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# 3D and 4D Geomodelling Applied to Mineral Resources Exploration—An Introduction

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## Abstract

3D geomodelling, a computer method for modelling and visualizing geological structures in three spatial dimensions, is a common exploration tool used in oil and gas since more than several decades. When adding time, 4D modelling allows reproducing the dynamic evolution of geological structures, and reconstructing the past deformation history of geological formations. 3D geomodelling has been applied to mineral exploration with some success since more than 15 years, but can be considered still challenging for modelling hard rock settings. If very few 4D modelling case studies have been carried out in mineral exploration, it nowadays begins to be applied in structural geology and mineral resources exploration. This paper describes the 3D and 4D geomodelling basic notions, concepts, and methodology when applied to mineral resources assessment and to modelling ore deposits. It draws on the state of the art of 3D and 4D-modelling, describing advanced techniques, limitations and recommendations. The text is illustrated by several 3D GeoModels of mineral belts across Europe, including the Fennoscandian Shield (Finland, Sweden), Hellenic (Greece), Iberian (Spain, Portugal) and Foresuedic (Poland, Germany) belts, all of those case-studies have been performed within the EU FP7 ProMine research project (Part of objectives of the 4 years ProMine project were to integrate the mapping of metal and mineral resources across the European Union, especially in WP1 and WP2). Perspectives and recommendations on applying 3 and 4 geomodelling in mineral resources appraisal are given in the conclusions.

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## 4.1 Introduction

3D and 4D Geomodelling is nowadays applied in mineral resources exploration as an exploration tool by geo-practitioners and geoscientists

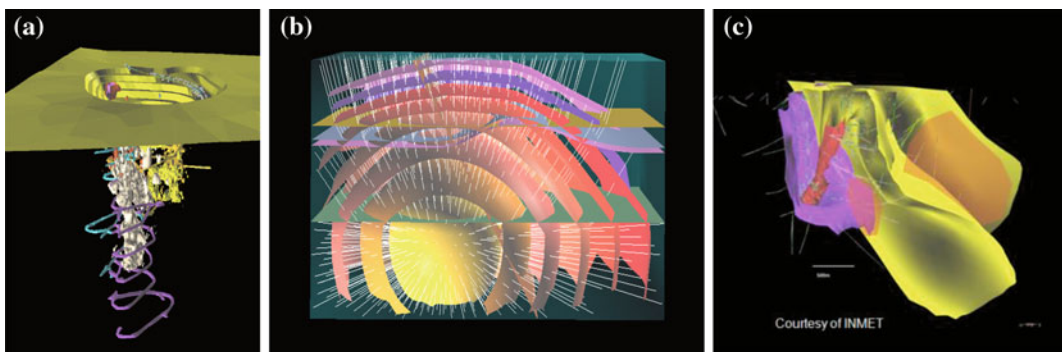
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involved in better understanding mineral resources appraisal, both at the mining exploitation and at the exploration stages for identifying potential new mineral resources. Data acquired during mining exploration and exploitation is interpreted and processed using computers. Several packages are available on the market for processing 2D and 3D datasets such as GIS and geomodelers (Bonham-Carter 1994; Mallet 2002; Internet Guide to GIS 2009). Among them, the most widely used are: 3D Geomodeler (Geomodeler 2012) from BRGM and Intrepid, gOcad-SKUA from Paradigm (2012) for geological applications, gOcad Mining Suite from Mira Geoscience (2013) for mining, AutoCAD (2012), Irap RMS from Roxar (2009), Isatis from Geovariances (2012), Leapfrog Geo (2013), MicroMine (2012), Microstation (2012), MineSight Implicit Modelling (MSIM) from Mintec (2012), Move3D from Midland Valley (2012), Petrel from Schlumberger (2009), Surfer (2012), Surpac from Gems from Geovia (2013) a subsidiary of Dassault System, and Vulcan3D (Vulcan 2012) from Maptek. These software programs generally address one or more specific modelling applications, but none of them can actually encompass all tasks generally required in an integrated mining study, including: structural and geobody modelling, restoration, geophysical inversion and interpretation, geochemical analysis, resource and reserves estimation, mine planning, mine design and risk and environmental impact mitigation. Such a general-

purpose modelling framework is nonetheless most relevant for geological modelling as observed for instance by McGaughey (2006), Caumon et al. (2005, 2006, 2009, 2013a) and Caumon (2010). Similar challenges have been considered in the Oil and Gas industry which has led to spectacular advances regarding the 3D modelling, geological history reconstruction (referred here as 4D modelling or restoration) and multi-disciplinary integration for better understanding basin history and target reservoir behavior. If the modelling of some ore deposits in igneous formations can be relatively simple, it can become extremely complex when poly-phase structural events are overprinted on inherited mineralization processes, like for ore deposits in regionally metamorphosed rock assemblages. Geological reconstruction and restoration techniques are now quite mature on sedimentary formations, but definitively calls for further research for hard rock settings where fault displacement cannot be easily inferred from topological relationships between geological formations and structures (Fig. 4.1). Basic geomodelling notions and concepts do not depend on the software package used, although some aspects such as geometry, topology, fault networks, geological interfaces etc., depend on the software package and its underlying technology.

This paper introduces geomodelling to geoscientist specialists and stakeholders involved in exploration and exploitation of mineral resources.



**Fig. 4.1** **a** Open-pit mine in Central Massif (France): an underground ore 3D model points out unknown mineralization which extended the mine life by more than 10 years. **b** Iso-value front surfaces representing the

propagation of seismic waves. **c** Complex folding of the Pyhäsalmi VMS deposit (INMET-Finland) reconstructed in 3D

