Computer-aided quantitative subsurface mapping — examples of utilization

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Abstract. The present age of digital subsurface mapping is represented above all by quantitative maps based on regular grids. They are created on the basis of various input data: digitized contours, widely comprehended well data, 2D and 3D seismic, and qualitative geological maps. Scope and the data utilization and the applied methodology of processing are strictly dependent on the scale and purpose of a given map; for regional and detailed maps they are significantly different. However, irrespective of the map scale, correct models, reflecting probable subsurface variability, instead of the input data spatial distribution and applied estimation algorithm themselves, are conditioned by chances of integrating of all the mentioned types of data. These purposes can be achieved only through the application of the most flexible interpretive programs such as ZMAP–Plus or mapping modules of the Geographix system. High quality quantitative subsurface maps based on regular grids are nowadays used first of all in petroleum exploration and geothermal research. But development of such studies may contribute to creation of high-quality, interactive, subsurface models, available not only for owners of expensive professional software but also for all geoscientists interested in these topics.

Key words: *Subsurface mapping, grid, quantitative map, ZMAP–Plus*

Quantitative subsurface mapping consists of preparing maps in regional, semi-detailed and detailed scales, first of all for the needs of petroleum exploration and geothermal research. In this day and age of widespread digitization in petroleum exploration, maps of satisfactory quality can be obtained, in substance, only with application of computer interpretation systems including a good “mapping” module that quantitatively models the subsurface structure in the form of regular interpretation networks of the grid type or in the form of irregular network of triangles, so called TINs, the latter being frequent in GIS and more and more common in CAD–based systems. Regular grid-based models do not allow to model multiple surfaces and do not secure full fit between the data and the model, but they are standard in petroleum industry. Their basic advantages is their ability to predict Z–values in areas not controlled with data. They can be used for performing mathematical operations on models, which are necessary for all kinds of subsurface 3D modeling (and time-to-depth conversion).

Maps used for the petroleum exploration and geothermal research, irrespective of their scales must integrate different kinds of input data such as digitized archival maps, wellbore data (stratigraphy, results of geophysical well logging, results of laboratory tests), and results of 2D and 3D seismic interpretation. These data sets are often huge, exceeding a hundred thousand control points. Efficient processing and integration of such numerous and different data can be secured now by few programs, for example the ZMAP–Plus modeling and contouring software, a module of the UNIX workstations-based interpretation system from Landmark Graphics Corp. or PC–based Geographix system.

Basic methodology

The main stage of grid-based map preparation is the procedure of estimation of the regular numerical model, so called gridding. General idea of the regular grid and basic steps of its calculation are outlined in Fig. 1. Map input data usually are represented by irregularly distributed points (Fig.1A). They are superimposed with the regular grid composed of equally spaced nodes (Fig. 1B). The model is given constant geometry (Fig. 1B), i.e., mesh minimum (X_{min}, Y_{min}), maximum (X_{max}, Y_{max}) and distances between rows and columns of nodes, so called grid nodes increment (grid spacing). The next step is estimation of a Z–value in every grid node. It is done based on a selected sample of points falling in so called “neighbourhood” (Fig. 1C), which can be shaped by altering search parameters — number of selected points, maximal search distance, anisotropy and quantity of search sectors (for details see, e.g., Harbaugh et al., 1977; Davis, 1986; Kushnir & Yarus, 1992). Modern modeling programs, among them the ZMAP–Plus, allow to modify the search and estimation procedures by introducing faults (Zoraster, 1992; Beyer, 1993, 1994). Estimation is finished when Z–values are calculated at each grid node (Fig.1D). The results of that procedure are also strongly dependent on a mathematical formula used during estimation, i.e., the algorithm which has to be matched to the type of data used, map resolution and its purpose (for general review see e.g.: Davis 1986, Swan & Sandilands, 1996; Jones et al., 1986; Chambers et al., 2000a, b).

