Inverse Modelling of Sedimentary Basins

Yuri Yu. Podladchikov[1], Stefan M. Schmalholz[2], and Daniel W. Schmid[1]

[1] ETHZ, Sonneggstr. 5, 8092 Zurich, Switzerland, yura@erdw.ethz.ch
[2] GeoModelling Solutions GmbH, Binzstrasse 18, 8045 Zurich, Switzerland

Abstract. An integrated model for oil and gas reservoir (sedimentary basin) formation that couples large-scale processes, such as flexural isostasy, necking of the lithosphere (the Earth's relatively rigid outer shell, ca. 100 kms) and consequent thermal contraction, with basin-scale processes (depth ca. 10 kms) of sediment deposition and compaction is being developed. The purpose is to reconstruct the thermo-tectonic history of real sedimentary basins. The forward model is coupled with an inverse module that automatically determines the best-fit parameters controlling the evolution of the lithospheric necking and palaeo-water depth through time. The primarily fitted data includes seismic and borehole based stratigraphy (the geometry of the sedimentary bodies deposited within constrained time intervals), and measurements of present day heat flux if available.

1 Forward Models

Extensional sedimentary basins in general, and especially rifted continental margin basins, are the world's largest repositories of oil and gas deposits. Many sedimentary basins have developed in the extensional tectonic settings. The lithosphere is subdivided into the "crust" (thickness prior to extension ca. 35 kms) and subcrustal mantle parts. Importantly, the crust is composed of significantly lower density material compared to that of the underlying mantle. During extension there are three different types of loads acting on the lithosphere: loads due to crustal thinning, loads due to gradually decaying thermal anomalies and loads due to sediment and water infill.

McKenzie [1] presented a uniform stretching model that describes sedimentary basin formation as the response of the continental lithosphere to stretching. Thereby, isostatic re-equilibrium leads to subsidence and sedimentary basin formation. Two phases are discriminated: a rift phase and a post-rift phase. During rifting, net subsidence occurs because of mechanical stretching and thinning. After rifting, a thermal re-equilibration with time takes place causing cooling of the lithosphere and consequently, post-rift subsidence.

Recently developed mathematical models of rifted, sedimentary basin evolution that elaborate on the basic lithosphere stretching model of McKenzie, incorporate the rheological, thermal, and flexural isostatic consequences of lithospheric extension, providing good facilities for two-dimensional forward modeling (e.g. [2] [3] [4] [5] and references therein).

Most of the contemporary two-dimensional forward modeling techniques have a large number of parameters that must be specified by the user. This makes it difficult to interpret the results in terms of the sensitivities or dominance of the various parameters. Many basin modelers are familiar with the tedious work of adjusting the numerous input parameters used in a forward modeling code to control the pre- and syn-rift lithospheric structure in order to fit the observed stratigraphy. The most laborious part is the search for the optimal set of thinning factors.

2 Inverse Models

In general, inverse modeling consists of finding the minimum of the chosen goal function. An essential factor is the appropriate choice of the goal function and of the minimization method for different model parameters. Additionally, a priori information should be used to define ranges of values for these parameters. This includes general geological information, for example such predefined parameters as compaction coefficients, rock densities for crust and mantle, etc. Other kinds of geological and geophysical data sets, specific to the particular passive continental margin being studied, should be used to constrain initial crust and lithosphere thickness, as well as time and duration of rifting events. Thus, the objective of the inverse modeling process is defined as finding the set of particular parameter values, restricted by a priori known limits, which result in a satisfactory fit of model predictions to the observed passive continental margin stratigraphy. This is rather similar to the practical work of most basin modelers.

2.1 1D Models

N.White [6] presented a method for inversion of the stratigraphic record in one dimension. The method results in numerical estimates of the lithosphere strain rate and its evolution through time, explaining basic features of the observed subsidence curves. This inversion method is based, however, on the original McKenzie formulation of the uniform stretching model, limiting its applicability to "real-world" sedimentary basins. Release of the "uniform stretching" simplifying assumption of the McKenzie model necessitates an at least two-dimensional approach and rebuilding of the inversion algorithm (although see [7]).

2.2 2D Models

Recently, an automatic 2D inverse modeling technique for sedimentary basin subsidence has been developed by Poplavskii and Podladchikov [5] in order to provide an automatic search for the best-fit parameter set in two dimensions. Their inverse modeling procedure requires a forward problem solver. The evolution of an extensional basin is simulated using a "black-box" forward modeling numerical code and is determined by a given input parameter set. The input data for the forward problem solver consist of a particular set of parameters that describe the state of the lithosphere prior to rifting and the thermo-mechanical effects of a given lithosphere-rifting process. The output data represent the resulting basin or passive continental margin stratigraphy at any time thereafter. The inverse modeling procedure varies the parameters in order to improve the fit between the observed and calculated basin stratigraphy. The estimate of the misfit between these is referred to as the "goal function" and is the function for which a minimum is to be found. The misfit between the observed and calculated present-day depths of the stratigraphic layers is an obvious candidate for the role of the goal function. Generally, this misfit value (the "global" misfit) should include all the differences between every observed and the calculated value. In the present case, it means the difference between observed and calculated depth of each stratigraphic horizon for a chosen number of points on a cross-section. In such a case, the minimization procedure will be equally sensitive for all data observed. However, the parameters inherent to the forward modeling procedure can contribute to the calculated stratigraphy in rather different ways, causing numerical instability of generic constrained minimization algorithms.