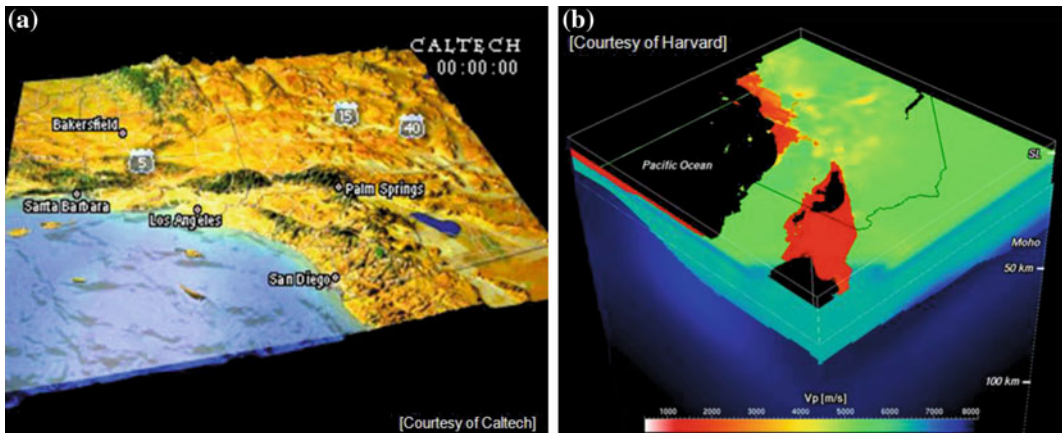
It aims at presenting a comprehensive overview of these new digital earth techniques and provides examples obtained on the gOcad™ software platform, which originated as an academic project in the 90's and is now a Paradigm product. This modelling topic meets the three phases of Knowledge Generation and Innovation technologies (2010), Knowledge Integration and Knowledge Distribution set out in the Communication Strategy and aims to direct, record and analyses the consequences for the future in mineral exploration (Critical raw materials for the EU, 2010).

## 4.2 Introduction to 3D Geomodelling

Geomodelling is a term coined in the 90's to refer to computer processes used to build 3D models of the real-world using geo-located data (Mallet 2002). These techniques have been extensively used in the geosciences for modelling underground reservoirs, ore bodies, aquifers, and natural hazards (Fig. 4.2). The different basic notions involved in geomodelling will be explained in the following.

### 4.2.1 Notions of Geometry, Topology and Properties

Modelling deep geological structures is difficult because geologists face a lack of information. The subsurface is generally sampled at irregular locations (borehole, outcrop sampling), and interpreted through maps and cross-sections or indirectly measured with geophysical tools (seismic data, potential fields). As a result, the geometry and the topology (i.e. spatial relationship and connection between geological structures) of the underlying geological objects are unknown: the connections between geological objects must be determined (and may change) during the geomodel building process. Depending on how geologists interpret connection between faults, a given geological structure can be split in many different structural blocks (Fig. 4.3c). Measuring this complexity is a challenging problem for which several authors have suggested some quantitative approaches (Pellerin et al. 2013). This topological uncertainty is a specific difficulty of geomodelling, which is seldomly addressed in classical computer-aided-design (CAD) approaches.



**Fig. 4.2** Geological (a) and velocity (b) geo-models built using gOcad of the Los Angeles basin. This model has been used by the SCEC Community Velocity Model—Harvard (CVM-H) for building a velocity model of the

crust and upper mantle structure in southern California for exploration purposes and seismic risk analyses (After Tape et al. 2009; Plesch et al. 2009)



**Fig. 4.3** Classical constructive solid geometry and parametric surfaces can be used to model manufactured objects (a) and (b) but are generally not used to represent

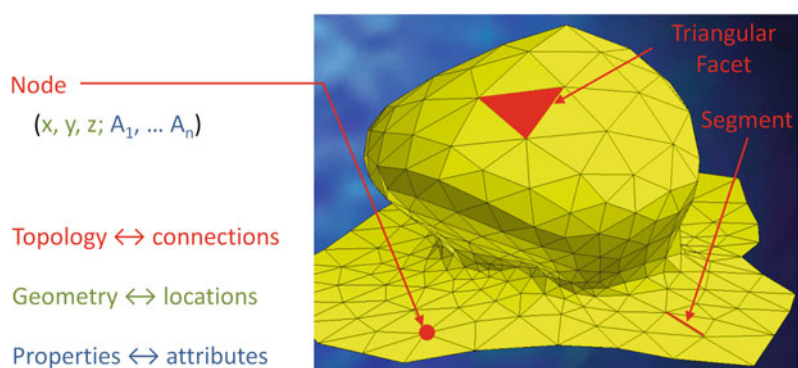
geological structures such as a circular graben (c). 3D models from the Grabcad library (<https://grabcad.com/library>) ((a) and (b)) and from Total/GocadConsortium (c)

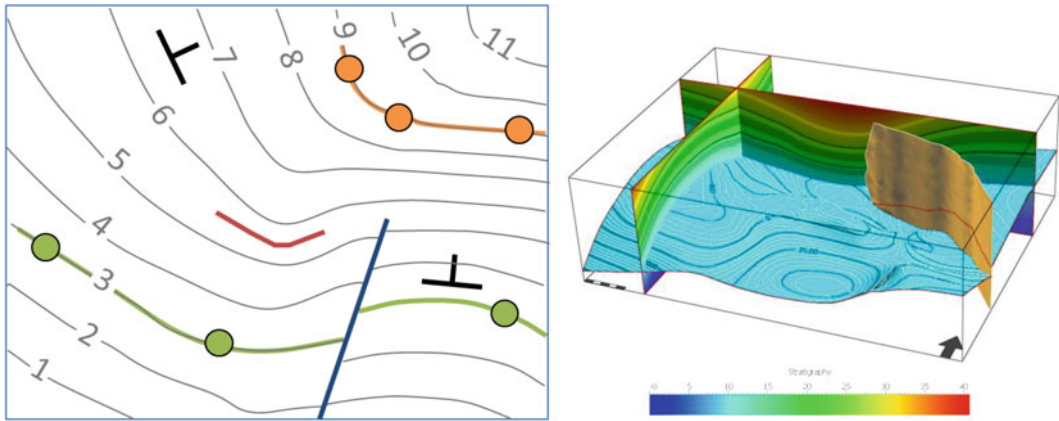
Classical computer aided design methods are based on parametric surfaces such as Bézier, Splines, NURBS, etc. for representing objects (Fig. 4.3a, b). They are easy to use and can fit sample points just accounting for numerical constraints in the parametric representation. They are well suited for representing regular surfaces such as folds (Sprague and de Kemp 2005), but raise difficulties to handle discontinuities induced by faults (Fig. 4.3c). In CAD systems, object shapes (car, plane, and building) are conceived by engineers. In geosciences shapes of geological structures are not known and must be assumed and interpolated in space from partial and scarce information. This makes all the difference between engineering and geoscience, and explains why CAD systems are seldomly used in geoscience applications.

