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New methods for the delineation of geological barrier rocks for waste disposal sites in northern Thailand

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In order to guarantee that the most suitable location is selected for a waste disposal site, the distribution of geological barrier rocks must be determined in the area or region in question. This is the first step of the search for a landfill site. The procedure as described in this paper provides results that are reproducible and of a purely scientific character, and above all, it is a process in which the public can participate. It has been tested in the Chiang Mai-Lamphun basin in northern Thailand. The target of the search is rocks that have potential barrier properties which will hinder the infiltration of contaminants into the groundwater. If rocks with these properties have a thickness of at least five meters and the cover rock is no more than two meters thick, they can be considered to be a geological barrier.

First, the lithologies shown on the geological map of the area or region are classified according to their potential effectiveness as a barrier. Second, a geological database containing the lithological logs of boreholes in the area is searched to determine whether rocks with potential barrier properties are present. Third, a Potential Barrier Rock Map is prepared from the results. This map displays all areas with a geological barrier and its thickness at the borehole locations.

The site search process

The problem

The management of the municipal waste (hazardous waste is not discussed in this paper) is one of the major tasks that will have to be undertaken in the future if severe environmental damage is to be prevented. Municipal waste has been a problem in the industrialized countries of the modern Western world for decades already. It is the focus of many NGOs and local environmental groups and is heavily debated wherever it becomes a political issue. The public is aware of the problems that a waste treatment facility creates. This is the case not only in the industrial countries, but also in all countries that are rapidly developing economically and technologically, including the Kingdom of Thailand. (Mantajit, 2000)

Many economic developments have taken place without their environmental impact being taken into consideration. As a consequence, the problem of waste production has risen to become a great threat to the natural environment, and adequate solutions are

urgently required. The figures are frightening: Piyapanpong (1997) calculates that the amount of waste generated in Thailand was about 13.15 million tons in 1996, compared to 10.78 million tons in 1993. This is an increase by almost one-third in only four years. In the project area, the Chiang Mai-Lamphun basin, the production of waste by the city of Chiang Mai alone is about 250 tons/day, or over 91,000 tons/year (Weinschenk & Kaen 1996, 49 ff).

A no-waste society, as conceived by the EU, may be achievable for highly industrialized countries. But no other country will be able to pursue this concept for a long time to come.

Reliable data for waste management can be obtained only with an appropriate scientific approach. Such an approach has to be a transparent, public process that avoids misunderstandings and the suspicion that reasons other than technological and scientific ones contributed to the solutions of the waste management problems.

Recently, de Mulder & Cordani (1999, 79) have pointed out in this journal the important role the geosciences can play in the search for a waste disposal site. This paper discusses an example of how de Mulder & Cordani's ideas can be carried out.

The public nature of the site search process

It is important to understand the complexity required to obtain reliable and reproducible results for a scientific landfill site search. The steps to be taken in a scientific landfill site search are not a matter of personal judgement or individual or social preference, but are based on scientific principles. They can be repeated to check the data, and new data can be integrated for updating. This is of prime importance for the search for a geological barrier, i.e., rocks that have a high barrier potential.

The scientific character of the procedure ensures that every one involved can agree on the results. And if the objective is not consensus based on scientific results, nothing else has a chance of leading to a consensus. Acceptance of the results of a scientifically based landfill site search process by the public will be high and conflicts can be reduced.

It is important that all the steps of the site search process be open to the public. Transparency, mediation between disagreeing parties, and the right to participate as an equal partner in the discussion strengthen the site search process. Its design as a public process avoids the impression that a site will or can be selected without taking the public's opinion into consideration.

It was mentioned above that the primary aim of a site search process is to minimize the environmental impact of a waste disposal site. The site search process must take the regional aspects and problems, i.e., regional planning decisions, special geological features, and economic conditions (affecting, for example, the amount of waste produced) into consideration. For example, the site search process described here for the Chiang Mai Province can lead to results different from those for other provinces in Thailand. Moreover, the process described here can be adapted to decentralized administrative structures.