The last factor affecting map quality and functionality is properly selected density of grid. Theoretically, if we want to calculate a model that would perfectly match the input data, we should apply grid increment not larger than 1/2 of the distance between the closest control points. However, in practice such grid density gives unreasonable results — statistically perfect but geologically absurd and computationally inefficient (Fig. 2). On the other side, too coarse grid spacing allows to retain primary geological directions, but completely loses most local structures, thus drastically decreasing map precision. As we can see, the optimal density of grid is a kind of compromise between

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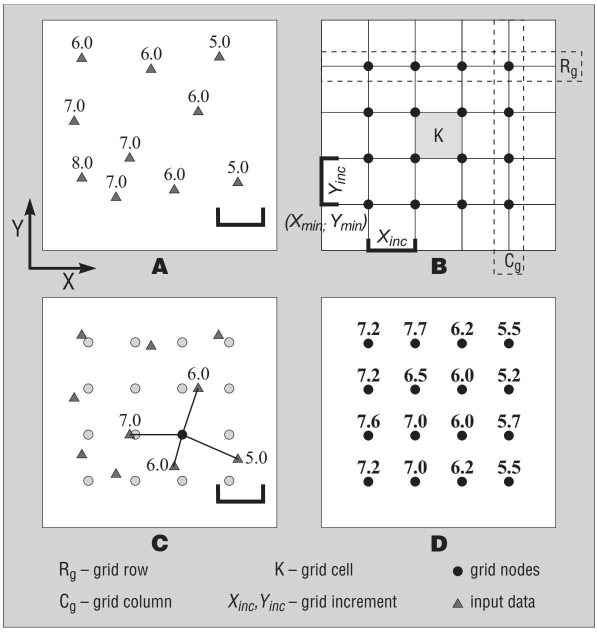

Fig. 1. Scheme of regular grid estimation (based on Davis 1986, modified); A) Irregularly spaced input data; B) Regular grid is superimposed onto the data; C) For each node Z–value is estimated based on data in the neighbourhood; D) Procedure is repeated until the last node is calculated

geology and statistical goodness of fit. Grid density has to be matched to map (model) scale and the user needs as it defines the final vertical and horizontal resolution of the model, i.e., height and diameter of the smallest structure to be depicted on the map.

Regional Maps (RMs)

Regional structural, thickness, reservoir–parameters variability maps and lithofacial maps, as well as models of amount of erosion, are used for sedimentary basin analysis, generation-potential modeling and evaluation of geothermal resources. In general, these are synthetic elaborations covering large areas, often comprising several geological units. Digitized, published and archival maps at the scales 1 : 1,000,000, 1 : 500,000 or 1 : 200,000 constitute most frequent source of data for regional models. Data obtained this way are generally characterized by high quality because they arise from considered geological interpretation. RMs that use data of this type often require local reinterpretation which takes into account new well data and interpretation of new seismic lines or sometimes incorporation of whole new materials in larger scales. Controlling of the above described RMs with wells and regional seismic may significantly improve their vertical resolution, which in case of the simplest RMs digitized from isolines only cannot be better than the contouring interval applied on a source map.

More rarely seismic RMs are based on seismic data interpretation (Kramarska et al., 2000; Papiernik et al., 2001). Accuracy of such elaborations is potentially the highest but they are limited by generally low availability of uniformly interpreted profiles gathered in one seismic project (Fig. 3).

RMs calculated directly from well data, for example thickness maps display relatively lowest quality. They can be considered rather reliable in areas of regular variations of thickness and well density. However, in case of non-uniform distribution of input data, resultant models often abound with “numerical structures” which are inconsistent with geological knowledge of the study area. Such artifacts can be removed from the maps only through good software which allows a geologist to reinterpret the map, store the reinterpretation results in the grid, and quantitatively assess the conformity between the generated model and the input data (Jones & Hamilton, 1992).

