Geological Quarterly, 2000, **44** (1):101 –108

# A compacted thickness correction in the palaeotectonic reconstruction

Michał STEFANIUK and Tomasz MAĆKOWSKI

Stefaniuk M. and Maćkowski T. (2000) — A compacted thickness correction in the palaeotectonic reconstruction. Geol. Quart., **44** (1): 101–108. Warszawa.

The thickness correction resulting from gravitational compaction is one of the significant parameters in the reproduction of the palaeothickness of sedimentary complexes in palaeotectonic reconstructions. Changes of sediment thickness during burial caused by compaction are taken into account in the calculation of a thickness correction. The reconstruction of the layer thickness may be based on a quantitative interpretation of absolute porosity changes. Here, an original method of introducing a compacted thickness correction is developed in which two components, a syn-genetic one and a post-genetic one, are separated and the continuous process of compaction during the burial of sediments is taken into account. The proposed approach is simple; however, a detailed determination of the palaeothickness of the layers during their burial involves computer calculations. In this paper the method is described and the computation algorithm is given. Some results of modelling and computations carried out for real data from the eastern part of the Polish Carpathians and Pomeranian Swell are also given. Examples illustrate changes in the recent thickness of layers after introducing the compaction correction.

*Michał Stefaniuk, Department of General and Mathematical Geology, University of Mining and Metallurgy, PL-30-059 Kraków, al. Mickiewicza 30; e-mail: stefan@geolog.geol.agh.edu.pl; Tomasz Maćkowski, Department of Fossil Fuels, University of Mining and Metallurgy, PL-30-059 Kraków, al. Mickiewicza 30; e-mail: mackowsk@uci.agh.edu.pl* *(received: March 4, 1999; accepted: November 3, 1999).*

Key words: palaeotectonic reconstruction, compaction, decompaction.

## INTRODUCTION

The analysis of the thickness of sedimentary complexes plays a significant role in the reconstruction of the subsidence history of a sedimentary basin. Throughout the basin's evolution, the thickness of sediments changes as a result of gravitational compaction and erosion. This is taken into account in the palaeothickness reconstruction by introducing a compaction correction and an erosion correction. In this paper we deal with the computation of a compacted thickness correction and thickness changes during the geological history of sedimentary complexes.

A measure of the compaction of sediments is the increase of bulk density and decrease of total porosity. In the case of a one-dimensional compaction model, the changes in thickness, bulk density, and total porosity are related by the so-called reduction coefficient (Nestorov, 1965; Baldwin, 1971):

$$\beta = \frac{m_r}{m_p} = \frac{\gamma_r}{\gamma_r} = \frac{1-\varphi_p}{1-\varphi_r} \quad [1]$$

where: $m_r$, $m_p$ — recent and primary stratigraphic thickness of a layer, respectively; $\gamma_r$, $\gamma_p$ — recent and primary density of sediments, respectively; $\varphi_r$, $\varphi_p$ — recent and primary total porosity of sediments, respectively.

The above given relations can be written in a generalised form for two arbitrary moments of geological time, $t_1$ and $t_2$ :

$$\beta = \frac{m_{t2}}{m_{t1}} = \frac{\gamma_{t1}}{g_{t2}} = \frac{1-\varphi_{t1}}{1-\varphi_{t2}} \quad [2]$$

where: $t_1$ and $t_2$ denote earlier and later geological time, respectively.

The compaction of sediments is determined mainly by the geostatic pressure (more exactly, by its exceeding of the pore pressure) and the time of its action (Rieke and Chilingarian, 1974). Both factors depend on the maximum depth of sediment burial to which the empirically established compaction parameters are referred. The compaction curves are constructed as generalised plots of changes of total porosity, density, and indirect parameters determined from well-logs versus depth of burial (Nestorov, 1965; Gorelov, 1972; Rieke and Chilingarian, 1974; Magara, 1978).

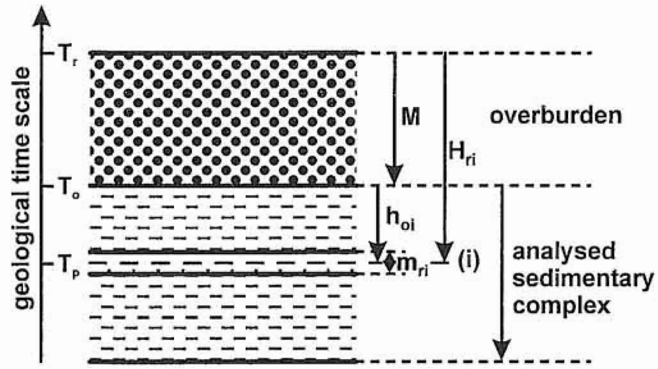


Fig. 1. Model of progressive compaction

$M$ — thickness of overburden; $H_{ri}$ — maximum depth of layer burial; $h_{oi}$ — depth of layer burial with time $T_o$; $m_{ri}$ — time of layer deposition; $T_o$ — time of deposition of the top of layer complex; $T_r$ — recent geological time; $T_p$ — time of layer deposition

In this paper we make use of a plot of porosity versus depth of burial. The generalised curve of the relation between porosity and depth of burial is obtained by solving the regression equation. For example, for argillaceous rocks, approximation functions of three kinds are used: exponential, parabolic, and hyperbolic (Gorelov, 1972; Rieke and Chilingarian, 1974; Vially *et al.*, 1990). A set of empirical data with great statistical scatter can be approximated with a fragment of each curve, giving no significant divergence; however, it seems that the physical character of the process tends toward the approximation with the exponential curve (Rieke and Chilingarian, 1974; Magara, 1978).

