# REFERENCE BIOSPHERES FOR THE LONG TERM SAFETY ASSESSMENT OF RADIOACTIVE WASTE DISPOSAL FACILITIES

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**Abstract.** Regulatory guidance on the safety assessment of radioactive waste disposals usually requires the consequences of any radionuclide releases to be considered in terms of their potential impact on human health. This requires consideration of the prevailing biosphere and the habits of the potentially exposed humans within it. However, it could take many thousands of years for migrating radionuclides to reach the surface environment. In these circumstances, an assessment model that was based on the present-day biosphere could be inappropriate while future biospheres would be unpredictable. These and other considerations suggest that a standardised, or reference biosphere, approach may be useful.

Theme 1 of the IAEA BIOMASS project was established to develop the concept of reference biospheres into a *practical system* that can be applied to the assessment of the long term safety of geological disposal facilities for radioactive waste. The technical phase of the project lasted for four years until November 2000 and brought together disparate interests from many countries including waste disposal agencies, regulators and technical experts.

Building on the experience from earlier BIOMOVS projects, a methodology was constructed for the logical and defensible construction of mathematical biosphere models that can be used in the total system performance assessment of radioactive waste disposal. The methodology was then further developed through the creation of a series of BIOMASS Example Reference Biospheres ('Examples'). These are stylised biosphere models that, in addition to illustrating the methodology, are intended to be useful assessment tools in their own right.

## 1. INTRODUCTION

There is a high level of international consensus regarding the safety principles [1], including radiological protection objectives, that should be applied to radioactive waste management practices. There is, however, little consensus on how compliance with these principles is to be demonstrated for releases to the environment that might take place in the distant future. This is of particular relevance to the geological disposal of long-lived radioactive waste where releases of radionuclides could occur thousands of years after repository closure. Various safety indicators have been considered for assessing the performance of geological disposal systems [2] and, indeed, the use of several indicators may be appropriate within a single assessment. However, even those safety indicators that are expressed in terms of engineering or geological standards (e.g. release limits), rather than in explicit radiological protection terms, involve tacit assumptions regarding the human health consequences associated with those standards.

The consequences for human health of a radionuclide release require consideration of the prevailing biosphere system, including the humans within it. A good (and important) example relates to food consumption. Here radiological impact depends on the quantity and type of food consumed and the associated levels of contamination by radionuclides — factors that mostly depend upon the biosphere system, its spatial relationship to the source of contamination and the habits of the potentially exposed humans that inhabit the system. To carry out these calculations, it is usual to construct mathematical biosphere models (called 'assessment biospheres' here) based on the features, events and processes that are known to occur within existing, and relevant, biosphere systems.

While often complex, biosphere systems that actually exist can be studied, understood and modeled. But in some cases, when comparing disposal concepts for instance, generic, as opposed to site-specific, data may be more appropriate. Biosphere systems that exist in the far future will be shaped by unknown technological advances and many natural forces. These biosphere systems cannot be predicted and can only be studied by reference to present day or historical examples. This difficulty means that assessment biospheres that are intended to apply to the far future will be largely hypothetical, albeit that they may be constrained by knowledge of the past (and possible future) evolution of a site. A typical approach is to construct a series of assessment biospheres to broadly represent a range of possible futures. However, faced with almost infinite possibilities, the difficulty lies in providing assurance that the modeled outcome is sufficiently robust and reasonable. Reference biospheres, if based on a good scientific appreciation of the key issues and a wide consensus as to what is reasonable, could be a useful way of providing this assurance.

Another issue is that of standardization. In 1975, ICRP publication 23 [3] stated that " although individuals vary considerably, it is important to have a well defined reference individual for estimation of radiation dose". The Commission hoped that such a reference individual would be recognized and used widely so that health physicists could compare and check their results without tedious enumeration of assumptions or without the risk of minor differences in these assumptions obscuring the basic agreement or disagreement of their results. Today we can say that 'Reference Man' was an important step forward in radiological protection, especially in the area of internal and external dosimetry. It might be similarly argued that, although future biosphere systems and associated potentially exposed humans cannot be predicted, it is important to have a well defined Reference Biosphere (with associated exposed humans) for estimation of radiation doses arising from long-term releases of radionuclides to the environment. As with Reference Man, wide use of Reference Biospheres would be helpful in cross-comparing and checking results.

