ray spectrometric response of exposed rocks in the region.

Modern AGRS surveys, carried out between 1994 and 2000, cover the whole of Ghana with the exception of the Voltaian and Keta Basins. Line spacing varies between 200 and 800 m and terrain clearance between 70 and 100 m. All of this more recent AGRS data is available from the Minerals Commission of Ghana.

I.2.38. Greece

Contact address:

Institue of Geology and Mineral Exploration (IGME)
70 Messoghion Str.
Athens 11527
Greece
www.igme.gr

Summary of coverage:

The following summary is extracted largely from a report covering the status of regional gamma data in central and Eastern Europe.

An early (1966) airborne radiometric survey covering 20% of the mainland area in the north was uncalibrated and recorded relative values (cps) along 1 km spaced lines in analogue format. The variable terrain clearance, due to the mountainous terrain, led to poor results. A carborne total count survey carried out over the period 1972–1982 covers the entire country, including the islands, with measurements along the irregular road network averaging 1 per km^2. During a similar period (1972–1985) a ground total count survey covered 30% of the country (in the NE) at a density of approximately 2 measurements per km^2. Results of both surveys, expressed in cps, are stored in analogue fmat by IGME.

I.2.39. Greenland

Contact address:

Geological Survey of Denmark and Greenland (GEUS)
Øster Voldgade 10
DK-1350 Copenhagen
Denmark
www.geus.dk

Summary of coverage:

A multi-sensor helicopter-borne survey in southwest Greenland included gamma spectrometry. The five survey blocks are situated near the southern Archean boundary of West Greenland and were initially selected to cover both Proterozoic and Archean supracrustal belts with a potential for economic base metal or precious metal mineralization. The survey was flown at a mean helicopter terrain clearance of 60 m with survey lines spaced at 200 m and orthogonal tie-lines at 2 000 m. A total of 8 756 line km of geophysical data were acquired. The gamma spectrometry data are digitally recorded in counts per second.

I.2.40. Guinea

Contact address:

Ministère des Mines et de la Géologie
CPDM
001 BP 5054
Conakry
Guinea

Summary of coverage:

A 1980–1981 survey covers almost the entire land area of Guinea at 1 km line spacing and a constant terrain clearance (exact clearance unknown) of less than 200 m. Flight line locations were recovered on aerial photographs of unknown quality and sensitivity constants were not determined. A 1997 survey covered approximately a third of the country at the same line spacing and a terrain clearance of 120 m. GPS was employed for navigation and the radiometric data are calibrated to ground concentrations. The data and survey reports may be purchased from the Ministère des Mines et de la Géologie.

I.2.41. Hungary

Contact address:

Magyar Geológiai Szolgálat
(Hungarian Geological Survey)
17-14 Stefánia
H-1440 Budapest
Hungary
www.mgsz.hu

Eotvos L. Geophysical Institute (ELGI)
Columbus utca 17–20
H-1145 Budapest
Hungary

Summary of coverage:

Approximately 45% of the area of Hungary is covered by airborne gamma spectrometry, which was acquired over several campaigns. Most of the coverage comes from Soviet–Hungarian surveys carried out 1965–1969, using 20 000 cm^3 Na(T1) crystal, a flight line spacing of 100–1 000 m (mostly 250 and 500 m) and altitude of 25–75 m. Recording was analogue but digital databases have since been generated from the analogue records. Low energy resolution was calibrated by flights over a test profile at Budaors airport and results are expressed in ground concentration, but rigorous back-calibration is required to bring the data to accepted baseline standards — later calibrated surveys may be used for this purpose (see below).

Smaller areas, most of which overlap the earlier survey, were flown in 1977, 1986, 1987–1991 and 1992. Line spacing varies between 50–250 m and terrain clearance between 25–100 m. All of these later surveys are calibrated and further technical specifications may be found in, or on the above website.

I.2.42. India

Contact Address:

Atomic Minerals Division,
Department of Atomic Energy
AMD Complex, Begumpet
Hyderabad 500 016
India

National Geophysical Research Institute
Uppal Road
Hyderabad - 500 007
India
Website: www.ngri.org.in

Geological Survey of India
27, Jawaharlal Nehru Road
Kolkata 700 016
India
www.gsi.gov.in

Summary of coverage:

Airborne geophysical surveys have been conducted in India since 1967, for the Department of Atomic Energy, the Geological Survey of India and the National Geophysical Research Institute of India. Many of these included gamma ray spectrometry.

I.2.43. Islamic Republic of Iran

Contact address:

Atomic Energy Organization of Iran (AEOI),
North Karegar Ave.
P.O. Box 14155-1339, Tehran
Islamic Republic of Iran

Geological Survey of Iran
P.O. Box 13185-1494
Tehran
Islamic Republic of Iran

Summary of coverage:

Much of the north and east of the Islamic Republic of Iran was surveyed during 1976–1978, at line spacings of 0.5, 1 and 2 km and a mean terrain clearance of 120 m. These surveys used 50 litres of NaI(Tl) crystal, were recorded digitally, and systems were calibrated over pads constructed at Tehran airport. Further details are available from the Atomic Energy Organization of Iran. Some gamma spectrometry has been flown more recently in the southern part of the country and the whole country is covered by aeromagnetic data.

I.2.44. Iraq

Summary of coverage:

A survey carried out in 1974 by Compagnie Générale de Géophysique (CGG) covers the entire country with the exception of the mountainous area in the northeast.

I.2.45. Israel

Contact Address:

Soreq Nuclear Research Centre
P.O. Box 2286
Holon 58117
Israel
www.gii.co.il

Geophysical Institute of Israel

Summary of coverage:

Parts of Israel were covered by an airborne gamma spectrometry survey carried out in 1981. The system used 40 L of downward looking Na(T1) crystals and 4 litres of upward-looking crystals. Measurements were made along lines at 1 km spacing and at an altitude of about 122 metres or 400 ft above ground, and the system was calibrated over stationary calibration pads constructed near the Soreq Nuclear Research Centre.

I.2.46. Ivory Coast

Summary of Coverage:

A survey covering approximately 80% of the land area of Ivory Coast was flown 1974–1976, with a line spacing of 0.5 km and a terrain clearance of 150 m.

I.2.47. Jordan

Contact address:

Natural Resources Authority (NRA)
P.O. Box 7 & 2220
Code No: 11118 – Cable NRA
Jordan
www.nra.gov.jo

Summary of coverage:

The entire Kingdom of Jordan was covered by airborne survey in 1979, which included four channel gamma spectrometry, except over a small area of mountainous terrain in the south of the country. Most of the survey was conducted at a 2 km line spacing with some 1 km spacing. The flying altitude was 120 m above terrain, except where increased clearance was dictated by rugged topography. Navigation and flight path recovery was by Doppler assisted visual/camera method. A Na(T1) crystal volume of 33.5 L was used. Prior to the survey the system was calibrated on pads and over the Brekenridge test range near Ottawa, Canada. Background radiation corrections were based on linear interpolation of pre- and post-sortie flights over large water bodies (south of country) or at high altitude (north of country). Raw and processed digital data are available at the Natural Resources Authority of Jordan.