It is now clear that the site search process described here is not only a scientific one, but also one that has significant social features. These features are at least as important as the scientific aspects of the site search process.

The phases of a site search process

In general, a search for a waste disposal site focuses on four aspects of the area in question:

1. the geology,
2. groundwater flow and hydrochemistry,
3. the contaminant retention capacity of the rocks, and
4. geotechnical restrictions.

General geoscientific criteria for an investigation of potential waste disposal sites are given by the Ad-hoc-Arbeitsgruppe Deponien der Staatlichen Geologischen Dienste der Bundesrepublik Deutschland (1997).

In Phase 1 of the site search, all available geological data (geological maps and borehole data) is compiled for a geological inventory of the area/region. The inventory should take the entire project area into consideration, and not only selected sites (Oeltzschner, 1996). If there are only a few boreholes, or even none at all, boreholes should be drilled at selected localities. The main product of Phase 1 is a potential barrier rock map; other maps may provide supplementary information.

When the regional planning authorities select the most suitable site for waste disposal using the results of the geological inventory, they need not only geological information, but information on other aspects, such as areas zoned for specific purposes, traffic, microclimate, economic and social conditions, and availability of land, which have to be added to the list of criteria for selection by the regional planning authorities. Their decision, therefore, is more of a political and less a scientific one, which is taken between Phases 1 and 2. A map of recommended areas for site investigations can aid this decision.

In Phase 2, a detailed investigation of all selected sites is conducted to obtain up-to-date data for a comparison of the potential sites selected by the regional planning authorities, in order to determine which one would be the best one for the construction of a new landfill. New boreholes have to be drilled, and a borehole logging program has to be conducted. A geophysical survey, especially a geoelectric one, of the area may have to be applied. For the groundwater flow and hydrochemistry data, *in situ* measurements of the k_f -value are necessary, as well as determination of the depth to the groundwater table and the analysis of groundwater samples. The contaminant retention capacity should be measured in the laboratory using core samples from the new boreholes. Penetration tests are then carried out to determine the consistency of the soil, to avoid settlement of the landfill foundation ground.

A preliminary search map is produced during Phase 2. This map is used to select the best site for a landfill in the project area, in close cooperation between the hydrogeologist and the regional planner. In Phase 3, the methods mentioned for Phase 2 are then used for small-scale mapping of the parameters of the four aspects mentioned above.

If Phase 1 yields only a single site—which often occurs—Phases 2 and 3 can be merged. Both political and economic conditions may be responsible for this. The planning authorities should be aware that in such a case the site may be found to be unsuitable for a landfill. A work-flow chart for the site search process discussed in this paper is shown in Figure 1 (from Dörhöfer & Siebert, 1998, Fig. 9, modified and adapted to the conditions in Thailand by the authors). It shows the order in which the various maps are used for the site search. Only the steps of the first phase (grey background in Figure 1) of the site search are described in this paper.

The first phase of the site search process

The first phase of the site search has a clear aim: to locate and delineate areas with rocks that have potential barrier properties, i.e., prop-

erties that will hinder infiltration of contaminants into the groundwater. These properties are:

- low permeability,
- low effective porosity,
- high natural retention capacity for hazardous substances, and
- high proportion of clay or silt.

If rocks with these properties are to fulfill the function of a geological barrier, the following conditions have to be met:

- The rocks should be at least 5 m thick.
- The cover rocks should not be more than 2 m thick.
- The rocks should extend without gaps at least 50 m in all directions from the planned landfill.

If the prerequisites for a geological barrier are met, the prospective waste disposal site should be located where

- aquifers are of minor importance,
- depth to the groundwater table is large, and
- the hydrogeological structures and flow system are known. This will entail a detailed investigation of the regional flow system (see Engelen & Kloosterman, 1996). Therefore, a hydrogeological survey has to precede the site search. Margane & Tatong, (1999) conducted such a survey of the project area previous to the work described here.

The task of a site search is to determine which areas fulfill all of these conditions, none of which can be neglected.