The compaction curve together with relations [1] and [2] are used to compute the compacted thickness correction and, hence, to determine the primary (earlier) thickness of layers. Using relation [1] we can compute the total thickness correction as well as the initial thickness of the layer. The initial thickness determined in such a way is correct only for thin and homogeneous layers. In a palaeotectonic reconstruction, it is essential to compute the layer thickness at that moment of geological time in which the top of the synchronous horizon was deposited and to which the palaeothickness is referred. Hence, the thickness correction included in the palaeotectonic reconstruction is related to the post-genetic compaction that takes place after the deposition of the relevant complex. Several different approaches to solving this problem have been presented in the literature (Perrier and Quibler, 1974; Liu and Roaldset, 1994; Sclater and Christie, 1980). In this paper we propose an original method for convenient and accurate computation of the compacted thickness correction both for a single layer and for a complex of sediments.

## DESCRIPTION OF THE METHOD

The method is based on the analysis of a model of progressive compaction, in which the total compaction of sediments, continuous in geological time, is divided into two components: syn-genetic compaction taking place during sedimentation whose palaeothickness is computed and post-genetic compaction occurring later (Stefaniuk and Kuśmierek, 1987). The essence of the method is explained in Figure 1. Below the top of a sedimentary complex covered with overburden, $M$, a layer with a recent thickness, $m_{ri}$, at a depth, $h_{oi}$ (in relation to the top of the complex) and at a depth, $H_{ri}$ (in relation to the recent surface) is separated ($i$ stands for the number of the layer in the profile). The thickness of the layer should be small enough so that vertical changes of porosity within the layer can be neglected. We define the following coefficients:

— an absolute reduction coefficient:

$$\beta_{PG} = \frac{m_r}{m_o} = \frac{1-\varphi_p}{1-\varphi_r} \quad [3]$$

— a post-genetic reduction coefficient:

$$\beta_{PG} = \frac{m_r}{m_o} = \frac{1-\varphi_o}{1-\varphi_r} \quad [4]$$

— a syn-genetic reduction coefficient:

$$\beta_o = \frac{m_o}{m_p} = \frac{1-\varphi_p}{1-\varphi_o} \quad [5]$$

where: $m_p$, $m_o$, $m_r$ — the layer thicknesses directly after the deposition, during the deposition of the complex top, and the recent one, respectively; $\varphi_p$, $\varphi_o$, $\varphi_r$ — porosity of the layer; time as above.

Note that the above given coefficients are related in the following way:

$$\beta_T = \beta_o \beta_{PG} \quad [6]$$

Having computed the recent thickness distribution and the compaction curve equation:

$$\varphi(H) = \varphi(H=0)\exp(-\alpha H) \quad [7]$$

we define the recent porosity, $\varphi_r$, for the maximum (recent) layer depth, $H_{ri}$, and porosity in time, $T_o$, for the depth of burial, $h_{oi}$. Using relations [3], [4], [5] and [6], we calculate the reduction coefficients, $\beta_T$, $\beta_o$, $\beta_{PG}$, and the layer thickness, $m_{oi}$, in time $T_o$, and the post-genetic thickness correction, $\Delta m_i$:

$$m_{oi} = \frac{m_{ri}}{\beta_{PG}} \quad [8]$$

$$\Delta m_i = m_{oi} - m_{ri} \quad [9]$$

While computing the syn-genetic and total corrections, the primary porosity can be taken from the compaction curve (for $H = 0$) or its value can be adopted from sedimentological studies.

To compute the palaeothickness and a thickness correction for the layer complex, individual corrections and corrected