I.2.48. Kenya

Contact address:

Ministry of Environment and Natural Resources
Maji House, Ngong Road
P.O. Box 49720
Nairobi
Kenya

Summary of coverage:

The first survey, flown in 1958, in the southeast, used a 400 m line spacing and terrain clearance of 140 m (crystal volume unknown). Surveys flown in 1969, in the northeast, mid west and southeast used a 1 km line spacing and terrain clearance of 150 m (crystal volume unknown). A later survey (1977) covering the southeast corner of the country flew lines of 1 km spacing, at a terrain clearance of 120 m using 23.7 L of Na(T1) crystal. There is possibly another pre-1970 survey covering some of the central east of the country, but no details are available.

I.2.49. Lesotho

Contact address:

Department of Mines & Geology
P.O. Box 750
Maseru
Lesotho

Summary of coverage:

A survey flown in 1975 by Northway Exploration Ltd acquired four channel gamma spectrometry data over the eastern margin of Lesotho. The survey employed an Exploranium DIGRS 3301 spectrometer with 15 L of crystal and acquired digital data along flight lines spaced at 275 m at a terrain clearance of 150 m.

I.2.50. Liberia

Summary of coverage:

Aeromagnetic and total-count gamma-radiation surveys were flown simultaneously over Liberia during the 1967–1968 dry season. The survey covered the entire land area along N-S lines at 0.8 km spacing and a terrain clearance of 150 m.

I.2.51. Madagascar

Contact address:

Ministère de l'Energie et des Mines
Service de la géologie
Rue Farafaty - Ampandrianomby
BP 322 Antananarivo 101
Madagascar

Summary of coverage:

Some early surveys (1962) flown in the south-east of the country for the Ministry of Mines may include radiometric data but this is unlikely to be multichannel or digital.

Recent airborne surveys (2004–2005) commissioned by the Ministry of Energy and Mines are cover approximately 50% of the onshore area of Madagascar in five separate geographical blocks. These were flown east–west at a line spacing of 500m and a nominal terrain clearance of 100 m, with a loose drape over more severe topography.

I.2.52. Malawi

Contact address:

Geological Survey Department
P.O. Box 27
Zomba
Malawi

Summary of coverage:

Early surveys conducted in 1971 covered small areas in the north and west of the country. In 1984–1985 the entire country was covered at a 1 km line spacing and 120 m terrain clearance. For the most part, this survey was conducted using a fixed wing platform and 50 L of Na(T1) crystal (+ 8.4 L upward-looking crystal). Selected areas in the southern part of the country were flown at a lower altitude (30–60 m) and closer line spacing (250 m) using a helicopter with 33 L of crystal on board. The on-board spectrometer installations were calibrated using the large concrete apron test pads at Lanseria Airport, South Africa. 'Broad source' sensitivity constants were determined from the pad measurements from which average sensitivity constants at survey altitude were calculated. Since the sensitivity constants were not obtained over a calibration range at survey altitude, it would be advisable to check the values determined during the 1985 survey using a back calibration procedure. The digital line data was recovered and reprocessed in 1998 and partly 'levelled' to match the Mozambique data for a 'cross-border' correlation project carried out during the GEODESA project at the Southern and Eastern Africa Mineral Centre (SEAMIC), United Republic of Tanzania.

I.2.53. Malaysia

Contact address:

Minerals and Geoscience Department
19th–22nd Floor, Bangunan Tabung Haji
Jln Tun Razak
50658 Kuala Lumpur
Malaysia
www.jmg.gov.my/english

Summary of coverage:

In 1980, the Government of Malaysia funded an airborne magnetic and gamma spectrometry survey over a large part of Peninsular Malaysia. The original digital data had levelling problems, particularly in the U channel and were not calibrated to give ground radioelement concentrations. In the early 1990s, data were reprocessed to improve levelling and back calibrated to obtain sensitivity constants.

I.2.54. Mali

Summary of coverage:

Several surveys were flown in the mid to late 1970s. The early surveys flown in the north and east of the country used a line spacing of 2 km and terrain clearance of 75 and 150 m, respectively. The small area of coverage in the southeast forms part of the regional survey carried out by Kentings (see Burkina Faso). More recent surveys include 176 000 line km covering the Birimian terrain in Mali, acquired by Fugro, in 2003, for the Ministry of Foreign Affairs as part of a national programme to develop the geological database. At least one survey for the private sector was conducted in 2001 for mineral exploration.

I.2.55. Mauritania

Contact address:

Ministère des Mines et de l'Industrie
BP 199

Nouakchott
Mauritania
http://www.bgs.ac.uk/mmi

Summary of coverage:

There are several 1955–1970 airborne surveys at 150 m mtc that may have included gamma spectrometry. The Ministry of Mines and Industry is executing a national programme of airborne geophysics (aeromagnetics and radiometrics) to cover the entire country. A large block in the north of the country was completed in 2001 and a block in the south, which had received financial backing, was scheduled to commence in the winter of 2002. The data for these recent surveys are available from the Ministry of Mines and Industry. A number of smaller surveys were flown for the private sector (mainly for diamond exploration) in 1999–2000. These amount to several hundred thousand line kms but several are uncalibrated.

I.2.56. Mongolia

Contact address:

Geologorazvedka
Knipovich 11, Building 2
Saint Petersburg
193019 Russia

Director of Uranium Company
Department of Geology
Ministry of Geology and Mineral resources
Baga Toirog 6
Ulaanbaatar 11
Mongolia

Summary of coverage:

This information was prepared by E.V. Visokoostrovskaya, E.I. Zubov, A.I. Krasnov, N.A. Mats (all Russian Federation) and O. Tchuloon (Mongolia).

A Mongolian geological prospecting expedition of Soviet experts (MGSE, Head V.F. Litvinsev) conducted airborne geophysical measurements over the territory of Mongolia 1981–1991. The project was based on an agreement between the Governments of the USSR and Mongolia.