Rocks that have potential barrier properties can be divided into the following categories:

- **High barrier-potential rocks** have a very high content of clay and/or silt, very low permeability, and show a high degree of homogeneity.
- **Medium barrier-potential rocks** have a high content of clay and/or silt, very low to medium permeability, and are presumably moderate homogeneous
- **Low barrier-potential rocks** have a significant content of clay and/or silt, with medium permeability.

The geological barrier and man-made barriers

The technical standard of today for a waste disposal site requires a man-made barrier (for more detail see Bouazza & Van Impe, 1998). Such a barrier consists of a mineral liner and a plastic liner—a “combined liner system”. This system hinders leachate from infiltrating into the ground and entering the groundwater.

The conclusion should not be drawn that the requirement of a combined liner system makes it unnecessary to conduct a search for the site with the best geological barrier. But as Doerhoefer & Siebert (1998) have pointed out, a man-made barrier cannot guarantee the long-term stability that is required to prevent contamination of the environment. The reduced resistance to certain organic chemicals and the susceptibility to mechanical damage have been repeatedly demonstrated. Even the construction of a combined liner system can lead to later damage.

The man-made barrier is, without a doubt, an important factor for the isolation of a landfill from the environment, but it does not replace either the geological barrier or the site search. The long-term stability of the geological barrier is the most important part of the modern system for isolating a landfill from the environment.

The site search

The site search process must be structured in such a way that it can be used in all parts of Thailand, and not just for a single project area. Therefore, it should be possible to carry out a site search designed for the Chiang Mai-Lamhun basin in all other regions of the country.

The Potential Barrier Property Map

The first step in a site search is a preliminary assessment of the potential barrier properties of the rocks in the search area. The scale of all maps of the project area is 1:100,000. The potential barrier properties

Figure 1 Preparation of the maps for the site search in the Chiang Mai-Lamphun area. Phase 1 (grey background) is discussed in this paper.

of the rocks in the Chiang Mai area are estimated on the basis of the permeability derived from the lithological description of the units in the legend of the geological map. The Potential Barrier-Properties Map is prepared entirely from the information on the geological map. No other information is used. To aid recognition of units on the Potential Barrier Properties Map, the stratigraphic and lithologic units are assigned the same colours as on the geological maps (Figures 2 & 3). The estimated potential barrier properties are indicated on the map by different symbols: High barrier-potential areas are indicated by horizontal hatching, medium barrier-potential areas by diagonal hatching, and low barrier-potential areas by vertical hatching. Areas with no potential barrier properties are left uncoloured.

The site search database

Purpose of the site search database

The database for the site search was developed to search areas of potential barrier rocks for the construction of a waste disposal site based on borehole and well data. It was designed to allow the site search to be carried out in any project area and to guarantee that the work of the project can be continued by the counterparts in other parts of the country. Another advantage of a database is that the data can be easily updated. For the project in the Chiang Mai-Lamphun basin, well data (Tatong et al., 1997), data from shallow boreholes (Chaimanee, 1997) and outcrop descriptions compiled for a raw materials inventory (Dhamdusdi et al., 1997) were entered in the database.

The site-search database is available as a stand-alone version as well as a client-server version, in which only the processed data are stored locally.

The search for a geological barrier

The search for areas with a geological barrier is the main purpose of the database. The following steps are involved in a database search:

- First, all boreholes for which a lithological description is available are selected. Only these are of interest for further processing.
- Adjacent strata with the same permeabilities are grouped together as a single unit.
- These units are classified as having a high, medium or low barrier potential, according to the permeability estimated from previous lithological descriptions.