Such thoughts suggest the following definition. A reference biosphere is a stylized assessment biosphere, intended to be widely applicable in the context of the total system performance assessment of disposal facilities for long-lived radioactive waste. Reference Biospheres serve three main purposes: providing generic biosphere information in the absence of site-specific data; providing assurance that assessment biospheres are both robust and reasonable, and serving as a standard to facilitate cross-comparisons and checking of results.

## 2. THE IAEA BIOMASS PROGRAMME

In October 1996 the IAEA launched an International Programme on *Biosphere Modelling and Assessment Methods* (BIOMASS). Since then, around 100 scientists from 30 countries have been regularly participating in the BIOMASS activities and meetings. The programme aims to provide an international focal point in the area of biosphere assessment modelling and to develop and improve models and methods for the analysis of radionuclide transfer in the biosphere for use in radiological assessments. The programme addresses important radiological issues associated with accidental and routine releases and solid radioactive waste management. There are three themes: (1) biosphere radiological impact assessment in the context of radioactive waste disposal, (2) modelling and assessment of environmental releases, and (3) biosphere processes analysis. This paper is concerned with the results of Theme 1.

Regulatory compliance criteria for the safety of facilities for the disposal of long-lived radioactive waste are frequently expressed as targets or limits in relation to radiological doses or risks to humans. This approach has a number of advantages: it recognises that different radionuclides can produce different kinds of harm and it provides an approach to safety that allows repository releases to be compared risk-for-risk with other human activities. Conversely, this approach has the disadvantage that, since radionuclides may not reach the biosphere for many thousands of years, it may invite fruitless speculation about the nature of the future biosphere and, especially, future human behaviour. A solution suggested by the ICRP is the use of a stylised approach based on general (human) habits and (biosphere) conditions [4].

Theme 1 of the BIOMASS project was established under the auspices of the IAEA with the objective of developing the concept of 'Reference Biospheres' into a practical system for application to the assessment of the long-term safety of repositories for radioactive waste. [5]. Starting in 1996, the project involved more than 60 participants comprising regulators, proponents of radioactive waste disposal and independent experts gathered from eighteen countries. The outcome is a BIOMASS methodology that incorporates the experience of constructing a number of 'BIOMASS Example Reference Biospheres'. These illustrate the use of the methodology and are also intended to be useful in their own right by acting as reference biospheres in line with the definition offered above.

## 3. BIOMASS METHODOLOGY

The BIOMASS methodology provides a formal procedure for the development of assessment biospheres, based on a staged approach in which each stage introduces further detail so that a coherent biosphere system description and corresponding conceptual, mathematical and numerical models can be constructed. The methodology is presented schematically in Figure 1 (although this figure does not reflect the important role of iteration in the methodology).

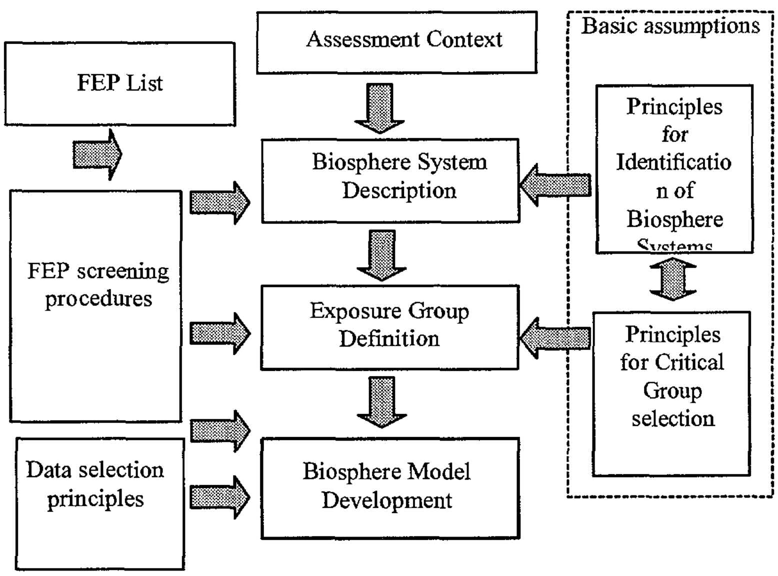


*FIG. 1. The Reference Biosphere Methodology.*

### 3.1. Assessment context

Defining the assessment context [6] is the first stage in the determination of a suitable assessment biosphere. This involves considering a number of fundamental issues that define the overall requirements, principally:

- the purpose of the assessment;
- the endpoint of any assessment calculations;
- the site context;
- the radionuclide source term;
- the geosphere–biosphere interface;
- the timeframe of the assessment; and
- the assessment philosophy (e.g. the level of caution/conservatism to be applied).