Fast data processing, which includes integration of digitized contours, well data, seismic data, tectonic faults and proper regard to qualitative information such as the extent of mapped sequences, is possible only with the use of the most advanced software. Among the few systems which fulfill, in essence, all the above requirements, there is the ZMAP–Plus which is equipped with special algorithms designed for efficient processing of great amounts of digitized contours (CTOG) and interpretation of 2D seismic (Line Gridding); the algorithms enable simultaneous control of the model with well data (treated as auxiliary data), profiles representing, e.g., hypsometry along the axes of linear structures or throws along fault traces, introduced to regional grids in simplified form of line that sharply separates fault sides. This program is also provided with an interactive editor that enables local reinterpretation of data or model. That function is particularly useful for correct imaging of near-fault zones (Jóźwiak & Papiernik,

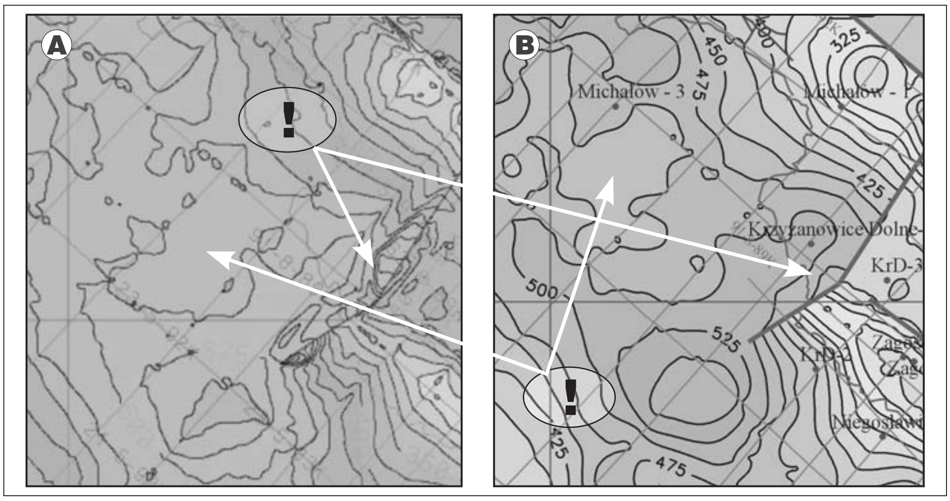

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Fig. 2. Possible pitfalls of modeling depending on grid density selection. Both maps were calculated with the use of the same computational procedures in ZMAP–Plus. A) Default (very dense) grid increment (50 × 50 m); B) Optimized grid increment (200 × 200 m) allowed to achieve geological reliability of the map and good statistical fit between input data and the grid