With expert support from collaborators at VIRG-Rudgeofizika, Saint Petersburg (E.V. Visokoostrovskaya, E.I. Zubov), two airborne geophysical groups (No. 1 Head A.I. Markov, No. 2 Head V.F. Litvinsev), which were equipped with between 2 to 5 survey aircraft and crew, performed the survey at scales of 1:25 000, 1:50 000, 1:200 000 and 1:1 000 000, with profile separation in the range 250 m–10 km. Areas covered at these given scales were 170 000, 100 200, 594 194 and 312 214 square kilometres, respectively. High sensitivity airborne gamma spectrometers with between 25.1 and 37.5 L NaI(Tl) scintillation detectors were mainly used. Airborne gamma spectrometry and magnetometry surveys were conducted in the western part of Mongolia (66.3% of the survey area). Three methods, including airborne geoelectrical surveying with a SDVR-A2 instrument, covered the rest of the survey area.

Third generation airborne gamma spectrometers (GSA-77, GSA-75M, GSA-80), manufactured by the company Geologorazvedka, were equipped with four detector packages. An analogue system using a ‘uranium differential’ channel was also used in the desert areas in the south of the country, where high levels of atmospheric radon are prevalent, to estimate radon corrections. This channel enabled the recording of parameter $\Delta U = q_U - \alpha q_{Th} - \beta q_K - \gamma$, where α, β, and γ are coefficients computed from the analysis of AGS data, and $q_{U,}$ q_{Th} and q_K are the concentration of U, Th and K available from the instrument. Instruments were installed in fixed wing aircraft (AN-2) and in helicopters (Mi-8) in mountain areas.

Two analogue chart recorders recorded the following parameters: TC (total count channel), uranium concentration (radium), thorium and potassium, plus additional count rates in energy intervals of interest, differential parameters $\Delta_{U\text{-}Th}$, $\Delta_{K\text{-}Th}$, and flight altitude. Flight path recovery was based on photo navigation.

Calibration sites Under-Than, Marts-Thuduk-1, Marts-Thuduk-2, Sant-1, Sant-2, were established in Mongolia for instrument calibration and tied to the standardized Russian calibration site at Thorinsk (Baikal region). Small radioactive sources of radiation were used for daily tests of the airborne gamma spectrometers. A measurement at 800 m on the afternoon of each day was also used to estimate background corrections.

Average flight line directions crossed the geological structures at angles of 70–90 degrees and enabled good flight conditions during the mornings. The operational flight altitude was 25–50 m, and up to 70–100 m in mountainous areas. 93% of the area was covered at an altitude of 70 m or less. Local radiometric anomalies with high exploration significance were subjected to detailed measurements during flying operations and their positions located on the ground.

Special maps of radon interference, compiled for the southern part of the country, enabled the assessment of uranium anomalies.

Manual processing of the data during field operations resulted in contour maps of uranium (radium), thorium, and potassium concentrations, maps of gamma exposure rate and of AGS anomalies. Data readings were taken at 0.25 cm intervals (at the scale of the map). Final computer processing of data was undertaken at the computer centre in Novosibirsk, using the computer program Aerokomplex (1981) and ASOM-AGS/EC (1984–1991).

The airborne gamma ray spectrometry coverage of Mongolia is shown on a separate map.

I.2.57. Morocco

Contact address:

Chef de la Division Géophysique
Direction de la Géologie
Ministère de l'Energie et Des Mines
PB 6208 Rabat Instituts Agdal
Rabat
Maroc
Web: www.mem.gov.ma

I.2.58. Mozambique

Contact address:

Direccao Nacional de Geologia
C.P. 217
Maputo
Mozambique

Summary of coverage:

Most of the Zambezi area was flown by CGG in 1970–1971, as several small blocks, all with a 2 km line spacing but at various barometric altitudes ranging from 250–2 500 m. Much of this early coverage was superseded by four channel gamma spectrometry surveys flown by Hunting Geology and Geophysics in 1981/82. During the same period a large area of the Tete province was also surveyed. These surveys were flown at a 1 km line spacing and 120 m terrain clearance with 50 L of crystal. Further surveys, which extend and improve the existing coverage, were commissioned and flown in 2003 and 2005, at a 1 km line spacing, 100 m terrain clearance and 30 L of Na(T1) crystal (+4 L upward looking). The 1981–1982 surveys covering the Tete province were later re-processed, back calibrated and merged with the 2003 data. Levelling errors in the older generation data, due largely to poor positioning (based on uncontrolled photomozaics) and the lack of background radon monitoring and correction, were removed as far as possible without reducing the, otherwise, excellent resolution of the surveys. Back calibration was based on overlap with the 2003 survey data.

I.2.59. Namibia

Contact address:

Geophysics Department
Ministry of Mines and Energy
Geological Survey of Namibia
1 Aviation Road, P.O. Box 2168
Windhoek
Namibia
www.gsn.gov.na

Summary of coverage:

Regional airborne geophysical surveys were conducted, 1968–1990, in a block-wise fashion in Namibia on a more or less annual basis, typically at a line spacing of 1 km and terrain clearance of 100 m. Much of this older data, including surveys recorded only on analogue charts, has since been recovered, reprocessed and back calibrated using measurements from a ground spectrometer calibrated on the portable pad facilities at Windhoek. A survey programme to complete and improve airborne coverage of Namibia commenced in 1994, flying large blocks with a line spacing of 200 m and terrain clearance of 80 m, and including most of the areas of earlier, lower-resolution surveys. A little less than 60% of the country is now covered. All of the high-resolution surveys have stripping ratios determined on the portable pad facilities at Windhoek and sensitivity constants determined over the Henties Bay dynamic calibration range. Prior to 1997, the Henties Bay range comprised one line only, along the salt road, but since then has been marked by a 11 km × 2 km grid for which ground concentrations and homogeneity were initially determined on a 100 km × 100 m grid using a calibrated GR256 ground spectrometer. During calibration flights ground radioelement concentrations are measured over the entire test range flown at survey altitude. Sensitivity constants are derived from the comparison of airborne and ground grids.

Recent experience in merging the survey blocks to produce ‘supergrids’ of countrywide coverage, using overlap areas, has revealed unexpectedly high scaling ranges (1.1–2.0) for some surveys (particularly the older of the post-1994 surveys), indicating calibration problems. During the calibration of these pre-1997 surveys, ground measurements along the ‘single line’ were taken ‘zig-zag’ off the road along its length. Hence the ground measurements did not represent the radiation, or attenuation thereof, of the road material itself while the airborne data was acquired directly over the easily navigable road. Furthermore, the spacing of the ground stations were too large to be adequately compared with the airborne footprint. Merging, standardization and calibration of Namibian gamma spectrometry data are currently being refined by geophysicists at the Geological Survey of Namibia.

The airborne survey campaign continues, currently at a rate of 130 000–150 000 line-km annually.

I.2.60. Nepal

Contact address:

Department of Mines and Geology, Ministry of Industry
Lainchaur
Kathmandu
Nepal

Summary of coverage:

There was possibly an airborne survey conducted by Comapgnie Générale de Géophysique (CGG) in 1993 over the southern foothills.