While these issues may seem obvious, the fact is that they are sometimes left unspoken, raising the unwanted possibility that they could be decided arbitrarily.

### 3.2. Biosphere system identification and justification

This stage of the methodology begins the process of creating an assessment biosphere based upon six Principal Components of the biosphere system: climate, geographical extent & topography, human activities, near surface lithostratigraphy, water bodies and biota. Biosphere system identification and justification takes place in four main steps.[7]

Identification (using a series of tables) of the type of Principal Component to be included within the assessment biosphere together with a explanation (justification) of the choice. For example, for the Principal Component 'water bodies', the identified Principal Component Types might be an aquifer and a river.

A decision on whether or not the assessment context requires biosphere change to be represented. In deciding this, two components of the assessment context are particularly relevant: the timeframe of the assessment and the geosphere–biosphere interface. At a coastal site, for example, it may be considered necessary to consider the effect of a change in sea level.

If biosphere change is to be represented, the third step considers possible mechanisms for change and their potential impact in order to identify (qualitatively) a range of possible future biosphere states.

Finally, it is necessary to decide whether these possible future biosphere states are to be examined independently or in sequence. If the latter, then one might wish to consider different sequences or perhaps to focus on the transitions from one biosphere state to another.

### 3.3. Biosphere System Description

This stage of the methodology [8] is aimed at providing sufficient detail about the biosphere system (or systems) to justify the selection and use of conceptual models for radionuclide transfer and exposure pathways. To begin, the methodology requires a decision to be made regarding the assumed level of human interaction with the biosphere system (for instance foraging in a natural or seminatural environment compared to intensive agriculture). Then, for each of the Principal Component Types, lists of potentially important characteristics (e.g. Table I) are screened to determine a short-list of those thought to be relevant to the assessment. So using the example given previously, if an aquifer and a river were the identified Principal Component Types for the Principal Component 'water bodies', Table I would be used to describe the characteristics of the of the aquifer and the river that were to used in the assessment biosphere.

Table I. Characteristics of water bodies, an example of one of the tables used in building the biosphere description

| Water Bodies Characteristics | |
|---|---|
| **1. Geometry**<br>• Level<br>– Position<br>– Variation (Global, local)<br>• Basal characteristics<br><br>**2. Flow rate**<br>• Variation<br>(e.g. permanent, ephemeral)<br><br>**3. Suspended Sediments**<br>• Composition<br>• Load | **4. Freeze/Thaw Phenomena**<br>• Ground freezing<br>– Seasonal<br>– Long-term (Permafrost, ice lens etc)<br>– Snowpack development<br>• Water body freezing<br><br>**5. Hydrochemistry**<br>• Composition of:<br>– Major anions and cations<br>– Minor anions and cations<br>– Organic compounds<br>– Colloids<br>• pH and Eh |

Working systematically through these lists allows the main features of the biosphere system to be described, alongside the reasons for the various choices. For example, consideration of the socio-economic context of the local human community allows the description of human activities leading to potential radiological exposures (shown for water bodies in Table 2). When all the Principal Component Types have been dealt with, if the assessment context requires it, the inter-relationships between the various Principal Component Types are then described.

The outputs of this stage of the methodology consist of (1) a description (a 'word picture') of the system that describes how the system components are arranged spatially and temporally, and how they interrelate; and (2) a description of the potential exposure pathways.

### 3.4. Candidate critical groups

During the Biosphere System Description stage, consideration of the interactions between the biosphere system and the associated human community allows a wide range of potential radiological exposure pathways to be described. Table II, for example, is part of a table produced as an aid to the methodology. It deals with human activities that could lead to potential radiological exposures from contacts with water bodies. The complete table (not reproduced here) also allows consideration of contacts with the atmosphere, geological media, soils, sediments, fauna and plants. It also lists the parameters for which data will be required.