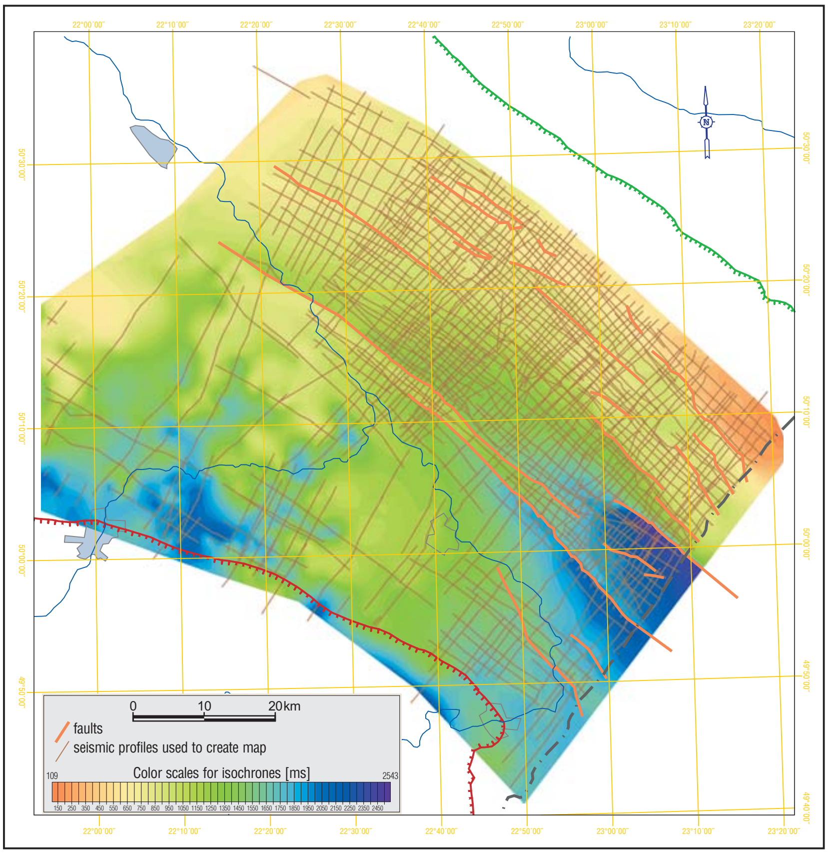

Fig. 3. An example of regional seismic map: "Seismic map of the time horizon at the top of Badenian evaporates". (Papiernik [In:] Peryt et al., 2001, simplified for publication purposes)

2003), as for well as for reinterpretation of the maps in areas where new wells were drilled (Fig. 4).

Wide possibilities of assessment of input data and model quality are very significant feature of the software under discussion. They allow to quickly locate and eliminate sources of error. Finally, it allows to get high-resolution basic models, which raise grounds for reliable multistage grid-based modeling such as hydrocarbon generation reconstruction (Maćkowski et al., [In:] Kotarba et al., 2000), calculation of hydrocarbon reserves in selected structures (Górecki et al., 2004) or estimation of geothermal resources in a geological unit (Górecki et al., 1995, 1999, 2003).

Similar editing possibility is revealed by mapping modules of the Geographix system that in studies conducted at the Department of Fossil Fuels is used mainly for solving geothermal problems. Possibility of easy exchange of data and grids between both programs mentioned above represents a great advantage.

At the Department of Fossil Fuels, AGH–University of Science and Technology (AGH–UST), Cracow, quantitative regional models have been implemented since the beginning of the nineties, starting from Carpathian models (Papiernik, 1995, 1996, 1997) through maps and atlases of the Mesozoic cover in the Polish Lowlands (Górecki et al., 1995, 1997, 1999, 1998 , 2002; Papiernik, 1998; Papiernik & Reicher, 1998) up to structural maps and thickness and lithofacies maps prepared in cooperation with the Polish Geological Institute (PGI) and petroleum industry (Papiernik et al., 2000; Papiernik [In:] Wagner et al., 2000).

Detailed maps

Grid-based detailed maps are most frequently constructed on the basis of 2D and 3D seismic interpretation results for relatively small areas, in the scales generally greater than 1 : 50,000. Thus, they must be characterized by high horizontal and vertical resolutions. Vertical resolutions for 2D seismic reach 5–10 m (or ms) and for 3D seismic maps can exceed 5 m (ms). It implies that they have to be based on much denser grids. Detailed seismic maps require also much more precise spatial interpolation of faults, including proper interpretation of courses, inclinations, throws and reconstruction of horizontal separation of their sides. All this causes that, despite of many similarities, methodology used for preparation of seismic maps is significantly different from the methodology required for regional maps.

Methodological problems related to construction of seismic maps have been solved at AGH–UST since the mid–1990s. In these studies special emphasis has been laid on quality assurance procedures which would enable identification of errors in seismic interpretation and optimization of grid density (Papiernik et al., 2001a, b, 2004; Papiernik, 2002).

Detailed seismic maps are most often used directly in petroleum exploration (e.g., Górecki et al., 2003). However, they can be used also for more advanced applications as for example for creation of geometrical frameworks for three-dimensional models of geological units (Górecki et al., 2002). An example of such a solution can be the 3D structural and facial model of the southern part of the Miechów Through, created and currently developed in programs ZMAP–Plus and StrataModel (Fig. 5).

Future applications

At present, grid-based maps are a very popular and accurate way of spatial restoration and prediction of subsurface "geovariability". They are employed in subsurface cartographic projects of both the regional and local scales. The most obvious field of grid maps usage is petroleum and geothermal exploration, but they can be very useful in exploration of water-filled structures for underground gas storage or indicating zones suitable for toxic waste storage.