I.2.61. Niger

Summary of coverage:

A 1974 survey at the northwestern border flew 1 km lines at a terrain clearance of 125 m using 24.5 L of Na(T1) crystal. Recording was digital. The extreme southwest corner of the country is covered by a trinational survey flown in 1976–1977 (see Burkina Faso for details). There is possibly a 1978 survey covering the central east part of the country. A new airborne gamma spectrometry survey, aimed at mineral exploration, commenced in the southern part of the country in the first quarter of 2005.

I.2.62. Nigeria

Contact address:

Ministry of Solid Mineral Development (MSMD)
New Federal Secretariate
Shehu Sagari Way, P.M.B. 107
Abuja
Nigeria

Summary of coverage:

Early surveys were carried out over much of the country (1975–1976), with a line spacing of 2 km, and a mean terrain clearance of 150. Navigation and flight-path recovery used 35 mm Camera and Doppler. Recording was digital. The reports and maps produced are in the custody of the MSMD. In 1981, a few small areas were covered in the east of the country for the former Nigeria Uranium Mining Co. Ltd (NUMCO). In 2002 the MSMD commenced a programme to conduct airborne geophysical surveys of most of the country, commencing with the Ogun State in the southwest. The programme is to continue with the remaining planned coverage in 2005. All blocks are to be flown with a 500 m line spacing at 80 m mean terrain clearance and will be calibrated, acquired and processed to IAEA standards.

I.2.63. Philippines

Contact address:

Philippine Nuclear Research Institute (PNRI)
Commonwealth Ave., Diliman
Quezon City
Philippines 1101

Summary of coverage:

In the late 1990s the Philippines Nuclear Research Institute carried out a pilot carborne gamma spectrometer survey over the small island of Marinduque (959 km^2).

I.2.64. Poland

Contact address:

Polish Geological Institute
Rakowiecka 4
00-975 Warsaw
Poland

Summary of coverage:

The Polish Geological Institute conducted a systematic ground gamma ray survey of the entire land area of Poland (1991–1992). The six portable 256 channel gamma spectrometers used were calibrated on pads at the calibration facility Bratkovice, near Pribram (the Czech Republic). Measurements were taken along N–S oriented lines separated by 17 km with 1 km sampling along-line. Two minute samples were measured at each station, with the detector positioned at an altitude of 1.5 m above the ground. K, U, Th, gamma dose rate and Cs activity data are archived by the Polish Geological Institute.

I.2.65. Portugal

Contact address:

Div. Geofisica
Instituto Geoloico e Mineiro
Estrada da Portela, Zambujal
Alfragide
2720 – 461 Amadora
Portugal

Summary of coverage:

Approximately 90% of the Portuguese mainland has been surveyed and natural radioactivity maps at 1:200 000, expressed as exposure rate, have been published.

The data used in the maps have different origins: (a) total count data collected in the 1960s, the analogue records of which have been digitized and back calibrated; (b) spectrometric 256 channel airborne surveys, of some five different geophysical surveys, collected with 32 L volume scintillation detectors; (c) newly acquired car-borne spectrometric data collected with 256 channel spectrometers using a 4 L detector.

Two areas in south-east Portugal, totalling 9 500 line km, were flown by GTK for a mining company in 1997. The surveys were flown at a 100 m line spacing and 30 m terrain clearance, with results presented as ground concentrations (confidential data).

I.2.66. Oman

Contact address:

Ministry of Commerce and Industry
Minerals Exploration section
Oman
www.mocioman.gov.om

Summary of coverage:

A patchwork of small airborne geophysical surveys covers the land area and offshore regions of Oman. A few of these include gamma ray spectrometry. Two surveys in the north of the country in 1990 provided data over the Al Batinah and Jabat Akhbar areas.Three surveys were conducted further south, in the Massirah Island and Nizwa areas, in 1995 by AGSO (Australian Geological Survey Organization, now Geoscience Australia). All of these surveys were flown with a line spacing of 200 m and at a terrain clearance of 80 m.

I.2.67. Pakistan

Contact address:

Pakistan Atomic Energy Commission (PAEC)
Atomic Energy Minerals Centre
P.O. Box 658
Ferozepur Road, Lahore
Pakistan

I.2.68. South Africa

Contact address:

Geophysics Unit
Council for Geoscience
Pretoria
South Africa

Summary of coverage:

Most of South Africa was surveyed during the 1960s and 1970s at 1 km line spacing. The data still available from these surveys are of variable quality but were recovered and compiled (where possible) by the Council of Geoscience. No back calibration of these older surveys has been undertaken. In 2002, the Council of Geoscience commenced a programme of high resolution surveying (200 m line spacing) using an ultralight aircraft. The new surveys: are calibrated on facilities at Pelindaba.

I.2.69. Romania

Contact address:

Institute of Geology and Geophysics
Caransebes Str. 1, Sector 1
78344 Bucharest
Romania

Summary of coverage:

The following summary is extracted from a report covering the status of regional gamma data in central and Eastern Europe.

Only limited areas of the country have been surveyed by airborne gamma spectrometry, using 4 000 cm^3 of NaI(T1) crystal installed in a helicopter. The measurements were conducted at a height of 50 m and a line spacing

of mostly 250 m. The four channel system was not calibrated and results are expressed in relative units (counts/s). Local areas have been surveyed using ground based gamma spectrometers but these are, again, uncalibrated and amount to less than 1% of the country.

I.2.70. Russian Federation

Contact address:

Geologorazvedka
Knipovich 11, Building 2
Saint Petersberg
193019 Russia

Summary of coverage:

This information was prepared by E.V. Visokoostrovskaya, A.I. Krasnov and N.A. Mats, Geologorazvedka company (Geological Survey), Saint Petersburg.

Airborne gamma spectrometric surveys (AGS) were initiated over the territory of the Russian Federation in 1964 for exploration, and since 1967 have also been used for environmental monitoring. AGS have been applied to exploration and prognosis of raw materials, geological mapping and the protection of the natural environment.

Airborne investigations have been performed at regional (1:1 000 000–1:2 500 000), medium (1:100 000–1:200 000), and detailed 1:10 000, 1:25 000, 1:50 000) scales. Approximately 98% of the Russian Federation had been covered by 2005. Investigations are systematic, starting with a reconnaissance survey, and then followed by more comprehensive surveys (airborne gamma spectrometry, airborne magnetometry, airborne geoelectrical survey, airborne geochemistry, thermometry, gas analysis etc.).