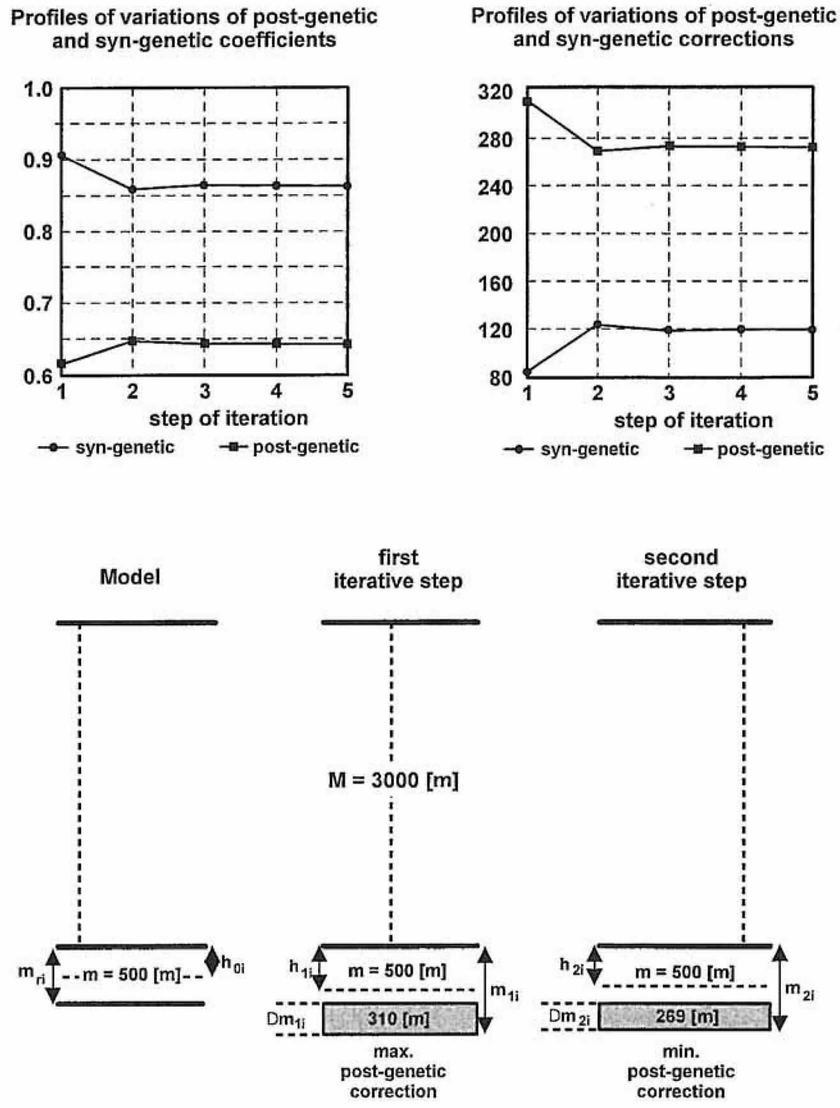


Fig. 2. Iterative computation of exact value of densometric correction

$M$ — thickness of overburden; $m_{ri}$ — recent layer thickness; $m_{1i}$, $m_{2i}$ — layer thickness in successive iterations; $\Delta m_{1i}$, $\Delta m_{2i}$ — thickness correction in successive iterations; $h_{oi}$, $h_{1i}$, $h_{2i}$ — depth of palaeoburial in successive iterations; computations were made using the compaction curve presented in the paper by Gorelov (1972)

thicknesses are summed. Note that the palaeodepth of burial, $h_{oi}$ (Fig. 2), determined from the recent thickness distribution, and related to the recent position of the roof of the layer complex, is reduced by the value of the post-genetic correction for sediments in the palaeo-overburden (i.e. deposits overlying the top of the given layer and underlying the top of the complex to which the computed palaeothicknesses are referred), and by half the value of the compacted thickness correction for the given layer. Thus, the porosity, $\varphi_{oi}$, computed from $h_{oi}$, is overestimated and the coefficient of the post-genetic reduction, $\beta_{PG}$, is underestimated (see relations [3]–[5] and [7]). In fact, it is the minimum value of $\beta_{PG}$ that can be computed under the given conditions.

The corrected layer thickness, $m_{1i}$, and the thickness correction, $\Delta m_{1i}$, have their maximum values. Introducing the correction computed in the first iteration for the layer and its palaeo-overburden, we can determine the corrected depth of burial, $h_{1i}$, which will be maximum in that case. Thus, the corrected thickness, $m_{2i}$, and the thickness correction, $\Delta m_{2i}$, computed from $h_{1i}$ in the second iteration will be minimum. Applying this procedure a number of times, we get — with the assumed accuracy — the real thickness of the layer, $m_{oi}$, in time, $T_o$. It is known from experience that 3–4 iterations are enough to get a satisfactory accuracy of computation. It is convenient to carry out iterations starting from the top of the layer complex. Thus, the thickness of the palaeo-overburden is corrected by now and does not change in successive iterations. The plots of changes of some chosen parameters during successive iterations for the assumed geological medium are shown in Figure 2. The example shows a model of an individual layer so that the