Most geomodelling softwares provide tools for interpolating object shape from drill hole or

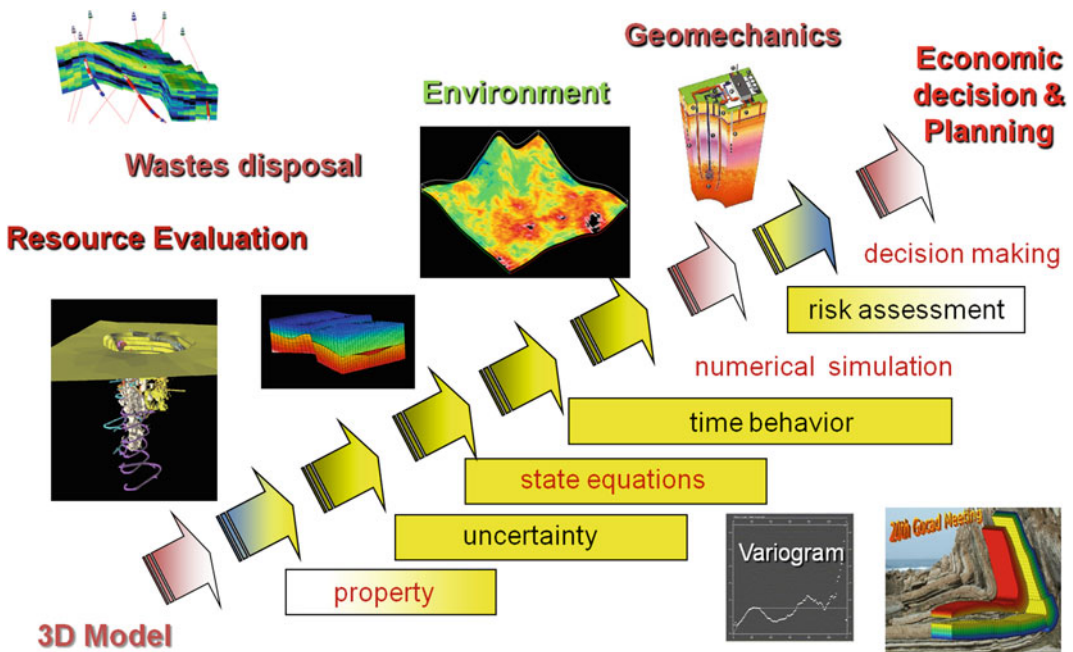
outcrop data. Beyond simple 3D digital elevation models, which are hardly applicable outside shallow or unfaulted domains, most geomodelers use a discrete representation of objects made of points set linked by segments (curves) and triangular elements (surfaces) (Fig. 4.4). The final surface is obtained by optimizing the spatial positions of nodes by best fitting sampled points, minimizing surface curvature and honoring other geometrical criteria such as fault contacts, etc. In the gOcad software, this method is referred as Discrete Smooth Interpolation (DSI) (Mallet 2002). This type of method is very flexible and can virtually honor all sorts of complicated geological structures (Fig. 4.5). The resulting models may be used to address several types of problems such as subsurface visualization, modelling of physical problems, resource and reserves estimation, etc. (Fig. 4.6).

**Fig. 4.4** Complex geomodels are decomposed into simpler connected elements (triangles, segments, vertices) (courtesy of Mallet 2002)





**Fig. 4.5** Implicit representation of a conformable stratigraphy. Concepts (*left*) and practice (*right*)



**Fig. 4.6** Various steps illustrating a geomodelling workflow

Other technologies are based on an implicit representation of the surfaces. These implicit surfaces are described by specifying locations in 3D through which the surface should pass, eventually defining the local slopes (gradient) and also identifying locations that are interior or exterior to the surface (Turk and O’Brien 2002). A 3D implicit function, generally defined at the nodes of a tetrahedral or hexahedral grid, is

created from these constraints using a variational scattered data interpolation approach, and the iso-surface of this function describes the surface. Several methods have been investigated to build the 3D implicit function, radial function such as in Leapfrog Geo (2013), potential fields in the Geomodeler (2012), discrete representation in gOcad™, a.o.. An example of implicit surface modelling based on a tetrahedral grid is given in

Fig. 4.5. Geostatistical tools or discrete interpolation can be used to run the computations, see discussion in Caumon et al. (2013b). One of the major benefits of these methods is that they can directly represent several conformable surfaces and remove the need for projections from data to surfaces. Therefore, they allow users to build 3D models more efficiently and in a more systematic manner. Implicit surface modelling is now becoming available in commercial software such as 3D Geomodeler, SKUA-gOcad and Leapfrog.

## 4.2.2 Geomodelling Concepts

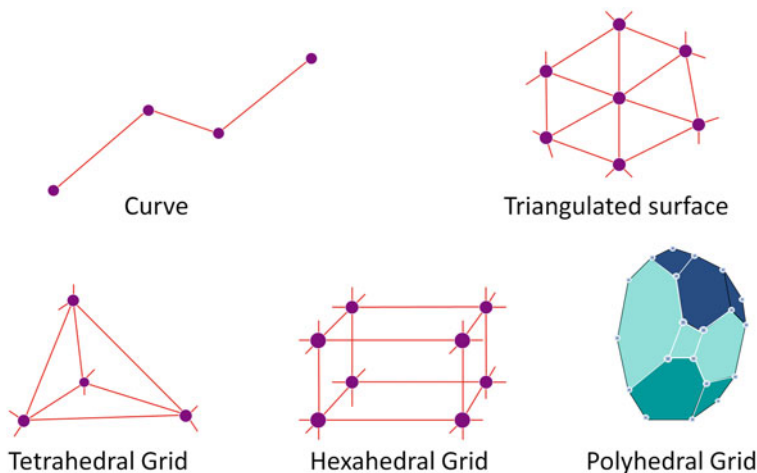
“Geomodelling consists of a set of mathematical methods and computer packages used to model the *topology*, *geometry* and *physical properties* of geological objects while taking into account any type of data related to these objects also called ‘Geo-Objects’”(Mallet 2002). Thus, 3D geomodelling is a computer method for modelling and visualizing geological structures in three spatial dimensions.