The territorial departments of the Ministry of Geology of the USSR, and the Ministry of Environment of the Russian Federation, with the participation of the research institutes VIRG — Mineral Geophysics, Institute of Applied Geophysics, Institute of Global Climate and Ecology, and others, performed the airborne surveys. At present, surveys are based on requests and agreement between regional geological organizations and institutions, and the company Geologorazvedka. About 100 airborne groups worked in the area of the former USSR during the 1960s to 1980s. Following the disintegration of the USSR, 6 or 7 airborne groups work in the Russian Federation. At present, surveys by the Ministry of Environment of the Russian Federation are oriented towards environmental applications, exploration for hydrocarbons, diamond-bearing pipes, and uranium. To a lesser extent, the surveys are applied to geological mapping at scales 1:200 000 and 1:50 000.

The airborne survey data 1964–2004 show a range of quality, with a tendency for temporal improvement associated with progress in science, construction of instruments and methods of airborne survey. The degree to which the numerical and graphical results of airborne surveys (precision and accuracy) conform to adopted standards, defines the quality of the surveys. Instrument type and precision, measurement in agreement with metrological requirements, data positioning technique, airborne data processing and the methodology of interpretation corresponding to the geological objective are all important for the assessment of the data quality.

The basis for metrological assessment of airborne measurements is the verified measurement methodologies. We use sets of ore models, sets of model gamma emitting sources, and natural test strips of known concentrations of the radioelements or surface contamination by ^{137}Cs and ^{134}Cs for rigorous metrological calibration. Eighty-three natural test strips were established to national standards (test strip Pusun-Saaryi), regional and local standards. They are in the territory of the European and Asian parts of the Russian Federation, including remote areas such as Ural, West Siberia, and Far East, Baikal region, Chukotka and other areas. The AGS data processing techniques ensure that the digital data, flight path recovery, and data standardization to a uniform level of radionuclide concentrations over Russia are performed to satisfactory standards.

Three categories classify AGS quality. The scale of surveys, and the precision and accuracy of surveys in a given period of airborne mapping, are the basic criteria for classification. The highest category corresponds to present-day AGS methods, and mapping at a detailed scale.

The low-quality category of AGS covers the period 1964–1973. These are surveys flown using the first generation of Russian, low sensitivity, airborne gamma spectrometers (AI-100-1, AGS-48, 48M, 48M2, ARS-1, ASG-38Zh), with both liquid and plastic scintillators. Field assay precision was of the order of ppm eU, ppm eTh, % K, and for exposure rate at the level of μR/h. Instruments were installed in aircrafts AN-2, IL-14, MI-4 and MI-1. Data were recorded analogue charts, and instruments were calibrated using high concentration ore models and natural non-standardized test strips. Visual navigation and aerial photography were used for flight path recovery. Data processing was both manual and partly automatic using first generation computers. The surveys were performed at regional and medium scales.

The medium quality category of AGS covers the period 1973–1992. These are surveys that used both Russian and Canadian, second generation, airborne gamma spectrometers with medium sensitivity (ASG-71, AGS-4K, GSA-70, AGS-6K, McPhar-I P, ORTEC, SNEG-M, ATLAS) with detectors of volumes of 8–12.5 L. Instruments were installed in AN-2, Mi-4, Mi-8 and Mi-2 aircraft. Data were recorded digitally, and instruments were calibrated using high concentration ore models and natural non-standardized and standardized field test strips. Radionavigational systems and video tracking cameras were used for flight path recovery. The precision of radioelement estimates was at the level of the average contents of uranium, thorium and potassium in rocks. Airborne data processing was performed by computers, using automatic systems 'Aeropoisk', and partly manual. Airborne survey was performed at medium and detailed scales.

The high quality category of AGS covers the period from 1977 to the present. These are surveys flown with the latest, third generation of Russian and Canadian airborne gamma spectrometers (GSA-77, 80, 99, 2000, AGS-2001, CV, SKAT-77, STK, ASMI, AGS-7.8k, McPhar-IV, GRS-410, Scintrex), and with detectors of volumes of 37.5–75 L. Instruments, with digital recording, are installed in AN-2, AN-30, AN-26, Mi-8, Mi-8T, Ka-26 and other aircraft. High concentration ore models and flights over standardized field test strips ensure instrument calibration. Radio-navigation and orbital satellite navigational systems are used for flight path recovery. Airborne data processing is by computers equipped with Russian and foreign programmes. Contemporary airborne geophysical databases include the raw digital data, their secondary transformation, and analogue maps. Technological schemes for airborne data interpretation and computer application are under preparation and in the process of verification. Mapping, prospecting, mineral prognoses and environmental application are contemporary programmes.

The airborne gamma spectrometry coverage of the Russian Federation is displayed in a separate map (Fig. 11)

I.2.71. Rwanda

Contact Address:

Royal Museum for Central Africa (RMCA)
Leuvensesteenweg 13
3080 Tervuren
Belgium
www.africamuseum.be

Summary of Coverage:

In 1981, the entire area of Rwanda was covered by a helicopter borne gamma spectrometry survey (east and west flown as separate blocks). Using 33 l of crystal, the data was acquired at a terrain clearance of 100 m along lines at spacing of 0.5 and 1 km. The data were fully corrected to the standards of the time with atmospheric radon being monitored daily over Lake Kivu and results presented as equivalent ground concentrations. Residual levelling errors, probably related to soil moisture effects, were addressed and corrected by Almaguer. The affects of dense vegetation on apparent radioelement concentrations were considered by Lavreau and Fernandez-Alonso. More recently the reprocessed gamma spectrometry data produced by Almaguer has been applied in a new integrated geological interpretation and mapping of the NE Kibaran Belt.

I.2.72. Saudi Arabia

Contact address:

Ministry of Petroleum and Mineral Resources
P.O. Box 247
Riyadh
Saudi Arabia
www.mopm.gov.sa

Summary of coverage:

Several surveys were flown by Huntings in the mid-1960s for the Ministry of Petroleum and Mineral Resources. A line spacing of 800 m was used for all surveys, but flying height varied between 150 and 300 m mean terrain clearance. Further gamma spectrometry surveys were conducted by CGG in 1981, for a mining company, and 1982, for the Ministry.

I.2.73. Senegal

Contact address:

Direction des Mines et de la Géologie
Ministère de l'Energie, des Mines et de l'Industrie
Km 4,5, Bd. du Centenaire
Dakar
Senegal

I.2.74. Slovakia

Contact address:

Ministry of Environment of the Slovak Republic
Division of Geological Research and Survey
Hlboka 2
812 35 Bratislava
Slovakia

Geological Survey of the Slovak Republic
Mlýnská Dolina 1
Bratislava
Slovakia

Uranpres
Frana Krala 2
052 80 Spišská Nová Ves
Slovak Republic

Summary of coverage:

The following summary is extracted from a report covering the status of regional gamma data in Central and Eastern Europe.