Table 1 *Classes of potential barrier rocks estimated from the lithological descriptions*

Class	main lithology	subordinate lithology
High	clay or silt	not like gravel
Medium	sand & clay laterite sand clay	like clay and not like gravel like gravel and like silt or like laterite
Low	clay & gravel clay	like gravel and not (like silt or like laterite)

- An important criterion for a geological barrier is the thickness of the unit with potential barrier properties, and the depth to the top of this unit. To qualify as a geological barrier, the unit must be at least five meters thick. It is best if this unit lies directly on the surface. However, in Thailand, a cover of not more than two meters is still acceptable, because it is not too uneconomical to remove it if the geological barrier beneath it is of prime quality for a landfill.
- With three categories of potential barrier properties and the presence or absence of a cover layer less than 2 m thick, there are six classes of potential barrier properties. Six files are created by a search for a geological barrier, each of which contains a list of boreholes in which the respective potential barrier property class occurs, with the borehole coordinates, thickness of the potential

Figure 2 *Geological map of part of the Chiang Mai-Lamphun area, scale 1: 165,000. Quaternary sediments are in the middle of the basin. East and west of them are Paleozoic rocks and Precambrian gneiss.*

Figure 3 The same chart as in Figure 2, scale 1: 165,000. Potential Barrier Properties Map of part of the Chiang Mai-Lamphun area. High barrier-potential areas are indicated by horizontal hatching, medium barrier-potential areas by diagonal hatching, and low barrier-potential areas by vertical hatching. Areas with no potential barrier properties are left uncoloured.

geological barrier and the thickness of the cover layer. Each file also contains a new data field SRF with a 1 if the borehole has a layer with potential geological barrier properties and a 0 if it does not. This information is needed for the cartographic presentation of the results of the database search. The results are exported as EXCEL files (*.xls). The following table is an example of such findings. Similar tables are generated for all six classes of potential geological barrier rocks

Table 2 Example of results (10 of 131 wells found) of a database search for boreholes with a layer with high potential barrier properties in the Chiang Mai-Lamphun basin

Wells with high barrier-potential rocks (no cover rock)
Project area: Chiang Mai-Lamphun basin
Cover thickness: 0.0 m; Potential barrier rock thickness: 5.0

Well No.	Easting	Northing	Thickness of cover rock	Thickness
BTM006	507550	2061950	0.0	10.3
BTM007	507350	2061900	0.0	9.2
BTM008	511250	2062750	0.0	10.7
BTM018	516950	2063750	0.0	13.7
BTM032	505800	2055900	0.0	56.4
BTM033	510210	2053899	0.0	33.6
BTM036	507150	2057750	0.0	35.1
BTM037	508450	2056850	0.0	10.7
BTM038	509550	2057100	0.0	10.7
BTM040	508790	2053968	0.0	45.8

The Potential Barrier Rock Map

Delineation of areas with a geological barrier

Areas with a geological barrier are delineated as follows:

1. The data in the six files mentioned above are imported by an interpolation program, e.g., Surfer, with a worksheet for each set of data.
2. A grid is calculated for each worksheet. The location of the 0.5 value is determined by interpolation between wells with a value of 0 and wells with a value of 1 in the SRF field. Of the available interpolation methods, the “inverse distance to a power” method has yielded the best results. This method provides a rather conservative estimate. In many cases it is advisable to increase the number of grid lines proposed by Surfer for the grid.
3. The results of the interpolation are plotted, showing the location of the 0.5 isoline (Figure 4). All areas within the 0.5 isoline may be considered to have potential barrier rocks.

What is special about this interpolation procedure is that the delineation takes the spatial distribution of the wells or boreholes into consideration. The interpolation does not take the thickness or depth of the potential barrier rock into consideration, but only the value in the SRF field, i.e., whether there is a geological barrier or not. The following reasons may be given for this:

- The only aspect of the thickness criterion for a geological barrier is that it must be at least five meters thick. If the thickness of a potential barrier rock is greater than this lower limit, the rock qualifies as a geological barrier. Certainly, the greater the thickness of a geological barrier, the better it is, but for the delineation of areas with a geological barrier, it is not important, except for the lower-thickness-limit criterion.

Figure 4 Example of a 0.5 isoline plot for delineating areas with a potential geological barrier. Boreholes penetrating no potential barrier rocks are dark, boreholes penetrating potential barrier rocks are lighter.