### 4.2.2.1 Basic Geometrical Elements of Geomodelling (Micro-Topology)

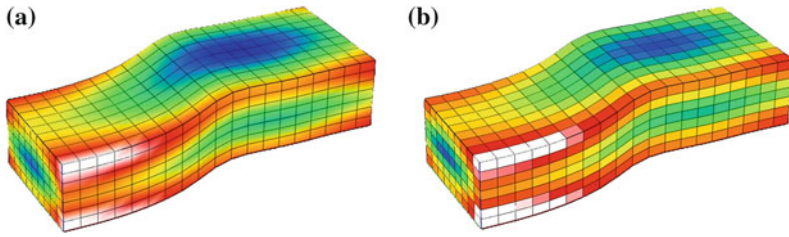
Philip II, king of Macedon (382–336 BC) applied his famous strategy “*divide and conquer*” to gain

power on the Greek city-states. As many smaller opponents are easier to manage than one large, this strategy can also be applied for mastering complex geo-objects by splitting them into several simpler elements as illustrated in Fig. 4.7. The basic simple elements are:

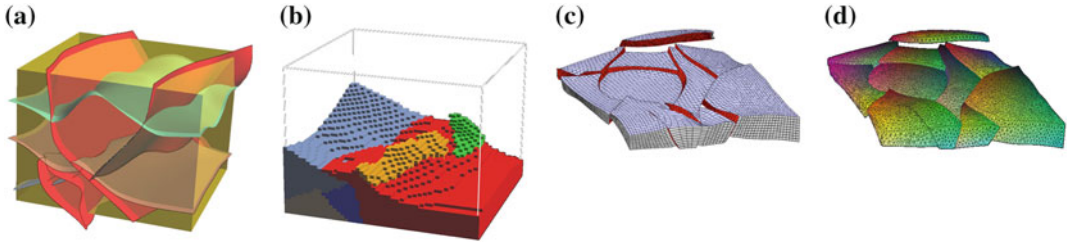
- *Points*: Sample locations defined by their coordinates X, Y, Z.
- *Curves*: Sets of points linked together by segments. A curve corresponding to a geological object may consist of several connected components, e.g. several contours or map traces (Fig. 4.8).
- *Triangles*: Three points are linked to form an elementary triangle; a set of adjacent triangles form a triangular surface (sometimes termed *TSurf*). As in the case of curves, a geological surface may have several connected components, for instance, when it has been cut by faults or unconformities (Caumon et al. 2009).
- *Tetrahedron*: Four points linked together delineate an elementary volume called a *Tetrahedron*. A set of tetrahedra forms an unstructured grid representing a volume in space. Such tetrahedral meshes are a classical support in the finite element method used to solve partial differential equations governing thermal, hydrodynamic and mechanical processes.



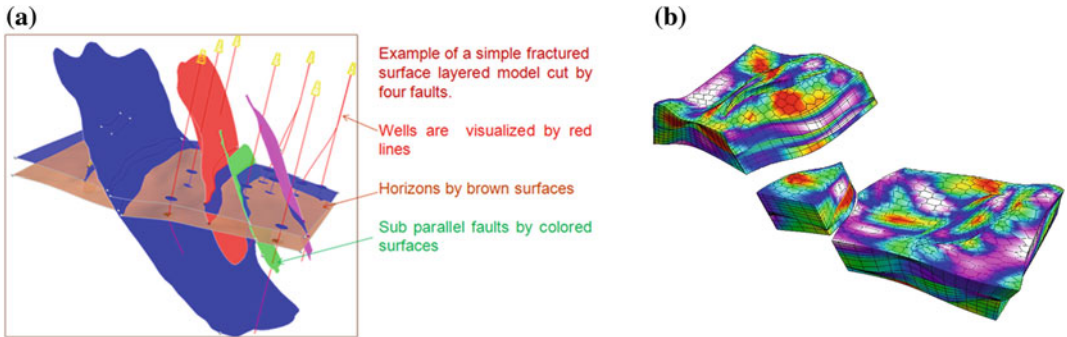
**Fig. 4.7** Basic elements used to build discrete geo-objects. The topology is the set of connections or links between nodes



**Fig. 4.8** Grid properties are stored at (a) the node location or at (b) the centre of cells



**Fig. 4.9** a Surface models. b Regular rectangular grid model (sugar box or Voxel). c Regular deformed cells (SGrid = Stratigraphic Grid). d Tetrahedral cells (unstructured grids)



**Fig. 4.10** a Faulted Surface Model (left). b Complex corner point polyhedral grids on which a continuous property is painted

- **Rectangular prisms (or Voxels):** A cube may be deformed so as to form an elementary hexahedron cell; when the cells are all identical (same sizes) and adjacent together, they define a regular Cartesian Grid (Fig. 4.9b). Prisms may also be deformed to fit curvilinear stratigraphic formations. These volumetric grids, referred as *SGrid* (Fig. 4.9c), are also commonly used to compute physical phenomena with numerical techniques.
- **Polyhedral cells:** Irregular cells whose juxtaposition forms unstructured grids (Fig. 4.10b).

**4.2.2.2 Notion of Topology**

The shape defines the geometry of an object that changes when deforming the objects during, for instance, a tectonic event, but there is another important notion used in geomodelling, this is the *topology* of the objects. This notion relates to

the object properties that are preserved under continuous transformations (including *stretching* and *bending*, but not tearing). In simpler terms, topology relates to the *connections and relative layout* between objects. For instance, a faulted surface can be made of several sub-surfaces (Fig. 4.10a) related to each other by other surfaces (the faults). As long as the number and faults connectivity remains constant in this model, the number of fault blocks in the horizon does not change, hence the topology remains constant.

A particular challenge in geomodelling is to efficiently interleave topological and geometrical operations. Geometrical operations imply being able to interpolate the shape (*geometry*) of geological objects from the available information (drill holes, geophysical interpretations, cross-sections, mining gallery, geophysical surveys, etc.). Topological operations basically amount to cutting surfaces or volumes to reflect the effect of faults, erosion, etc. Because such cutting operations are sometimes difficult to revert, it can be useful for flexible model updating purposes to replace topological operations by clipping operations performed by the graphics card. This is commonly done by most packages and is very useful for visualization and model prototyping purposes. However, in most model-related decisions, quantitative modelling is involved (e.g., flow simulations or mechanical computations). In that case, the model topology must generally be strictly honored in the representation and calls for robust topological operators and conformable meshing tools. Few geomodelling packages have this capability because limited computer numerical accuracy calls for delicate computational geometry algorithms.

#### 4.2.2.3 Notion of Properties

Quantitative modelling needs to process qualitative (e.g. rock types, alteration types) and quantitative properties (e.g. grade, thickness). In discrete models, properties or attributes are stored at the node location (Figs. 4.4 and 4.7) or at the centre of cells (Fig. 4.8). The cell-centered technique is the simplest as it represents the property values constant in the elementary cell

(see Fig. 4.8b). On the contrary, when properties are stored at the cell corners, it is necessary to interpolate the attribute within the cell. In general, linear interpolation between nodes is generally used and non-linear variations of the physical parameters are represented through local mesh refinement, leading to a smooth visualization of continuous properties (Fig. 4.10b). Higher-order interpolates could be used in principle, but in practice only when the physical processes are locally highly nonlinear such as in wave propagation.