The entire country, with the exception of a few high mountains was covered by an airborne total count survey in 1957–1960, at a 2 km line spacing and 100 m altitude. Recording was analogue and results produced as stacked profiles of exposure rate. Airborne gamma spectrometry was conducted in selected regions (70% of country) from 1976, initially using a four channel spectrometer and 14 600 cm^3 of NaI(T1) crystal, progressing to a 256 channel spectrometer and 33 600 cm^3 of crystal from 1988 onwards. The airborne measurements used a line spacing of

250 m with flying altitude of 80–250 m. All equipment was calibrated over test strips of known ground concentrations of radioelements. Results are available as digital data and maps.

Approximately 28% of the country was covered by carborne total count surveys 1970–1982, with analogue recording and results presented as maps of exposure rate. Systematic ground based gamma spectrometry has been carried out since 1992, using 256 channel spectrometers calibrated on pads at Bratkovice, the Czech Republic. Gamma spectrometry maps of K, U, Th concentrations and a map of gamma dose rate, based on ground measurements at 15 573 sites in the grid mostly 3 × 3 km, were compiled at the scale 1:1 000 000.

I.2.75. Slovenia

Contact address:

Institute of Geology, Geotechnics and Geophysics
Dimiceva 14
61000 Ljubljana
Slovenia

Summary of coverage:

During the period 1991–1993, the Inštitut za geologijo, geotechniko in geofiziko prepared radioelement concentration maps for the entire territory of Slovenia using ground survey methods. The survey was carried out on a 5 km × 5 km grid (1 km × 1 km in some areas) using a portable, four channel gamma spectrometer calibrated on pads of the Austrian Geological Survey near Vienna. A total of 816 sites at 5 × 5 km and 226 sites at 1 × 1 km spacing were measured, each comprising five individual point measurements of 100 s. Soil samples were also collected at each survey location and each sample analysed for 33 elements.

I.2.76. Somalia

Contact address:

Ministry of Mineral Resources and Water
P.O. Box 774
Mogadishu
Somalia

Summary of coverage:

Early surveys (1970, 1971) were flown by Hunting Geology and Geophysics in the north and central south of the country. Survey locations are very approximate and details not yet found.

I.2.77. Spain

Contact address:

ENUSA Industrias Avanzadas S.A.
Santiago Rusiñol, 12
28040 Madrid
Spain

Summary of coverage:

A number of radiometric surveys have been conducted over Spain. Between 1967 and 1977 JEN carried out airborne total count surveys at 1 km line spacing and with analogue recording only. Later airborne surveys (1978–1982) were conducted by Huntings and Geodata, using four channel spectrometers and 21 and 33 L of NaI(T1) crystal, respectively. A line spacing of 1 km and flying height of 120 m was used in both surveys. Results of these surveys are reported as counts/s and ground concentrations but methods of data correction (particularly for atmospheric radon) and determination of sensitivity constants probably do not meet acceptable 'baseline' standards. As part of the MARNA Project, aimed at generating natural radiation maps for Spain, both carborne and footborne surveys were conducted to (a) increase coverage and (b) establish the relationship between airborne radiometry (counts/s) and ground radiometry (μR/h). Details of these surveys may be obtained from ENUSA.

I.2.78. Sri Lanka

Contact address:

Geological Survey and Mines Bureau
Senanayake Building
No. 4, Galle Road
Dehiwala
Sri Lanka
www.gsmb.slt.lk

Summary of coverage:

An airborne multisensor (magnetic and radiometric) survey was carried out in 1958 over the southwest quadrant of Sri Lanka, with the objective of exploration for iron ore deposits. The survey was conducted by The Photographic Survey Corporation Ltd, Toronto, Canada, under the Canada–Ceylon Colombo Plan at the request of the Government Mineralogist of Ceylon. The N–S flight lines were flown at a line spacing of 400 m and 152 m terrain clearance. Data recording was on analogue chart recorders and navigation visual, supported by 35 mm film strips.

I.2.79. Sudan

Contact address:

Geological Research Authority of Sudan (GRAS)
P.O. Box 410
Khartoum 11111
Sudan
www.gras-sd.com

Summary of coverage:

No known coverage.

I.2.80. Swaziland

Contact address:

Geological Survey and Mines Department
P.O. Box 9
Mbabane
Swaziland

Summary of coverage:

A country wide airborne survey was undertaken in 1966 as the initial phase of a UNDP investigation of mineral resources. Data was collected in analog format at a line spacing of 800 m and a terrain clearance of 152. Total counts from a 5 in × 2 in NaI(T1) crystal were recorded and final results presented as contours of four binned count levels. The data were subsequently digitally recovered and reprocessed by the British Geological Survey and, although of limited resolution, do show larger scale features that are consistent with follow-up ground measurements. Further details and the data are available through the BGS.

I.2.81. Sweden

Contact address:

Geological Survey of Sweden (SGU)
Villavägen 18,
Box 670
SE-751 28, Uppsala
Sweden
www.sgu.se

Summary of coverage:

Digital data sets of radioelement concentrations were generated from data acquired between 1969 and 1998, at a line spacing of 200 m, terrain clearance of 30–60 m and along-line sampling interval of 16–40 m. Levelling of the component survey data was assisted through a tie-line survey conducted over the whole of Sweden in 1998, at a line spacing of 18 km and terrain clearance of 60 m. Data is available from the SGU.

I.2.82. Switzerland

Contact address:

Swiss Geophysical Commision (SGPK)
Current President: Prof. E. Kissling
Institut für Geophysik
ETH Hönggerberg
8093 Zurich
Switzerland
www.sgpk.ethz.ch

Swiss Federal Nuclear Safety Inspectorate (HSK)
CH-5232 Villigen-HSK
Switzerland
www.hsk.psi.ch

Summary of coverage:

During the early nineties helicopter borne gamma spectrometry surveys were conducted over the crystalline rocks of the Central Massif of the Swiss Alps and over selected areas representing other typical lithologies (approximately. 3 000 km^2 in total). In addition, three small surveys cover the areas surrounding nuclear power plants and nuclear research facilities. The surveys employed 16.8 L of NaI(T1) crystal and a 256 channel spectrometer. In situ gamma spectrometry measurements have also been collected at 166, sparsely distributed locations over the country. Rybach documents the calibration of the airborne and in situ measurements to ground activity and dose rate using soil and rock samples but it is not clear whether or not theses surveys are calibrated in terms of ground concentration and/or tied to the global radioelement baseline.

I.2.83. Thailand

Contact address:

Department of Mineral Resources
Ministry of Industry
Bangkok
Thailand

Summary of coverage:

In 1984, the Department of Mineral Resources commenced a five year project of nationwide airborne geophysical survey, including gamma spectrometry. The survey was flown in blocks using fixed wing and helicopter platforms as appropriate for the topography. All survey blocks were flown using 50 L of NaI(T1) crystal and a terrain clearance of 122 m. Line spacings were 1, 2 or 5 km. Radon corrections were based on overwater or high level flights, stripping ratios determined on specifically constructed large pads and sensitivity constants determined over a calibration range.