- It should be pointed out that in the database search only those wells or boreholes are selected that have a potential geological barrier that fulfills the minimum thickness criterion of five meters. Therefore, thickness need not be taken into consideration for the interpolation.

Intersection of the 0.5-isoline map with the Potential Barrier Properties Map

In the next step, the 0.5-isoline map is intersected with the potential barrier properties map using a GIS program, e.g., ArcInfo. In this intersection, the polygons defining the areas within the 0.5-isoline are plotted first. The areas within a certain distance from the wells with an SRF value of 0 are plotted next. The polygons on the Potential Barrier Properties Map which indicate potential barrier properties outside these two types of areas are plotted last.

This intersection is a crucial step for the production of a map of potential barrier rocks. The first two steps ensure that the borehole data will have priority over all other information. The lithological description of a borehole is usually a comprehensive compilation of data, and is the main source of information for a site search. It therefore has to be treated as top-level data.

As the Potential Barrier Properties Map was prepared using only information from the geological map, boreholes with indications of potential barrier rocks in the areas of the polygons of the Potential Barrier Properties Map showing no potential barrier properties are also plotted. This is to guarantee that new areas based on borehole data will not be excluded by the Potential Barrier Properties Map.

The priority of the borehole data also applies to those areas where there is a borehole indicating the absence of potential barrier rock. This information has the same level of importance as the polygons of the interpolation map, the only difference being that these boreholes provide evidence that there is no rock with potential barrier properties. Boreholes with no potential barrier rock are considered as important as those with potential barrier rock.

Only in those areas where no information based on borehole data is available are polygons from the Potential Barrier Properties Map included on the intersection map. The areas for which no information based on borehole data is available should not be confused with areas with no potential barrier rocks!

Interpretation of the Potential Barrier Rock Map

Nine maps units are shown on the Potential Barrier Rock Map (Figure 5): areas with a high, medium or low barrier potential and no overlying rocks; areas of high, medium and low barrier-potential rocks under a cover of not more than two meters. Both groups result from the borehole database search. In areas where no borehole data was available, areas of high, medium and low barrier-potential rocks shown on the Potential Barrier Properties Map are included on the Potential Barrier Rock Map. The map shows all borehole locations together with the thickness of the geological barrier if the borehole penetrates one.

Figure 5 The same chart as in Figures 2 and 3, scale 1: 165,000. The Potential Barrier Rock Map of the Chiang Mai-Lamphun area. For details see the text.

Figure 6 The same chart as in Figures 2, 3 and 5, scale 1: 165,000. *Recommended Areas for Site Investigation Map in the Chiang Mai-Lamphun basin.*

The Potential Barrier Rock Map is the main product of the first phase of the site search. It combines all available geological data on one map: from the geological map and from the lithological logs. It results from a comprehensive evaluation and scientific interpretation of the available data.

It must be kept in mind that in this first site search phase, areas are selected that have *potential* barrier rocks. It must not be forgotten that all areas with potential barrier rock that are selected for the second phase of the site search can be viewed as suitable for waste disposal sites only after detailed further geological and hydrogeological surveys have been carried out. This is necessary to assess areas with potential barrier rocks in order to select the best one.

The map of potential barrier rocks is not only important for the site search, it is also a very useful tool for all kinds of planning purposes:

- It can provide a quick initial indication of whether groundwater pollution is possible, e.g., in the case of a contaminant spill. The presence of a barrier rock will retard the infiltration of the contaminant into the groundwater, in its absence the contaminants can infiltrate quickly into the groundwater.
- The same is true for an assessment of an abandoned waste site.
- The map can assist planning of, for example, pipelines or new industrial sites. Such construction should be carried out only where the groundwater is protected by potential barrier rocks.
- In general, the map of potential barrier rocks can be used for planning all activities that may influence the groundwater. If the planned activity represents a hazard, it should be located in an area with potential barrier rocks.