#### 4.2.2.4 Notion of Regions

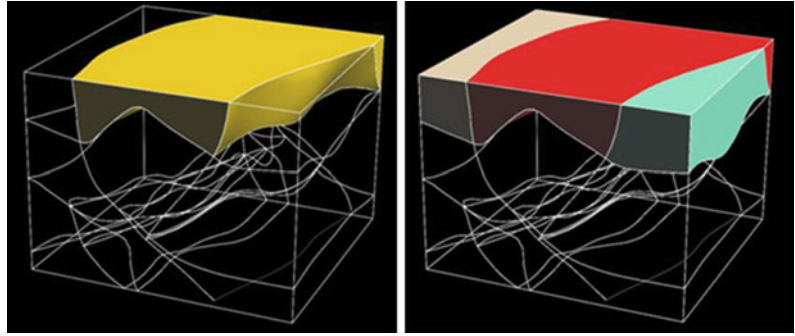
In geosciences, it is important to be able to manipulate the notion of rock type (or geological facies). More generally, the concept of region is very useful to consider object's subsets for processing and querying tasks. In quantitative geology, regions are often represented by a binary indicator, whereby a point or cell belongs to a region if its indicator value is equal to 1 and outside the region if the indicator is equal to 0. This binary technology is used in gOcad to facilitate spatial queries<sup>1</sup> in its 3D GIS plug-in developed by Apel (2006) and commercialized by Mira Geosciences. GIS does not in general use regions to define queries, they directly apply binary overlay principles when combining spatial objects; however, they are often limited to 2D.

Regions may be defined according to various criteria, which can be *geometric* (above, nearby a surface), or defined using a *property* (grade greater than a cut-off), or using an *indicator* (rock type). Several logical operations are available to manipulate regions (e.g. union, intersection, complimentary). The regions can be *static* when defined once by a condition and stored in a string of bits, or *dynamic* when the region is continuously updated when the model geometry or values change. Figure 4.11 gives example of regions delimited by surfaces on a structured regular grid. This region concept is simple but extraordinary well adapted to geosciences applications. They can be used to build 3D geological maps, an innovative technology existing in research

<sup>1</sup>Isatis uses a similar technology.



**Fig. 4.11** Geological rock types are represented by regions delimited by surfaces



laboratory (see the BGS website 2014). Some 3D map of England are currently done successfully and offer to the public by the BGS, British Geological Survey, the Geological Survey of Denmark (on cell phone), and at the Canadian Geological Survey. They are using regular triangulated surfaces and grids as well as regions to represent and query 3D geological structures (Fig. 4.12).

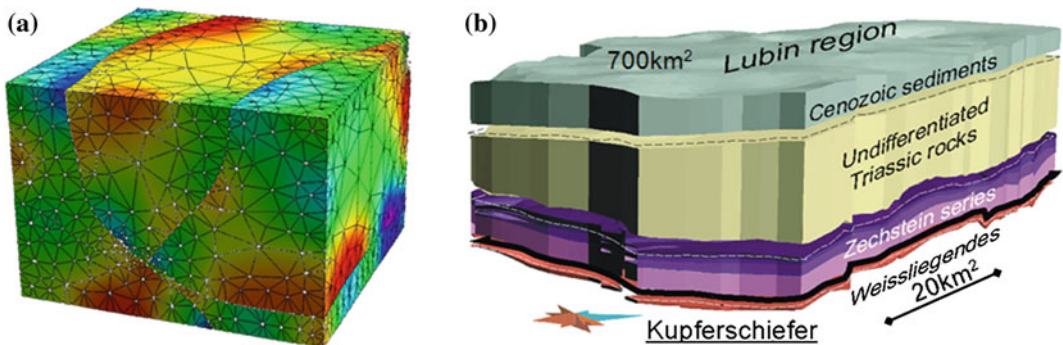
**4.2.2.5 Representing Volumes**

Several volume representations can be used to model 3D objects, see Figs. 4.9 and 4.11 (Caumon et al. 2004):

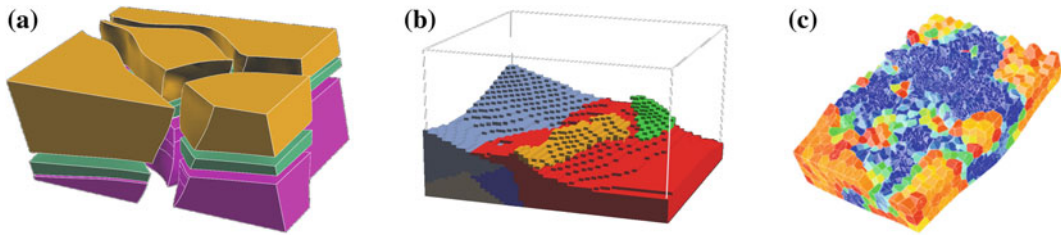
- *Closed surfaces* for delimitating the boundary of the volume (called *Boundary Representations or Sealed Geological Models*) (Figs. 4.9a and 4.13a). Geological surfaces corresponding to different geo-objects, must be glued together to form sealed regions. Ensuring the sealing of

the contacts between the surfaces (i.e. a surface model without “holes”) is one of the main issues when using this representation.

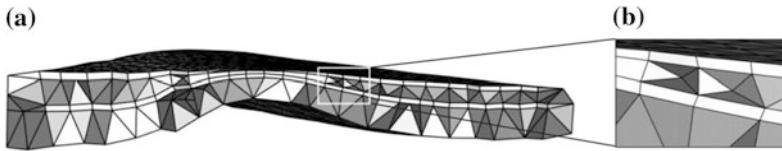
- *Regular rectangular cells*, Sugar box or *Voxel* (Figs. 4.9b and 4.13b). Each cell is within or without the defined regions. This method is easy to use, but the rock types and regions limits are irregular and approximated with stair-steps (aliasing effect). Precision depends on the cell size. Huge grids are generally needed to get acceptable accuracy.
- *Regular deformed cells* (*Sgrid* = stratigraphic grids) (Fig. 4.9c). It derives from the previous regular rectangular cells method, but the grid is deformed according to various layering styles corresponding to different deposition environments (e.g. proportional to a top and bottom horizon, eroded). They are well adapted to model sedimentary structures, or vein type deposits, and have become the standard in the oil and gas industry to