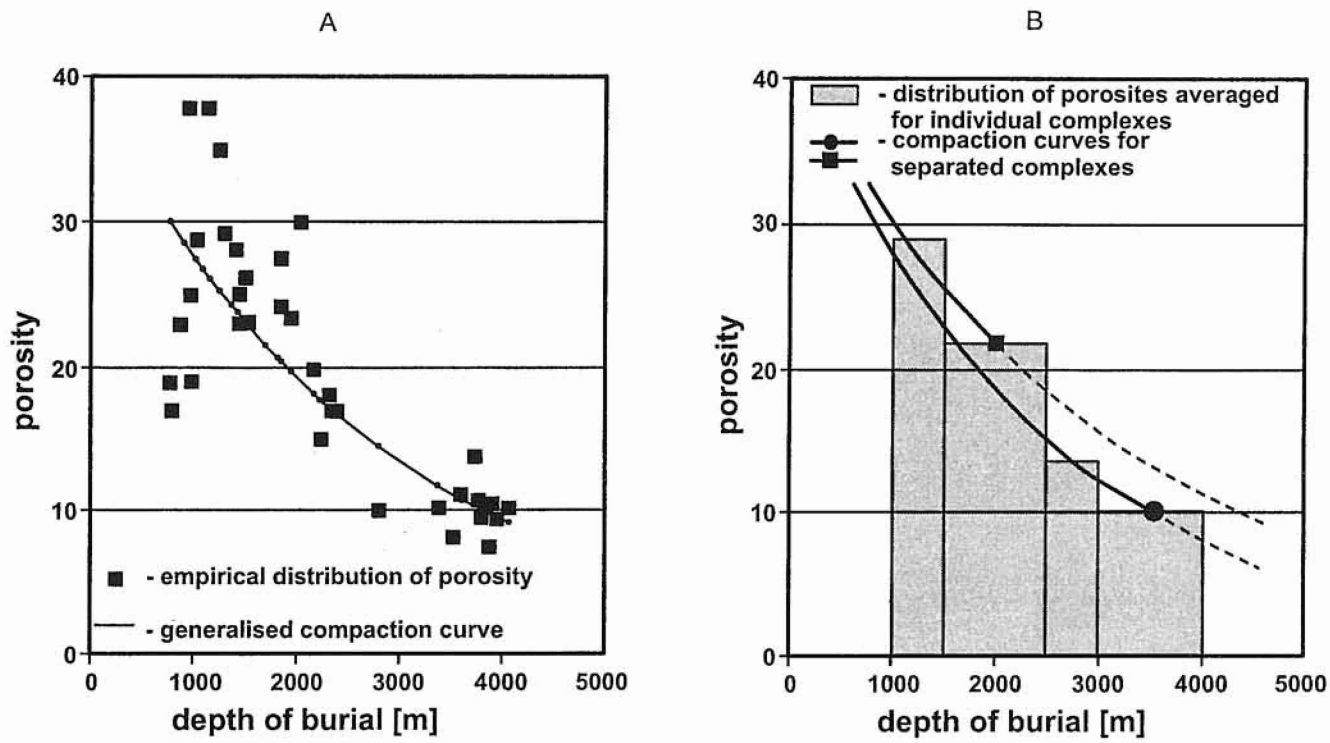


Fig. 3. Example of porosity distribution and a compaction curve (eastern part of Polish Carpathians)

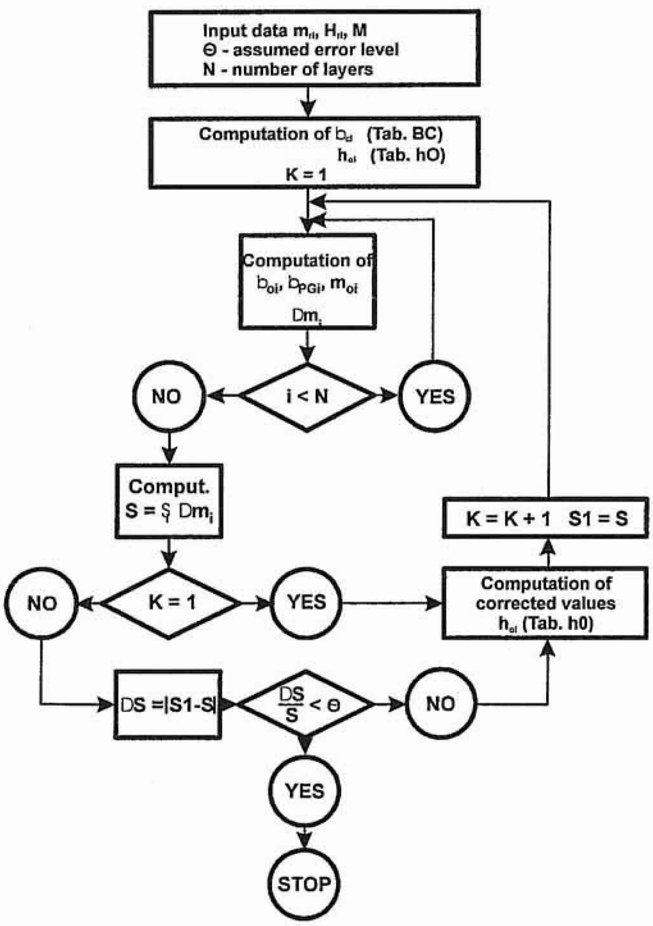


Fig. 4. Scheme of computer programme

first estimation of the palaeodepth of burial, $h_{oi}$, is reduced to half the layer thickness. It is the position of the top layer of the layer complex.