The map of potential barrier rocks presents all of the geological information for an area relevant to the site search. This map does not include any other themes. It is, first and foremost, a geoscientific map; it does not include political or social aspects. Its great value for planning is that it can induce planners to change previously made decisions. If, for example, an area with a geological barrier is particularly suitable for a waste disposal site, revision of previous plans should be reconsidered.

Interpretation of the Potential Barrier Rock Map of the Chiang Mai-Lamphun basin

The Potential Barrier Rock Map of the Chiang Mai-Lamphun basin shows, as may be expected for an intermontane basin, many areas with potential barrier rocks. Many of them are high barrier-potential rocks. High barrier-potential rocks are located north and east of Chiang Mai, where the Potential Barrier Properties Map indicates no potential barrier rocks are present. There are other areas of high barrier-potential rocks northeast and south of Lamphun and around San Pa Tong. The geological barrier rocks with the greatest thicknesses (up to 153 m near Ban Thi) are around Lamphun. Smaller areas with high barrier-potential rocks are distributed across the map, often indicated by only one or two wells, e.g., around Doi Saket, San Kam-paeng, Saraphi, and Hang Dong.

The Recommended Areas for Site Investigation Map

Design of the Recommended Areas for Site Investigation Map of the Chiang Mai-Lamphun basin

The "Recommended Areas for Site Investigation Map" (Figure 6) is the result of the next step of the site search. It is primarily not a geological map (result of a geological interpretation of data), it is a product of an application of GIS. This is the important difference between the Potential Barrier Rock Map and the Recommended Areas for Site Investigation Map.

The Recommended Areas for Site Investigation Map (Figure 6) is a map from which all areas noted on the Potential Barrier Rock

Map, where a waste disposal site cannot be constructed, are excluded. These areas are:

- areas of a highly productive aquifer,
- areas for nature conservation,
- forest areas,
- flood prone areas,
- mining areas,
- lakes and ponds with a buffer of 300 meters around them,
- settlement areas with a buffer of 300 resp. 500 meters around them,
- places of special significance, e.g. a wat (Buddhist temple),
- airports with a buffer of five kilometers around it.

Only those areas of the Potential Barrier Rock Map, independent of their classification, that are not covered by one of the areas mentioned above are plotted on the Recommended Areas for Site Investigation Map. In addition, all areas plotted on the Recommended Areas for Site Investigation Map have to be larger than 0.25 km². This size is the minimum size for the construction of a modern landfill that may be operated for at least 15 years.

Interpretation of the Recommended Areas for Site Investigation Map

The Recommended Areas for Site Investigation Map is a map on which all other planning items have priority to the geological one. It gives the status quo of the actual planning, but, unfortunately, it precludes the chance of altering a plan or a decision.

Certainly, flood prone areas, forest areas, areas with highly productive aquifers or settlement areas are places where the construction of a landfill will always be prohibited, but the possibility of exclusion from the site search of areas with a very good geological barrier should not be neglected, as well as the exclusion of areas with a poorer geological barrier, if the geological information is kept at the "end of the pipe". It is up to the planning authorities which way they want to proceed with the site search. Therefore, the Recommended Areas for Site Investigation Map and the Potential Barrier Rock Map should be used together to select sites for further investigation. The geological data and their interpretation, as presented in the Potential Barrier Rock Map, and its intersection with other planning purposes, as presented in the Recommended Areas for Site Investigation Map, can provide a unique and optimal foundation for the selection.

Conclusions

A major aspect of the first phase of the site search as described here is its extensive use of computers. The database, the interpolation and the intersection of information from different directions are done with a computer. Each step of the site search can be implemented with one of several different programs. Therefore, the cost of the data processing is not high.

The applicability of this site search procedure is not restricted to special areas or geological circumstances: It can be conducted in hard-rock areas as well as in soft-rock ones. Both small and large areas can be investigated.

Results are quickly obtained and a preliminary check of an area done if the relevant data is available. An objective site search is guaranteed if it is carried out in a public way, as described here. Especially in the less-industrialized countries, this site search method is an important tool for protecting the environment from the negative impact of waste pollution.

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