**Fig. 4.12** a Unstructured grid made of tetrahedral elements. b 3D geo-model of the Kupferschiefer Foresuedic belt around the Lubin region (Poland), famous for its copper deposits (courtesy of CUPRUM and University de Lorraine)



**Fig. 4.13** a Boundary model. b Cellular model (Voxel grid). c Hybrid grids



**Fig. 4.14** a Conformal hybrid grid consisting of tetrahedra, triangular prisms and pyramids; with b details showing a perfect fitting with the horizons (from Pellerin et al. 2012)

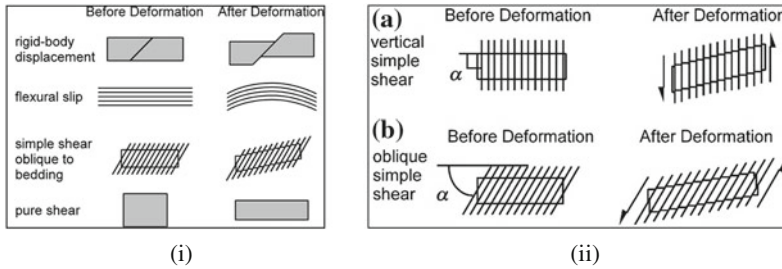
simulate flow in reservoirs. In complex faulted cases, the generation of these grids can be extremely difficult and calls for compromise between geological and numerical accuracy by using stair-step approximations. Over the recent years, improvements in implicit methods have significantly enhanced the robustness of creation of these grids (e.g. Gringarten et al. 2008). Notably, these grids are suitable for local grid refinement, whereby locally high-resolution meshes are embedded into coarser meshes.

- *Tetrahedral cells* of various sizes (*tetrahedral grids* i.e. grids using tetrahedral meshes, also called *unstructured grids*) (Fig. 4.12a). This is the most adapted method to model complex faulted geological objects. The main advantages are that the size cells can be smoothly adapted to honor local complexity. They are extensively used in mechanics and civil engineering because they are suitable to the finite element method. However, fully automatic conforming tetrahedral mesh generation is still a matter of research because of conflicting requirements between accuracy, element shapes and numbers (Fig. 4.14) (Caumon et al. 2005; Pellerin et al. 2012). As a result, tetrahedral meshes are not so commonly used in geosciences.

- *Mixed polyhedra* (hybrid grids) aim at combining the merits of hexahedral and tetrahedral grids in terms of number of elements, numerical properties and geological accuracy. This is an active research area (Pellerin et al. 2012) with important possible consequences in coupled transport, hydraulic, geomechanical and chemical (THMC) models<sup>2</sup> of geological processes.

Regular block grids are generally used in the mining industry because of their simplicity at the exploitation stages. However, in complex faulted ore bodies, or when the selectivity of mining blocks is an issue at the exploitation stage, regular blocks are not enough accurate and tetrahedral grids should be more adapted (Fig. 4.12a), especially for rock mechanics and civil engineering studies. This remains an issue because most of geostatistical packages are not available on unstructured grids (the same holds for fluid flow modelers in oil and gas exploration). However, ongoing and future progresses in up-scaling and gridding technologies are expected to

<sup>2</sup>Those models couple the heat transport (T), and the hydraulic (H)/geomechanical (M) behavior as well as chemical processes (C). They are referred in the literature as THMC models.



**Fig. 4.15** i Various basics restoration kinematic models; ii Simple shear oblique to bedding. a Vertical simple shear. b Oblique simple shear (after Groshong 2006)

make unstructured grids a major element of future earth modelling. In particular, unstructured grids are the most convincing support to accurately model coupled THMC processes through geological time in faulted areas (e.g. Nick and Matthäi 2011).

kinematic models (Groshong 2006) are necessary to reproduce a pertinent geological deformation history or deformation style. Several elementary deformation style models (kinematics models) are usually investigated including: *rigid-body displacement*, *flexural slip*, *simple shear* and *pure shear* (Fig. 4.15).

### 4.3 Introducing the 4D Modelling

The past two decades have seen a rapid development in structural restoration as a key tool to identify favorable target, source and host rock formations, to reconstruct fluid migration in oil and gas surveys and to predict faults and fracturing in the rock mass.

#### 4.3.1 Restorable and Non-Restorable Models

A restorable model can be unfolded and unformed to its original pre-deformation geometry with a perfect or near-perfect fit of all its segments. Its geometry is internally and topologically consistent. A non-restorable structure is topologically impossible and therefore is geologically not possible (Dahlstrom 1969). Chamberlin (1910) was a pioneer in performing a restoration of geological cross sections using the surface conservation principle (keeping areas constant). Later, this concept has been expanded to constant volumes by Dahlstrom (1969). However, time plays a fundamental role in the restoration method, and

#### 4.3.2 Deformation Modes

The *rigid-body displacement* (or *block rigid deformation*) is the simplest method, which restores the un-deformed shape by translations and rotations of elementary blocks until they fit together.

The *flexural slip* involves slip along bedding planes or along surfaces of foliation keeping the individual strata thickness constant (unless otherwise specified) and the resultant folds being parallel. It preserves the area of the structures to be restored, their lengths and thicknesses in a vertical plane.

If the restored structure is isopach, the preservation of both thickness and length results in area conservation. If the thickness varies, the strict preservation of bed thickness and bed length may lead to area changes (Moretti 2008).

*Simple shear* is produced by slip on closely spaced parallel planes with no parallel or perpendicular to the slip planes length or thickness changes. Simple shear parallel to bedding is the mechanism of *flexural slip*. Simple shear that is oblique to bedding is a kinematic model that causes *bed length* and *bed thickness changes*. Simple shear methods preserve distances in the

shear direction, but length and thickness are not kept constant, consequently the area is not preserved. *Pure shear* is an area-constant shape change for which the shortening in one direction is exactly balanced by orthogonal extension (Groshong 2006). The *Flexural slip* and *simple shear* methods are available in the restoration module known as KINE3D-2 of the geomechanical software gOcad (Moretti 2008). Both methods have been used in a first approximation for the restoration of the Kupferschiefer case-study (Mejia and Royer 2012; Mejia et al. 2013). Block rigid deformation, simple and pure shear, and geomechanical modelling are implemented both in 3DMove (Midland Valley 2012) and gOcad.