Apart from geostatic pressure and geological time, the compaction of sediments is affected by other factors including circulation of fluids, the content of sedimentary fractions and carbonate rocks, and tectonic stresses (Chapman, 1972; Magara, 1978; Waples and Kamata, 1993). As a result, there is a great scatter of empirical values of parameters upon which a generalised compaction curve is determined, and we should not regard this scatter as statistical error (Fig. 3A). Some complexes for which the scatter is substantially smaller can be separated in the geological profile (Fig. 3B). Thus, the compaction process takes place for individual complexes, depending on a combination of factors that affect it. Assuming a primary porosity, $\varphi_p$, and applying the general compaction curve equation (relation [7]), we can determine the compaction curve for a chosen complex (Stefaniuk and Maćkowski, 1992). When the complexes are duly separated, we can compute the arithmetic mean (or the weighted mean) of porosity and find the compaction curve on the basis of two known points (Fig. 3B). The compaction curve can be also determined using the solution for the exponential regression equation with the so-called stabilised point to avoid significant errors when a local trend of compaction in the given complex is anomalous or when there is great statistical scatter of empirical data.

The above given approach allows the compaction thickness correction to be accurately computed; the only limitations include the way of dividing the profile into smaller complexes and the accuracy of defining the empirical distribution of porosity. The method can be applied to the detailed palaeotectonic analysis of local structures under conditions of great scatter of porosity caused, for example, by abnormal compaction.

The compaction and compaction curves are different for different lithotypes. For example, for sandstones and sands the compaction curve has the shape of a tangential function (Alekseev *et al.*, 1982). Thus, the detailed computation of palaeothickness should be made independently for layers with different lithotypes.

## COMPUTATION OF A THICKNESS CORRECTION

The above-presented approach is simple; however it involves the use of a computer. A computer program was written in the Pascal language; the algorithm is shown in Figure 4. The program runs in an interactive mode. The post-genetic, total and syn-genetic thickness corrections as well as corrected thicknesses and depths of burial can be computed in two ways:

— using a generalised compaction curve,

— using compaction curves for separated layer complexes.

The program also has an additional option using the equation given by Perrier and Quiblier (1974) and a hyperbolic compaction curve (Vially *et al.*, 1990). The results of computations made with the two methods for several models (including those shown in Figure 2) are consistent with an accuracy of about 0.5%.

The input data set contains values for the thickness and depth of burial of tops of a layer or complexes of layers. It also includes percent contribution of the lithotype for which the computations are made. The program can be used to analyse the compaction process during geological history as well as to compute the corrected palaeothickness in a palaeotectonic reconstruction. Examples of results of the computation are shown in Figures 5, 6, and 7.

Figure 5 shows plots of changes of syn-genetic and post-genetic thickness corrections with depth of burial, and their mutual relationship. The computations were carried out for a geological model consisting of an argillaceous rock complex with a constant thickness and a variable depth of burial. The compaction curve presented in the paper by Gorelov (1972) was used in the computations.

In Figure 6 the reconstruction of the subsidence of the Carpathian geosyncline is shown along the Wola Michowa–Przemyśl line (eastern part of the Polish Carpathians).

Examples of the reconstruction of primary thicknesses of sediments include chosen profiles of flysch formations obtained from outcrops and boreholes. These formations were deposited in mobile sub-basins developing from the Early Cretaceous to the Older Miocene. They are characterised by rapid changes in thickness and lithofacies in the direction perpendicular to the strike of the tectonostratigraphic units. These units were formed into complex, disharmonic nappe structures during the Neo-alpine tectonic phases.

The compaction process deviates from the normal trend as a result of the complicated geometry of structures and the variability of sedimentary profiles. The anomalous pressures measured in boreholes confirm this. Therefore, the actual compaction curves are complex and it is difficult to average them. To