Grid-based modeling and contouring programs, represented by the above described software, are created first of all to effectively estimate accurate spatial models of subsurface geology. Basic models of all scales, obtained as a result of gridding procedure, can be used in many different ways — as input for more sophisticated modeling (e.g., migration and accumulation), to create printouts or to construct a framework for a 3D interactive model of geology which will be valuable only when it is based on high quality grids, similar to those obtained from ZMAP–Plus. Their weaker side is represented by visualization that is not as perfect as in the CAD–based systems, e.g., GoCAD (Mal-

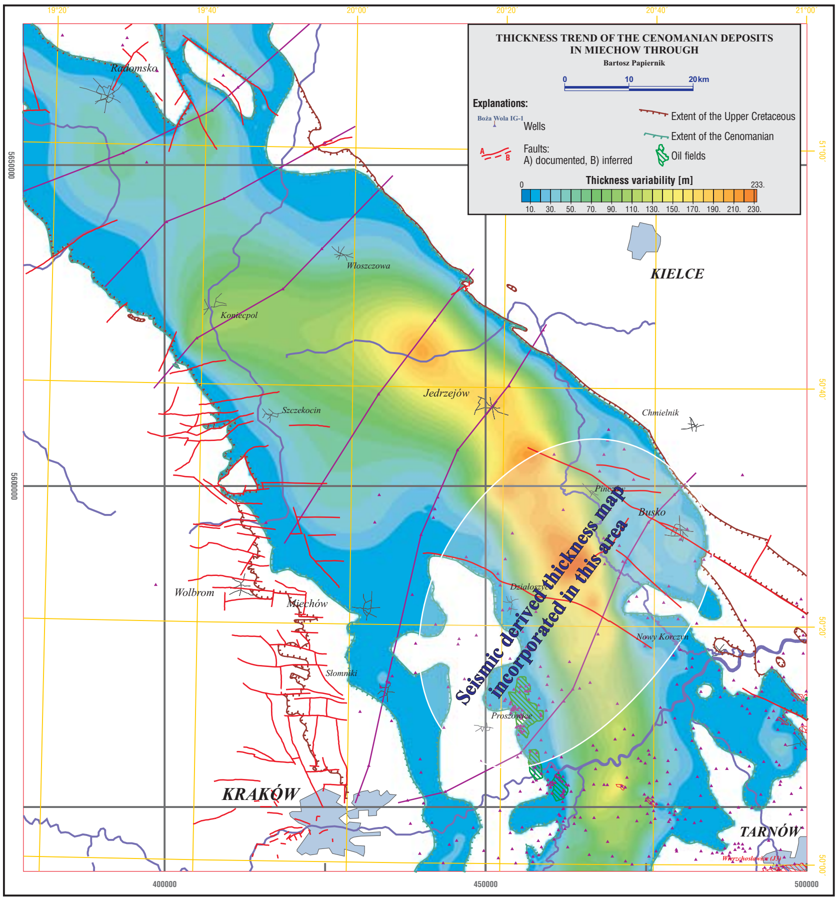

Fig. 4. An example of an interpretative regional map integrating well data, seismic-derived data and qualitative geological information — map of the Cenomanian thickness. (after Papiernik [In:] Górecki et al., 2002, simplified for publication purposes)

let, 2002), or in visualizing modules of GIS programs (Małolepszy, 2003). But it seems that it will not be a problem to convert high-quality Landmark's grids to a format readable by any program offering high-resolution graphics and opportunity of easy use and editing of pictures, containing only the graphic information desired by user. Such a kind of solution for GIS data and maps is the widely known ArcView program. To reach such an aim in Polish conditions, probably the best solution would be integration of technical abilities and skills of scientists from UST–AGH, PGI, petroleum industry and other institutions dealing with subsurface cartography.