### 4.3.3 Unfolding and Unfaulting

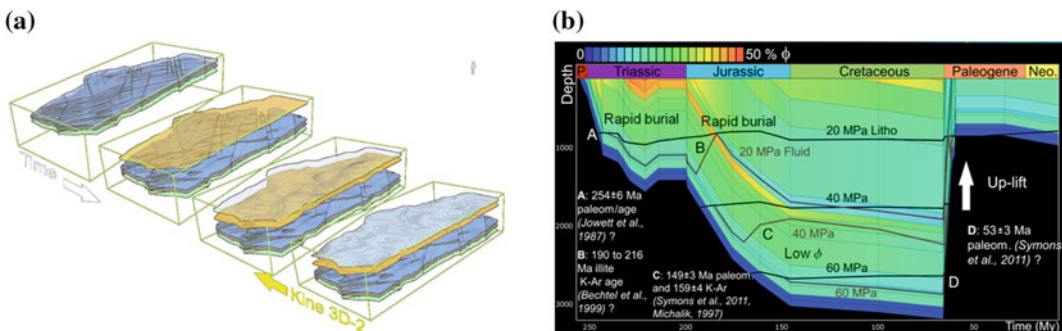
Removing the effect of folding and faulting generates a different restored geometry depending on the method used. For the simple shear case, the restored area is less than or equal to the original surface, and all geometric elements within the structure are shrunk by the same ratio. The use of this deformation mode for restoring competent beds in compression areas remains highly questionable in 3D and in 2D since the horizon area is not preserved and, when more than one layer is restored, the thicknesses are not preserved (Moretti 2008). Simple shear is commonly used for restoring surfaces of granulated materials,

poorly consolidated sediments, extensive domains affected by listric faults, and in shear zones. By contrast, the flexural slip method preserves the areas and lengths, so its results are sometimes more realistic, depending on if the strain is non-coaxial to the structure. In the Kine3D-2 restoration module, this method uses a global parameterization that preserves the lengths and areas of the horizons if the surface is developable (i.e. a surface that can be flattened onto a plane without distortion) (Mallet 2002). If the surface is not developable (for instance domes, diapirs), the algorithm searches the best solution in a least squares sense. For faulted surfaces, an optimization method that closes the gap where the surface was cut is applied for searching the best fit.

In the case of sediment-hosted ore deposits such as the Kupferschiefer deposits in the Foresudetic basin (Fig. 4.16), the restoration procedure can be used to identify mineralizing fluids pathways and the locations of economic mineral resources. This is usually done using 3D reconstruction and restoration tools considering geometric or geomechanical constraints (Rouby et al. 2000; Durand-Riard et al. 2010, 2011, 2013).

### 4.3.4 Discussion and Perspectives

Despite the extraordinary developments of geomodelling during the last decades, practical and



**Fig. 4.16** **a** A Kine 3D-2 reconstruction of the burial history of the Kupferschiefer deposits in the Lubin region which is coupled with the pressure, temperature, organic matter maturation and hydraulic fracturing, calculated by

PetroMod. **b** Mineralization events are suggested at 250, 149 and 55 Ma during tectono-regional events observed during the geological history of the basin (After Mejia et al. 2012; Mejia and Royer 2012)

theoretical challenges remain. Standard workflows have been introduced by software companies to streamline geomodelling tasks and increase productivity (e.g. fault framework modelling, ore body modelling, gridding, petrophysical modelling). Robustness has made significant improvements and now makes it possible to improve automation and run multiple scenarios. However, automation can never be perfect and often calls for essential quality control (QC) steps after the main workflow steps. To facilitate model updating and uncertainty management, improvements are clearly needed in geomodelling workflows to further reduce these QC tasks and modelling effort once the initial controls have been made (Caumon et al. 2013b).

Another significant avenue for research is in the management of scales during geomodel construction. The dynamic regional modelling of ore concentration processes relies on large-scale, relatively coarse models, in which small-scale features have been conserved explicitly or homogenized. This calls for considering multiple scales during structural modelling itself, for instance by defining ways to automatically simplify fault networks.

Moreover, whereas geomodelling workflows are well adapted to sedimentary contexts, especially for oil and gas exploration, they still remain limited when applied to hard rock settings including igneous and metamorphic terranes. For the last decade, mineral resource modelling has gained momentum especially among Australian (the Australian Geological Survey offers now 3D mineral exploration maps on line, see AGS 2014) and Canadian (Caumon et al. 2006; Pouliot et al. 2008; Janssens-Coron et al. 2010) geoscientists. More recently, the ProMine project has explored the possibilities of 3D modelling in the European mining community.

4D modelling has been proved to be helpful in many exploration projects in the oil and gas sector in sedimentary rocks. It is still in its early stages when applied in mineral resources exploration in hard rocks. If restoration techniques can be applied with some success for understanding deformation phases of stratiform or sediment

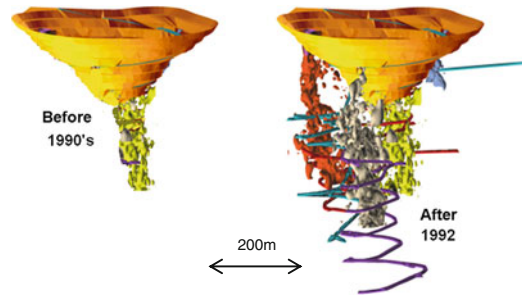
related ore deposits (Mejia et al. 2012, 2013; Mejia and Royer 2012) using similar techniques as those applied in oil and gas, they are still limited for understanding poly-folded hard rock settings and cryptic discontinuities (De Kemp and Jessell 2013). The main unknowns are: (i) measuring the role and extent of the subsequent deformation phases is difficult as only the final stages can be observed; (ii) the history of the deformations is generally subject to high uncertainty; (iii) modelling is subject to underlying hypotheses and results are uncertain and non unique; (iv) hard rock properties, especially for fractured rocks, are difficult to account for in mechanical models, a still active research topic. Nevertheless, 3D and 4D approaches provide significant knowledge and improvements in better understanding the geological background of the mineralization zones. There is a growing interest in many parts of the world, including Europe, in 4D geomodelling to assess mineral potential. Challenges for future developments in the 3D and 4D research geomodelling are: (i) a geological 3D model is never complete. It is continuously developed with the acquisition of new data and new ideas, and automatic procedures would be helpful in up-dating geomodels when new data are acquired; (ii) current 3D and 4D software enables 4D geological structural modelling, and can be used to make more than a single interpretation or model to support a range of alternative interpretations when knowledge of the geologic history is poorly constrained (de Kemp and Jessell 2013). Although, in case of more than two deformation phases, 4D modelling remains very difficult to apply, especially in hard rock settings. New breakthroughs are needed in this field, for instance, by better incorporating mechanical and hydraulic failure aspects in the restoration procedure. Most of current mechanical models are based either on block or elastic deformation behavior. The two aspect must be combined as major faults do not behave according to elasticity theory. Some results on this subject have been published (Laurent et al. 2012a, b).