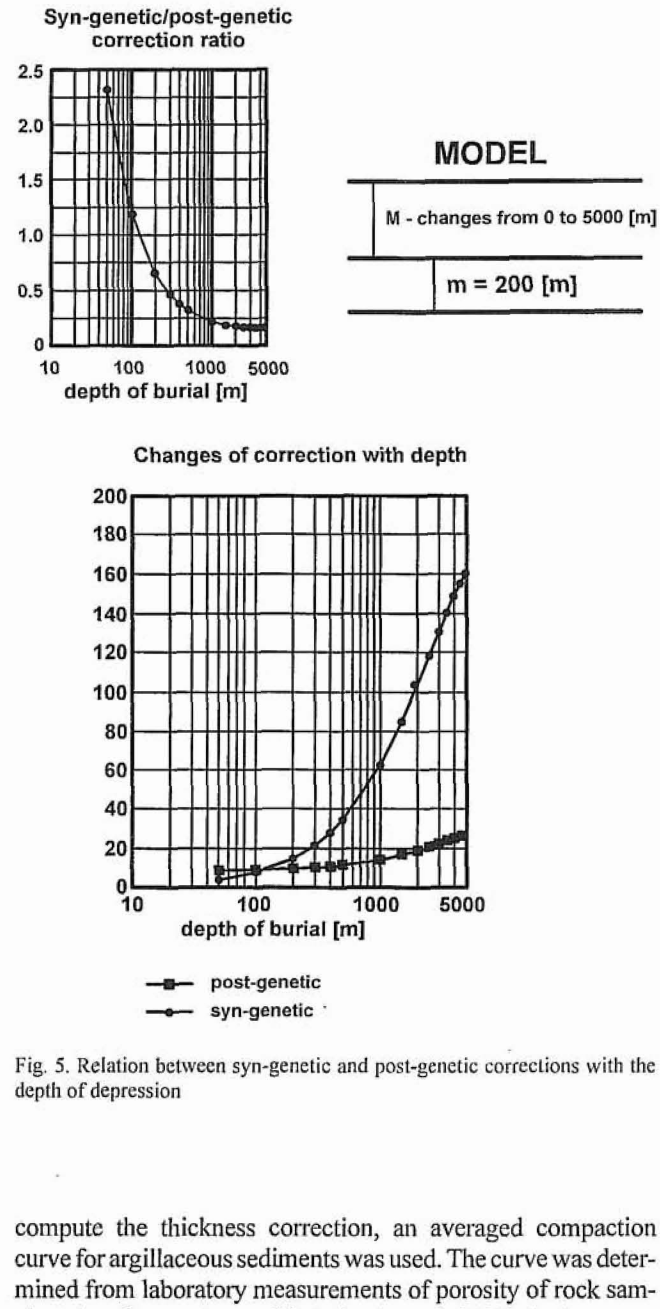


Fig. 5. Relation between syn-genetic and post-genetic corrections with the depth of depression

compute the thickness correction, an averaged compaction curve for argillaceous sediments was used. The curve was determined from laboratory measurements of porosity of rock samples taken from outcrops (Kuśmierek *et al.*, 1991). In the reconstruction, lithostratigraphic profiles were divided into five complexes: Lower Cretaceous, Paleocene, Eocene, Oligocene (sub-Jasło complex), and Miocene (supra-Jasło complex); the tops of the complexes were taken as successive reference horizons. The computations were carried out for argillaceous rocks; the input data were generalised, and the thickness of the separated complexes was multiplied by the coefficient of percent contribution of the argillaceous lithotype. An error analysis proves that deviations resulting from the use of the above given approach are negligible when compared to results obtained from the accurate method.

An example of using the method to verify the burial history of Carboniferous and Devonian complexes in the Pomeranian Swell is presented in Figure 7 (Stefaniuk *et al.*, 1996). Thickness corrections for arbitrary moments in geological time were computed for the Devonian, Carboniferous, and overlying