I.2.84. Turkey

Contact address:

General Directorate of Mineral Research and Exploration
Geophysics Department
06520 Ankara
Turkey
www.mta.gov.tr

I.2.85. Uganda

Contact address:

Geological Survey and Mines Department
P.O. Box 9
Entebbe
Uganda

Summary of coverage:

The earliest surveys were flown in 1961 with a line spacing of 0.8 km at a terrain clearance of 137 m. The southern half of the country was fully covered by a 1981 survey at 1 km line spacing and 120 m terrain clearance. This survey was not calibrated, with the four channel records being archived in counts/s. Subsequently the data have been recovered from the original archives, re-processed to minimise residual errors and converted to ground concentrations using comparison with calibrated data across the Uganda–Rwanda border. The area of survey overlap and dynamic range of the radioelements at the common border are, however, somewhat limited and the 'back-calibration' may only be considered as approximate. Two small high resolution surveys (100 m line spacing and 80 m terrain clearance) were flown in the southeast of the country during 1998. The Geological Survey and Mines plan to commence flying of the northern half of the country in the near future.

I.2.86. United Kingdom

Contact address:

British Geological Survey
Kingsley Dunham Centre
Keyworth, Nottingham
NG12 5GG
UK
www.bgs.ac.uk

Summary of coverage

Airborne and ground radiometric surveys have been carried out in the UK since the 1950s, when uranium exploration was the primary focus. There has not been any systematic national coverage and only about 25% of the UK land area has been surveyed. However, the Hi-RES-1 survey in 1998 over 14 000 km^2 in central Britain should form the first part of a nationwide airborne geophysical survey acquiring radiometric, magnetic and electromagnetic data. A second survey of 960 km^2 in SW Scotland was flown in 2004 and was to followed in 2005–2006 by systematic coverage of N Ireland as part of the Tellus project. Data will be held by the British Geological Survey (BGS) and will conform to IAEA standards. Line spacing will be 200 m with a flying height of 56 m, rising to 240 m over developed areas and at least 32 L NaI(Tl) detectors will be employed.

Prior to 1998, airborne coverage comprised individual surveys of varying size and specification, mostly flown for mineral exploration. The earliest airborne surveys, such as those in SW England in 1957–1959, had a typical line spacing of 400 m and a flying height of 150 m. Relatively small volume (by modern standards) total count NaI systems were used for these surveys. Data were recorded only in analogue form, but have in some cases been digitized subsequently. Later surveys were flown mainly for exploration or environmental purposes. They range from detailed site specific surveys to more regional coverage. Line spacing varies from 50 m to more than 1 000 m and flying height from 50–150 m. Since the 1970s, data were recorded digitally and the later surveys were conducted to IAEA standards using, typically, 16 or 32 l NaI(Tl) detectors.

Almost all surveys were either flown for the BGS or acquired by the Scottish Universities Environmental Research Centre (SUERC) on behalf of a range of clients. Both BGS and SUERC have transportable calibration pads and have established calibration ranges.

In addition to airborne surveys BGS carried out many carborne investigations, particularly for mineral exploration up to the 1970s. The results are summarised in a series of reports. BGS also hold offshore radiometric data from the UK continental shelf. They were acquired by hovercraft-borne surveys (in the intertidal zone) and towed seabed systems.

I.2.87. United Republic of Tanzania

Contact address:

Mineral Resources Department – Madini
P.O. Box 903
Dodoma
United Republic of Tanzania

Summary of coverage:

Airborne surveying began in the 1950s, with scintillometer data being acquired for uranium and other mineral exploration. During 1977–1980 a countrywide, four channel survey was compiled. In the northwest of the country data from an earlier (1975–1976) survey, which used only 7 L of NaI(T1) crystal, was incorporated into the compilation but, for the rest, this was new flying with 16.78 L of crystal at a 1 km line spacing and terrain clearance of 120 m. Several smaller, follow-up areas were also flown at a line spacing of 250 or 500 m and sometimes a smaller (90 m) terrain clearance. These surveys were not pad calibrated. Although the data were digitally acquired, not all of the flightline data could be successfully recovered from the archive tapes. In areas where the original digital data has been unrecoverable, 1:100 000 scale contour maps have been digitized to complete the country wide coverage. There are internal levelling problems in this data set, probably partly arising from the fact that background estimates were made from daily flights over water or at high altitude. It is probable that stripping ratios were determined from point sources and not on pads. In 1988 the BGR conducted a helicopterborne survey over the Siga-Mabale Hills, using 16.8 L of crystal, a line spacing of 250 m and terrain clearance of 75 m. The system was fully calibrated over pads at Borlänge.

A significant increase in mineral exploration activity since the mid-1990s has included several gamma spectrometry surveys commissioned both by the private sector and the Mineral Resources Department

I.2.88. United States of America

Contact address:

US Geological Survey
Reston, Virginia
United States of America

Summary of coverage:

A summary of the national gamma ray spectrometry coverage for the United States of America is given in Duval.

I.2.89. Yemen

Contact address:

Ministry of Oil and Mineral Resources
P.O. Box 297
Sana'a
Yemen

Summary of coverage:

Approximately 80% of the country is covered by surveys carried out in the period 1975–1978. In 1991, Robertson Research International Ltd (now Fugro Robertson Ltd) produced an authorized compilation of the existing airborne data which is available as a 1 km grid.

I.2.90. Zambia

Contact address:

Geological Survey Department
P.O. Box 50135
Lusaka
Zambia
www.zambia-mining.com/government.html

Summary of coverage:

Some 80% of the country is covered by airborne gamma spectrometry but most of the surveys are pre-1980 and many are of questionable quality. These early surveys used small Na(T1) crystal volumes (3.22–7.38 L), sometimes combined with short accumulation times and high flying speeds, inadequate spectral stabilization and generally applied no background, stripping or height corrections. For the earliest surveys only analogue charts (of variable quality) or posted anomaly maps exist. For the most extensive survey (60% of the country) data were digitally recorded but only the raw field tapes are available. The spectrometry data are reported to be of poor quality, particularly over areas with low-moderate radioactivity. Similarly the positional accuracy is poor for a number of reasons. A thorough description of all airborne surveys for Zambia, including products (tapes, maps, original analogue charts, etc.) is given in reports by Parker, which are available at the Geological Survey Department and SEAMIC. Parker also details steps required to recover, relocate, and re-process the data and recommends that only the total count channel would be of any significant value, if back calibrated.