### 4.3.5 3D Geomodels as a Mean to Extend the Life of a Mine

At the end of the ProMine project (2012), it is too early to identify examples in which 3D models lead to a major mineral discovery. So, a well-documented case study selected in the French Massif Central is presented here.

A 3D Model of a mine in Massif Central (France) has been built (Fig. 4.17). Before 1990, the mine was considered as a sub-vertical mineralized socket (yellow) exploited in an open-pit (orange). At a given depth of the open-pit, the exploitation of the deeper levels would have required the enlargement of the open pit and the extraction of a huge amount of waste rock. Given the high stripping ratio, it was considered as non-profitable, and the owner company decided to close the exploitation. Before closing, they integrated all the available drill hole assays from more than 1000 drill holes into a unique 3D model on gOcad, and used them to estimate the grade using the Discrete Smooth Interpolation (DSI) method (Mallet 2002).

To their surprise, the DSI method pointed out unknown sub-vertical mineralized sockets confirmed by additional drillings.<sup>3</sup> Given the huge in situ tonnage in place (about 6600 t U @ 0.56 % U) and the structure being open at depth, the company decided to sell the deposit to another company instead of closing the mine. This saves jobs and mining activity in the region and extended the life of mine by 10 years (this mine was among the most recent mines to be closed in France). The new company converted open-pit extraction into an underground mine exploited at >400 m depth (Fig. 4.17). This short success story demonstrates that: (i) there could still be mineral resources at depth even in mature mining districts (typically for U, French mines were mined to than 100–200 m depth); (ii) 3D modelling can extend the life of mature mines; (iii) innovative technologies can maintain and create jobs.



**Fig. 4.17** Geomodelling a mine in Massif Central (France). The mine was considered as a sub-vertical mineralized socket (yellow) exploited by open-pit (orange) (left). After integrating all the available drill holes and modelling the mineralized zone, two major mineralized structures (red and grey) were discovered (right). The mine was then exploited underground (galleries in blue and violet) an additional 10 years

## 4.4 Discussion

Various case studies related to mineral exploration or/and mining using different 3D and 4D geomodelling technologies have been investigated during the ProMine project. They demonstrate that new geomodelling methods and ore potential mapping tools can be used in mineral exploration 3D and 4D geomodelling technologies contribute in improving knowledge and understanding of the mineralized zones and geological setting. In ore exploration, they provide new ideas and methods for helping new discoveries. Since a decade, there is a growing interest in 4D modelling as a tool for investigating future availability of minerals in Europe (ETP SMR 2007). Beside this ideal picture, there is still a lot of hard work to explain the benefit of these new technologies to stakeholders, in order to make them fully accepted by the mining industry and to improve geomodelling technology applied to mineral resources. Improvements can be made on the technological point of view:

- Most of the 3D regional models in mining exploration are based on surface data, drill holes being available at the mine camp scale. It reflects more or less the subsurface geological knowledge at the moment when the model is built, assuming some hypotheses and

<sup>3</sup>Personal communication from P. Jamet, the mining geologist in charge of the project at this date.

containing a lot of uncertainty in terms of concepts. Of course, 3D models are never complete as they evolve as soon as new data are acquired. It is therefore important that 3D models include metadata describing location of available data, quality of data and assumed hypotheses. It also requires better compilation of available surface and subsurface data sources and interpretations in 3D geodatabases;

- As models evolve through time, it is important to benefit from simple procedures and technologies making data model updating as simple as possible, such as those used in real time geosteering (Pelling et al. 2010) or using tetrahedral mesh such as in real-time updated modelling (Tertois and Mallet 2007). Present workflows are more or less linear making up-dating complicated and time consuming, especially in 4D. More research is needed in this field;
- Data quality is an important issue of geomodelling as well as uncertainty. Advanced modelling and visualization techniques must be investigated to quantify conceptual uncertainty, to visualize colors, textures, sounds and animation (see Viard et al. 2011) and to express uncertainty;
- Mineral resource exploration handles data coming from different sources such as drilling observations or measurements, sampling in galleries, chemical analyses, etc. (referred as *primary data*) or indirect measurements or modelling such as from geophysics (*secondary data*). These data are heterogeneous and need to be integrated on the same platform.

Improvements must be made in European infrastructures related to deep mineral resource exploration in order to benefit from new technologies. Partnerships between mining companies, software providers, public research institutes and geological surveys were made possible during the ProMine project where good talents from different areas and disciplines worked closely together as a team with common interests and not as isolated units. This approach must be strongly sustained and encouraged in the coming years before becoming a market-driven activity.

## 4.5 Conclusions

It is too early to state that 3D and 4D modelling of the ProMine project has led to a major mineral resources discovery. Nonetheless, we are convinced that it indirectly supported discoveries of new targets, confirming the add-on value of geomodelling to mineral exploration. Publication by industrial partners of discoveries based on 3D models would benefit the whole mining community, justifying a posteriori the initial public investment in the ProMine project. In Canada it is assumed that for one dollar invested from public money in similar 3D exploration programs, two and half dollars are collected indirectly through taxes.<sup>4</sup> In the case of an ore deposit discovery, the investment is multiplied by hundreds<sup>5</sup> (depending on the commodities) (Duke 2010, p. 6). European governments and Europe at large benefited by this project which made it possible to improve their mineral resources policy to stimulate future mining activities in Europe.

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<sup>4</sup>If a major exploration campaign is undertaken by the Geological Surveys on public funds, revealing new possible targets, mining industries generally invest in drilling programs for evaluating these new targets. This additional exploration works, even in case of no major new ore deposit discovery, generates revenues for the government from taxes paid by the companies when present in the country.

<sup>5</sup>According to Duke (2010), the Mining Association of Canada estimated that, from 2004 to 2008, revenues paid to Canadian governments from mining as royalties, corporate and individual income taxes averaged \$5.5 billion/year. Federal, provincial and territorial geological survey expenditures over the same period to promote exploration averaged \$80 million, or just 1.5 % of revenues.

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