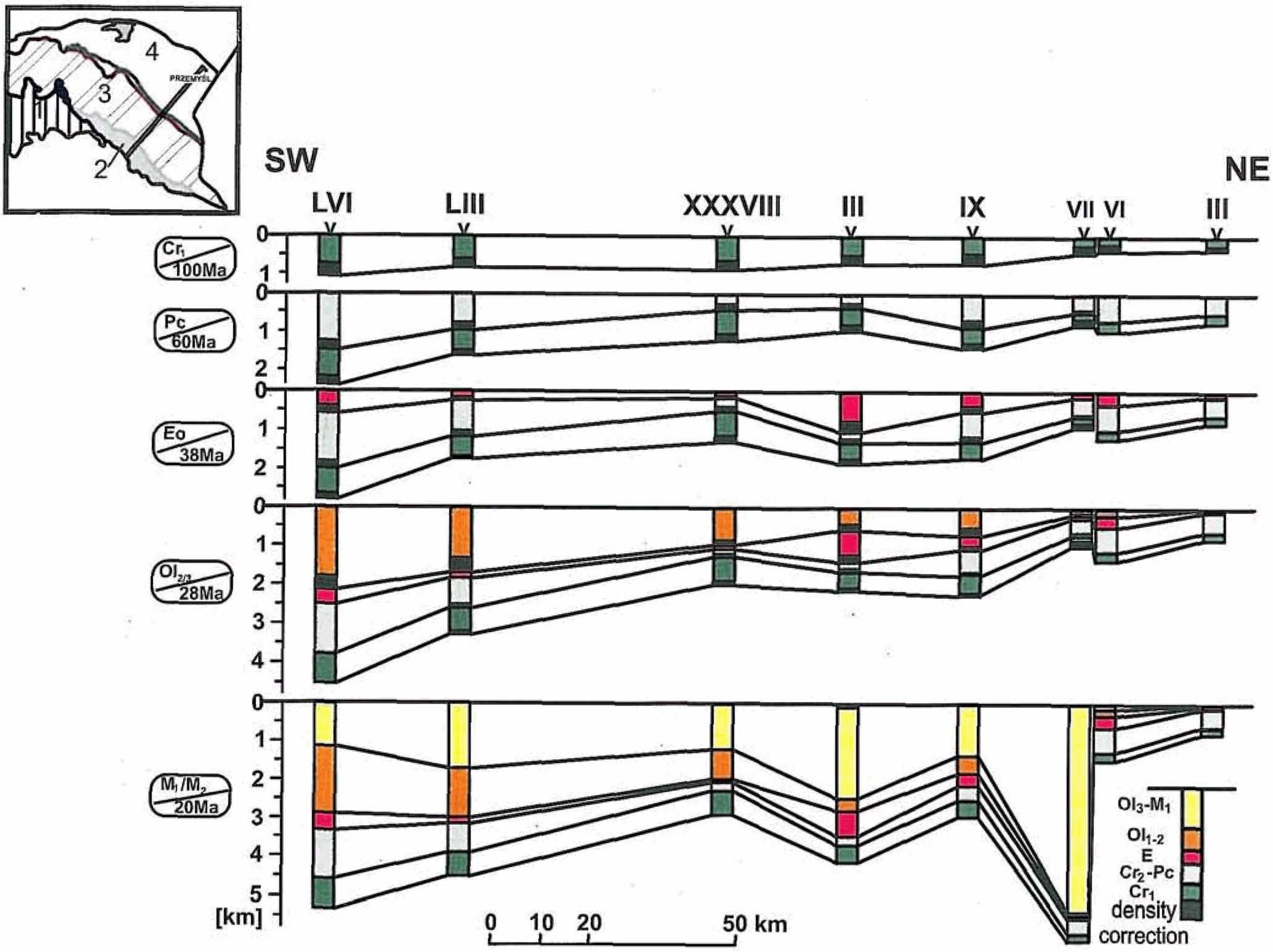


Fig. 6. Example of subsidence reconstruction along the line Wola Michowa–Przemyśl (eastern part of the Polish Carpathians)

1 — Magura Unit; 2 — Dukla Unit; 3 — Silesian Unit; 4 — Skole Unit

complexes. Computations were carried out separately for sandy and silty-clayey lithotypes, and then added up. In constructing the subsidence curves, the degree of Laramide-aged erosion was also taken into account.

## CONCLUSIONS

The presented approach of computing a compacted thickness correction allows the accurate reconstruction of the palaeothickness of sediments for any moment of geological time to be made. The method may be applied to the thickness reconstruction of thick sedimentary complexes, local structures, and single layers as well. The computations can be carried out separately for different lithotypes; the differentiation of compaction due to lithological characteristics of sediments is taken into account. The method also enables independent computations to be made for separated complexes with anomalous compaction process. The computations are relatively fast and their accuracy is affected by the accuracy of the input data alone.

*Acknowledgements.* The studies on compaction of flysch sediments of the allochthonous units from the eastern part of the Polish Carpathians, that gave rise to the formulation of the fundamentals of the presented approach, were carried out in the Department of Fossil Fuels of the University of Mining and Metallurgy, Kraków, in 1984–1986, and sponsored by the Polish Academy of Sciences. The method was developed and implemented to detailed analysis of the development of local structures in the Department of General and Mathematical Geology, and sponsored by the Committee for Scientific Research.