This information then serves as a basis for the identification of candidate critical groups to which may be added any other potential exposure groups that might be of interest. The methodology also provides detailed guidance [9] on issues such as what is meant by a 'cautious' (as opposed to an 'equitable') approach and how one might address the issue of age-related effects.

Table II Human activities leading to potential radiation exposures from contact with water bodies

| Principal Components | Potential Exposure Mode -> Exposure Routes | Related Activities |
|---|---|---|
| Water Bodies | *Inhalation*<br>Spray, Aerosols, Volatile | Spray (Irrigation, surface waters), Domestic (showering/sauna/cooking) |
| | *Ingestion*<br>Drinking | Drinking |
| | *Ingestion*<br>Incidental ingestion | During bathing/swimming |
| | *Ingestion*<br>Eating | Cooking practices |
| | *External*<br>Submersion in water<br>External from water bodies | Bathing, swimming, working near contaminated water bodies (including water tanks and filtration systems) |
| | *Dermal Absorption*<br>Submersion in water | Swimming, bathing, interception of irrigation spray |

### 3.5. Model development, data selection and calculation

Model development begins with the construction of a conceptual model, which requires the identification of the relevant 'conceptual model objects': these are distinct environmental media that may influence the dose to the candidate critical groups. These should become evident from screening the 'human activities' table, part of which is shown in Table II. Examples of conceptual model objects might be soil, water, crops, livestock, but also less obvious items such as a water or crop storage system. The next step is to consider the interactions between the conceptual model objects. Here, an interaction matrix has been found useful and Table III shows such a matrix relevant to BIOMASS Example Reference Biosphere 2A, an agricultural system in which contaminated water is used for irrigation (the matrix has been simplified for reproduction here). The conceptual model objects appear in the shaded boxes (generally known as the leading diagonal elements of the matrix) and the interactions are shown in the un-shaded boxes (the off-diagonal elements). Further explanation is provided in the Table caption.

At this stage it is useful to check the conceptual model against the International FEPs (features, events and processes) List [10] to ensure that no important FEPs have been excluded from the conceptual model.

The next step is to construct a mathematical model to quantify the relationships contained in the conceptual model and there may be a number of alternative mathematical models for any one conceptual model. Compartment models are familiar tools for implementing a mathematical model of radionuclide transport in the biosphere and here one would expect that, put at its simplest, the conceptual model objects would correspond to the model compartments while the off-diagonal elements in Table III would correspond to the transfer factors between the compartments. The exposure model would incorporate the candidate critical groups and, indeed, any other potential exposure group that was of interest.

The availability of appropriate data to use in the model is clearly of great importance since the data will directly affect the numerical outcome. Less often appreciated is the fact that data availability will also affect the choice of mathematical model. For these reasons data selection is seen as an important activity within the methodology.[11] Experience with BIOMASS showed that data selection, if carried out with due rigour, puts high demands on expert resources. The combination of data and mathematical model allows the calculation, first of the radionuclide concentrations in the media of interest and second, of the doses (or other endpoints) resulting from exposure of the candidate critical groups to these media. The candidate critical group with the highest dose would be the hypothetical critical group. Almost inevitably, there will be a need for some iteration to ensure that there are no other potentially exposed groups that might receive higher doses than the hypothetical critical group. This might entail additional calculations ('side calculations') that, while they do not affect the calculated doses, provide confidence that the calculations are robust.

Table III. Simplified radionuclide transfer matrix for an agricultural irrigation well. The leading diagonal (shaded) elements show the contaminated media (the conceptual model objects) and the off-diagonal elements show the pathways between them. The matrix always works in a clockwise direction so that, for instance, radionuclides in the 'water abstracted from aquifer' (element 1,1) transfer directly to 'food and fodder crops' (element 3,3) via 'irrigation / leaf interception' (element 3,1). Similarly radionuclides in 'farm animals' (4,4) find their way into 'cultivated soil' (2,2) via 'manuring' (2,4). Each of the matrix elements can be related to a component or a feature of the mathematical model. 'x' signifies no radionuclide transfer in the conceptual model