Three areas were surveyed in 1981 using a system fully calibrated over pads and 33 L of crystal. The data are corrected for background and stripped, with background being determined from over-water or high altitude flights and digital, processed data are available. The sensitivity constants are not specified in the contractors report. Only total count contour maps were produced but Parker suggests that the Th, U and K data could be effectively re-processed and imaged; back-calibration would be necessary if the sensitivity data cannot be found.

I.2.91. Zimbabwe

Contact address:

Geological Survey Department
P.O. Box CY 210
Harare
Zimbabwe
www.geosurvey.co.zw

Summary of coverage:

The earliest radiometric surveying in Zimbabwe was conducted by the UK Atomic Energy Authority (UKAEA) in 1957. Data was acquired in analogue format at a flying height of 137 m — no further details were available for this report but the survey is unlikely to be calibrated to modern standards. Three areas were surveyed by Geosurvey International in 1981 along the northern border of the country, mainly for uranium exploration. All

surveys used a 1 km line spacing, terrain clearance of 120 m, 50 m Doppler driven sample spacing, Geometrics GR-800B spectrometer and 33 L of NaI(T1) crystal. Data for the 1981 surveys are available at the Geological Survey Department.

Appendix II

WORLDWIDE GAMMA RAY SPECTROMETER CALIBRATION SITES

II.1. STATIONARY (FIXED) CALIBRATION PADS FOR PORTABLE INSTRUMENTS

Canada — Calgary, Ottawa
Argentina — San Rafael
Brazil — Rio de Janeiro
Denmark — Risø
South Africa — Palindaba
Czech Republic — Straz pod Ralskem
Sweden — Malå
Australia — Sydney

II.2. STATIONARY (FIXED) CALIBRATION PADS FOR AIRBORNE INSTRUMENTS

Canada — Ottawa
United States of America — Grand Junction
Sweden — Borlange
Finland — Helsinki
Turkey — Ankara
South Africa — Johannesburg
Israel
Iran, Islamic Rep. of — Tehran
India — Nagpur
Thailand — Bangkok

II.3. TRANSPORTABLE CALIBRATION PADS

Canada — Ottawa, Toronto
Brazil — Rio de Janeiro
Norway — Trondheim
Finland — Helsinki
United Kingdom — Glasgow, Nottingham
Portugal — Lisbon
Austria — Vienna
Greece — Athens
Egypt — Cairo
Namibia — Windhoek
United Republic of Tanzania — Dar Es Salaam
Iran, Islamic Rep. of — Tehran
Jordan — Amman
Pakistan — Lahore
Korea, Rep. of — Seoul
China — Hong Kong
Philippines — Manila
Australia — Perth, Adelaide, Canberra, Sydney

II.4. BOREHOLE CALIBRATION FACILITIES

Canada — Ottawa
Czech Republic — Straz pod Ralskem
United States of America — Grand Junction
South Africa — Pelindaba
Sweden
Australia — Adelaide

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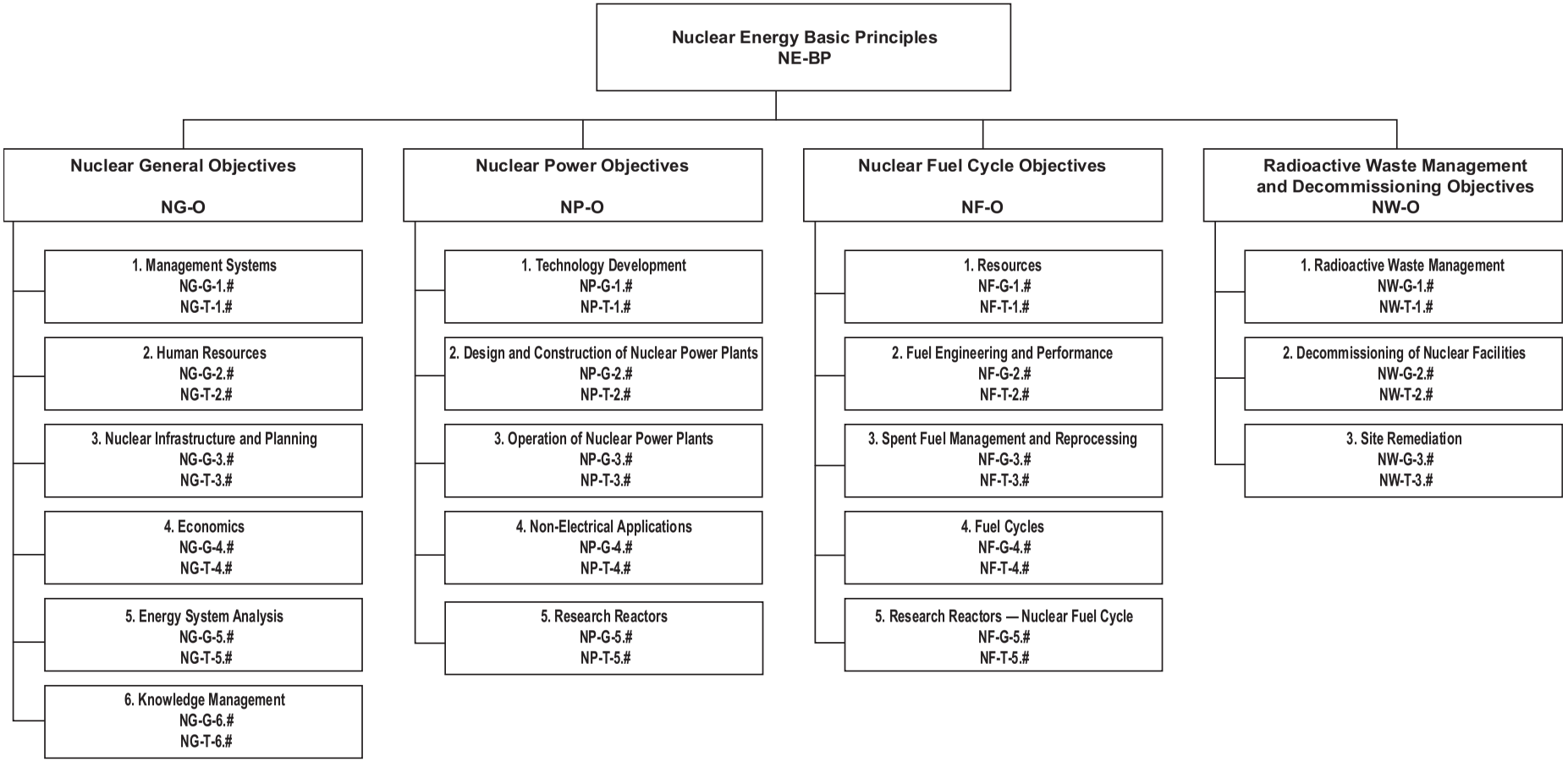

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