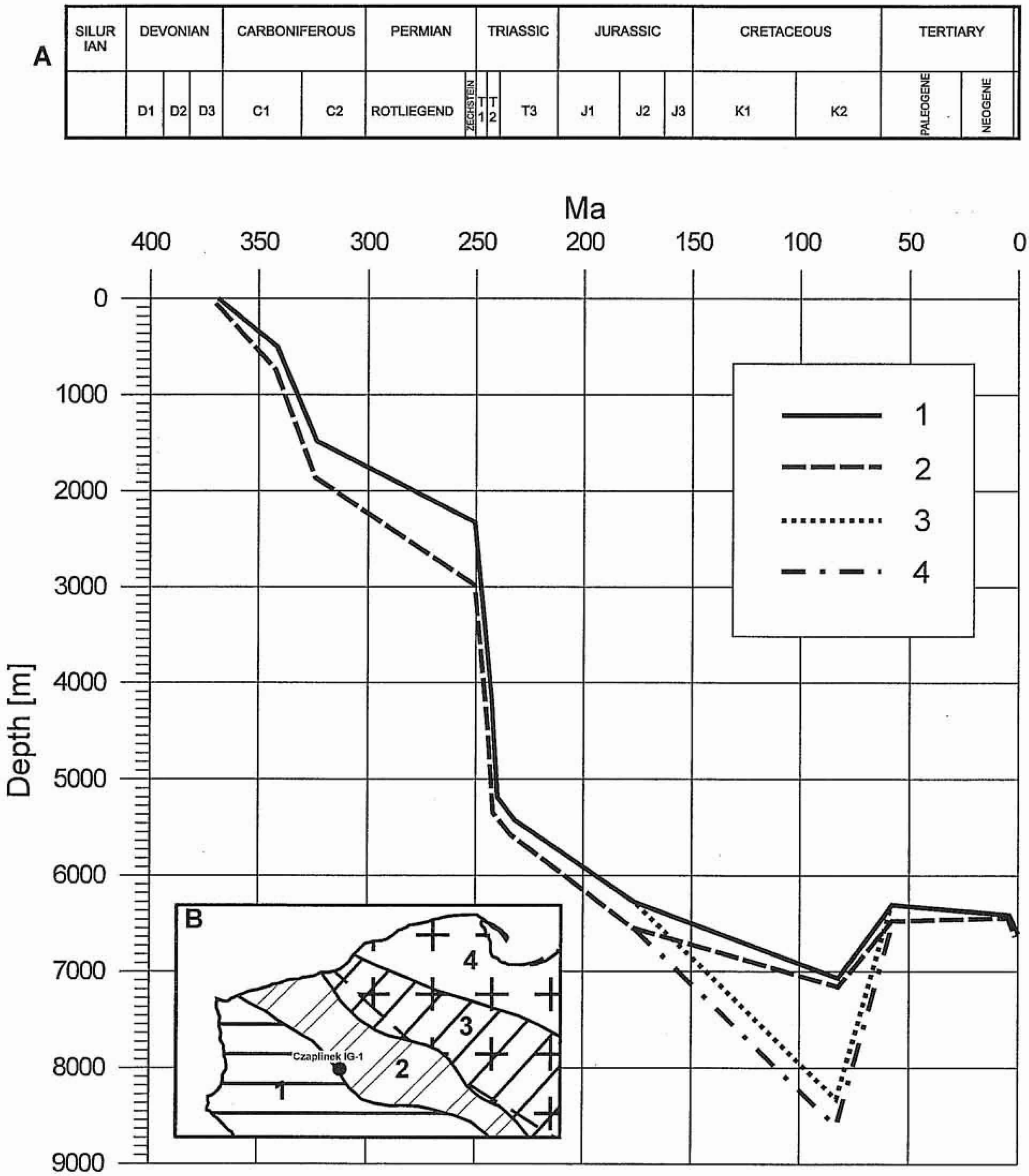


Fig. 7. Subsidence curve for the top of Devonian in the Czaplinek IG 1 well (after Stefaniuk *et al.*, 1996)

**A**: 1, 3 — curves without a compacted thickness correction; 2, 4 — curves with a compacted thickness correction; 1, 2 — curves with Laramide erosion estimated from lithofacies and palaeotectonic data; **B**: 1 — Szczecin Synclinorium; 2 — Pomeranian Anticlinorium; 3 — Pomeranian Synclinorium; 4 — Precambrian Platform

The authors acknowledge the assistance of Jan Kuśmierek, D.Sc., who gave a few words of advice, and thank him also for the access to measurement data from the Carpathians. We also thank our colleagues, Maria Cicha, Danuta Ilcewicz and Maciej Borowiec for their help and ready assistance.

## REFERENCES


ALEKSEEV G. I., ANDREEV W. N. and GORELOV A. A. (1982) — Metody izučenia uplotnienia gornych porod pri paleogeologičeskich rekonstrukciach. Nedra. Moskva.

BALDWIN B. (1971) — Ways of deciphering compacted sediments. J. Sed. Petrol., **41** (1): 293–301.

CHAPMAN R. E. (1972) — Primary migration of petroleum from clay source rocks. Bull. Amer. Ass. Petrol. Geol., **56** (11): 2185–2191.

GORELOV A. A (1972) — Ob učete gravitacionnogo uplotnenija glinistych porod pri paleotektoničeskom analize lokalnych podnjatij. Neftegaz. Geol. Geofiz., **10**.

KUŚMIEREK J., MRUK J. and WYPYCH L. (1991) — Wpływ piaskowców na kompakcję osadów ilastych w profilach serii ropogazonośnych fliszu karpackiego. Techn. Poszuk.Geol., **3–4**: 81–90.

LIU G. and ROALDSET E. (1994) — A new decompaction model and its application to the northern North Sea. First Break, **12** (2): 81–89.

MAGARA K. (1978) — Compaction and fluid migration. Elsevier. Amsterdam–Oxford–New York.

NESTEROV I. I. (1965) — Uplotnenie glinistych porod. Sov. Geol., **12**.

PERRIER R. and QUBLIER S. (1974) — Thickness changes in sedimentary layers during compaction history. Bull. Amer. Ass. Petrol. Geol., **70**: 103–130.

RIEKE H. H. and CHILINGARIAN G. V. (1974) — Compaction of argillaceous sediments. Elsevier. Amsterdam.

SCLATER J. C. and CHRISTIE P. A. F. (1980) — Continental stretching: an explanation of the post mid Cretaceous subsidence of the central North Sea basin. J. Geophys. Res., **85**: 3711–3739.

STEFANIUK M. and KUŚMIEREK J. (1987) — Dyskusja nad sposobem wprowadzania poprawek densometrycznych w rekonstrukcjach paleotektonicznych. Sympozjum nt. "Zastosowanie metod matematycznych w geologii". Kraków.

STEFANIUK M. and MAĆKOWSKI T. (1992) — Numerical computation of density corrections in paleotectonic reconstruction with regard to syngenetic compaction. International Symposium "Geodynamic Evolution of Sedimentary Basins". Moskwa.

STEFANIUK M., BARANOWSKI P., CZOPEK B. and MAĆKOWSKI T. (1996) — Study of compaction in the Pomeranian Anticlinorium area. Oil and Gas News From Poland, **6**: 150–162.

VIALLY R., CASERO P. and ROURE F. (1990) — Petroleum potential and source-rock maturation modelling in the southern Apenine. Appendix 1. In: Petroleum and Tectonics in the Apennines and Sicily. Institute Francais du Petrole.

WAPLES D. W. and KAMATA H. (1993) — Modelling porosity reduction as a series of chemical and physical processes. In: Basin Modelling: Advances and Applications (eds. A. G. Doré *et al.*). NPF Spec. Publ., **3**: 303–320. Elsevier. Amsterdam.