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| | Water abstracted from aquifer | Irrigation and sediment transfer | Irrigation / leaf interception | Water and sediment ingestion | x | Water and sediment ingestion |
| | x | Cultivated soil | Root uptake Soil splash | Consumption of soil on fodder crops | Transfer of soil on crops | Ingestion |
| | x | Weathering Leaf litter | Food and fodder crops | Ingestion of fodder | Harvesting | x |
| | x | Manuring | x | Farm animals | Slaughtering, milking and egg collection | x |
| | x | Green manuring / composting | x | Consumption of stored fodder | Farm product storage, distribution & processing | Ingestion |
| | x | x | x | x | x | Human community |

## 4. BIOMASS EXAMPLE REFERENCE BIOSPHERES

### 4.1. Development of the examples

If a reference biosphere is to be useful, it clearly needs to be capable of being used in a wide range of circumstances. The most widely applicable assessment biosphere in common use is, perhaps, a drinking water well intruding into a contaminated aquifer. Unfortunately, this suffers from the disadvantage that the range of exposure pathways is narrow, so raising the possibility that potentially important exposure pathways and, indeed, important FEPs might be omitted. A more complex biosphere would allow these complexities to be included but might then become less widely applicable. In devising a practical reference biosphere therefore, the problem is to find an appropriate balance between simplicity and complexity. Within the BIOMASS project, this problem was addressed by developing a range of BIOMASS Example Reference Biospheres ('Examples') of increasing complexity. By taking these through to a numerical calculation it was hoped that it might be possible to make a judgement regarding both the benefits and disbenefits of the additional complexity.

Four Examples were taken all the way through to a numerical calculation. All of them relate to a temperate climate though with no specific location in mind; all four assume unchanging biosphere conditions:

(1) Example 1A: a drinking water well intruding into an aquifer that is contaminated with a specified concentration of radionuclides.[12]

(2) Example 1B: a drinking water well intruding into a aquifer that is contaminated by radionuclides and where the radionuclides are released into the aquifer at a specified rate.[12]

(3) Example 2A: an agricultural irrigation well intruding into an aquifer that is contaminated with a specified concentration of radionuclides.[13]

(4) Example 2B: a natural discharge from a contaminated aquifer (specified concentration of radionuclides) into a number of different habitats, including arable, pasture, semi-natural wetland and lake.[14]

While the Examples have been used to develop the BIOMASS methodology, they also serve to demonstrate its application. In taking these Examples right through to the point of deriving numerical endpoints, the intention was to fully exercise the methodology, including the issue of data selection. It was this aspect that demonstrated that data selection requires high levels of expert resources. Indeed, the project greatly underestimated the level of effort that would be required to satisfactorily complete the work of data selection and, as a result, it became necessary to restrict Examples 2A and 2B to a relatively narrow range of radionuclides (Nb-94, Tc-99, I-129 and Np-237).

The project also developed the methodology to allow changing biosphere conditions to be addressed and three 'changing biosphere' cases have been taken through to the 'biosphere identification and justification' stage [15].

A case based on Äspö (Sweden) incorporating biosphere change induced by land rise due to glacial rebound and different, non-sequential, global climate states.

A case based on Harwell (UK) incorporating biosphere change induced by different, non-sequential, global climate states.

A case based on Example 2A with biosphere change induced by different, sequential and non-sequential, global climate states.

### 4.2. Numerical outputs from the examples

As intended, the Examples displayed significant differences, particularly with respect to the radionuclide transfer pathways, the exposure pathways, and the characteristics of the hypothetical critical groups.

Calculations were carried out for Examples 1A and 1B ('drinking water well' pathway) for a wide range of radionuclides. Calculated dose values for the different radionuclides spanned five orders of magnitude, reflecting their different radio-toxicities. The results for Example 1B highlighted the influence of dilution processes at the geosphere–biosphere interface.

For Examples 2A and 2B, results were determined assuming unit concentrations of four radionuclides in groundwater: I-129, Np-237, Tc-99 and Nb-94. These four radionuclides were chosen to demonstrate a range of chemical and biological properties and to be relevant to the disposal of high-level radioactive waste. Doses from the first three radionuclides were dominated by ingestion whereas for Nb-94 (a penetrating gamma emitter) external exposure dominated. A comparison of the calculated doses to the candidate critical groups from these four radionuclides in Examples 1A, 2A and 2B revealed that:

— Ingestion exposures from irrigated agricultural land (Example 2A) were about five times higher than from drinking water alone (Example 1A); for Nb-94 the external irradiation doses were very much higher than those due to ingestion. This led to the conclusion that consideration of the drinking water pathway alone may result in underestimation of the doses to the hypothetical critical group.
— For the four radionuclides examined, ingestion exposures for the natural discharge Example (2B) were up to two orders of magnitude less than those for the irrigated agricultural land Example (2A), provided that consumption of 'wild' (i.e. undomesticated and uncultivated) foods were excluded from Example 2B.
— Radiation exposures due to the ingestion of wild foods have the potential to dominate doses in Example 2B, the natural discharge case. In part at least, this may be because lack of data (on technetium uptake into fungi for example) made it necessary to adopt a cautious approach.

In broad terms, the data requirements for Example 2B were one to two orders of magnitude greater than for Example 2A, which in turn, were one to two orders of magnitude greater than for Example 1A. At the same time Example 2A generally produced higher doses than 2B, or broadly similar doses if wild foods are included in 2B. This suggests that Example 2B may be approaching the upper limit of what is desirable in terms of complexity.

### 4.3. In what sense Reference biospheres?

In addition to demonstrating and developing the methodology, Examples 1A, 1B, 2A and 2B were designed to serve as practical reference biospheres. As outlined in the Introduction, reference biospheres should be stylised and widely applicable. Three possible uses are suggested:

— Reference biospheres may be used generically e.g. for comparing the levels of safety provided by different disposal concepts in the absence of site-specific information.

— Reference biospheres may be used to complement site-specific assessment biospheres by providing assurance that the latter are both robust and reasonable. For instance, the Examples indicate the possible level of significance of potentially relevant features, events and processes. Further, side calculations demonstrate how it is possible to determine when sufficient sub-division of processes has been provided to meet the requirements of the assessment context.
— Reference biospheres may be used as standards to facilitate cross-comparisons and checking of results

Discussions within the project concluded that all four of the fully-worked Examples provide generically applicable conceptual and mathematical models that would allow them to be used as reference biospheres for radionuclide releases occurring via groundwater, at least for those assessments that have corresponding assessment contexts. For Examples 1A and 2A, where the geosphere–biosphere interface is simple, it was possible to go further. Here it was considered that the numerical results provided (i.e. dose per unit concentration in groundwater) were sufficiently well justified to allow their use as indicators of potential radiological impact. The results for the many radionuclides included in Example 1A were considered to be very widely relevant, since ingestion exposure from a drinking water well is commonly considered in repository performance assessments. (Example 1B is less widely applicable because here it was necessary to use a dilution factor whose numerical value was somewhat arbitrary.) The Example 2A results for Tc-99, I-129, Nb-94 and Np-237 are relevant to agricultural use of well water in a temperate climate; again, this is a fairly common feature of repository performance assessments. It was considered that the numerical results from Example 2B would be similarly applicable, provided that the geosphere–biosphere interfaces used in the Example are appropriate to the system under consideration.

## 5. COMPLETION OF THE BIOMASS PROJECT

The BIOMASS methodology and the Examples can be found in the series of IAEA 'working documents' cited here. In effect, these documents provide draft material describing work in progress. In some cases it was found necessary to make late changes to the methodology in response to issues that arose during the development of the Examples. Where such changes were made this was documented in the Examples documents rather than in the methodology documents. With the completion of the technical phase of the project therefore, current work is focused on consolidating the documents into an Overview, and single documents describing the methodology and the Examples. It is intended that these should appear as an IAEA Tecdoc

## 6. CONCLUSIONS

Over a four year period, the BIOMASS Theme 1 project has utilised expertise from all over the world to develop a methodology for the logical and defensible construction of 'assessment biospheres': mathematical representations of biospheres used in the total system performance assessment of radioactive waste disposal.

The methodology has been used to create a series of reference biospheres: the BIOMASS Example Reference Biospheres. These are stylised assessment biospheres that, in addition to illustrating the methodology, are intended to be useful assessment tools in their own right.

These Examples include numerical calculations, some of which, given an appropriate assessment context, could be used to calculate dose directly from radionuclide concentrations in groundwater. The Examples may also be useful to other assessments by, for instance, indicating the possible level of significance of potentially relevant features, events and processes.

It is hoped that these BIOMASS reference biospheres will find widespread use.

## 7. ACKNOWLEDGEMENTS

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