In some countries geological surveys elaborated sets of detailed digital subsurface maps depicting the most important surfaces, e.g., the Danish Geological Survey GEUS [1] elaborated a series of ZMAP–Plus-based subsurface maps. In Poland, such semi-detailed maps (e.g., 1 : 200,000 scale) could allow to unify and verify archival maps, combine them with modern seismic and well data, and finally they would provide the the best way to verify location and stratigraphy of wells collected in the Central Geological Archive database. Such a step could be the first one in modern and synergic development of digital subsurface cartography in Poland.

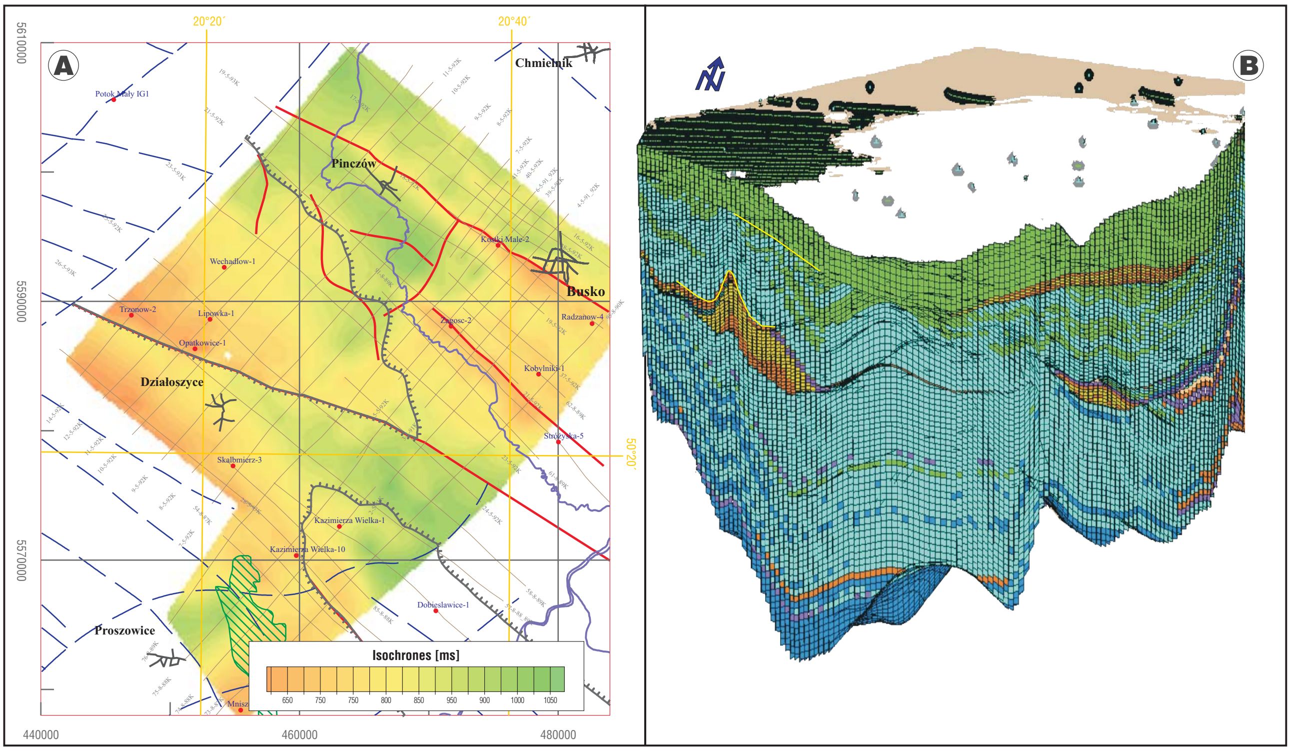

Fig. 5. Detailed seismic model and its application for construction of geometric framework of 3D facial model. A) Detailed seismic map of the Cenomanian top in southern part of the Miechów Through (after Papiernik [In:] Górecki et al., 2002, simplified for publication purposes); B) 3D model comprising among others the surface of the Cenomanian top (after Łapinkiewicz [In:] Górecki et al., 2002, simplified for publication purposes)

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