2.3 Difficulties of 2D Inversion

As a first attempt, a Newton-optimization based algorithm for the simultaneous multi-parameters minimization of the "global" goal function equally sensitive for all data observed was investigated (Poplavskii and Podladchikov, 1995, unpublished). With each iteration, partial derivatives were calculated for every parameter, thereafter the penalty functions were applied to the resultant matrix in order to restrict the solution instability. The solution of singular value decomposition problem was treated as a direction vector and linear (1-dimensional) optimization was performed to find the optimal step length. The algorithm quickly converged to the neighborhood of the global misfit minimum. However, following this the non-linearity of the problem starts to play a more and more significant role and iterations diverge due to very complicated relief of the "global" goal function surface in the model space [5]. In such a case, the adaptive algorithms of the multi- parameter minimization, based on the assumption of goal function smoothness, are either divergent or "trapped" in a local minimum.

The release of the "uniform stretching" simplifying assumption of the McKenzie (1978) model further complicates the problem. Two sets of thinning profiles (variable laterally and growing in time) must be introduced for the crust and subcrustal mantle. This completely decouples the loads due to crustal thinning and the loads due to gradually decaying thermal anomalies. The crustal thinning profile, the so-called delta factor, is relatively well constrained by present day observations. The subcrustal thinning profile, the so-called beta factor, is linked entirely to the thermal history and is not related to any deformation or other signatures easily observable today. Unfortunately, the major goal of the inverse modeling is to reconstruct the thermal history and temperatures at early rifting stages as these are the conditions primarily controlling hydrocarbon maturation. The thermal evolution is entirely controlled by the beta factor profile that is to be determined by an inversion algorithm. Since the beta profile has only thermal consequences, its numerical search is complicated by the well known instability of the inverse modelling of the thermal history. Indeed, if the "global" goal function includes equally weighted late post-rift sequences, then the inverse algorithm will tend to introduce large variations for parameters controlling lithospheric thinning (the beta profile) at early rifting stages in order to fit small variations in the data, and the convergence will not be achieved. Two dimensionality of the forward thermal solver is the major feature strengthening this instability. Thermal consequences of high-lateral frequency and high-amplitude thinning modes at early rifting times are quickly diffused by the lateral heat conduction. Negligible thermal consequences result in irresolvable contributions to the subsidence at late post rift time, which is the most precise fraction of the observed data (being most recent and most shallow). Insufficient control of this data on parasitic modes of the searched beta profile causes numerical instability of the inversion algorithm.

2.4 Weighted Goal Function and Regularization

The soul of the inverse problem solver algorithm is the definition of the weighted goal function for minimization and its regularization (see [5] for details). Using the weighted goal functions, a stable algorithm is built for the search of optimal delta and beta profiles. The algorithm is based on the Newton method and results in a fast convergence. The tuning of the crustal and subcrustal mantle thinning factors are done iteratively with a nested delta loop within each beta iteration.

In order to test the method for convergence and stability, a series of synthetic models were generated. Disturbances introduced into models include arbitrary determined delta and beta factors along the geological cross-section, changes of the level of lithospheric necking and variable intraplate stress values at different ages. Results of these tests proved the ability of the algorithm to resolve all disturbances with an accuracy depending mostly on the time of the calculations.

3 Current Development

The inversion algorithm of Poplavskii and Podladchikov [5] was designed to be insensitive to the implementation details of the "forward solver". However, the algorithm was only tested using the computer code BMOD developed by

H.Kooi [2] for the forward modeling of the formation of extensional sedimentary basins. Strictly speaking, the details of the BMOD implementation constrain the usage of this code to "single rift phase cases" of basin formation. Unfortunately, a great number of real-world basins suffered several rifting phases with "postrift" subsidence in between. We therefore developed a new forward module to resolve this particular shortcoming of the BMOD code and to include several additional important features that were recognized only recently [4]. Moreover, we updated the BMOD "scheme" with some basic features important for thermal modeling, such as heat production source terms, incorporating of the newly formed sediments into the thermal modeling domain and formation of new oceanic crust. The upgrade of the forward solver from the "single" to "several" rifting phase option, dictated major reorganization of the inverse algorithm thought to be insensitive to the details of the forward solver. The new automatic inversion algorithm allows future addition of new forward solver features, such as lithospheric phase transitions, flexure solver with faults, viscoelastic flexure and crustal flow. Additionally, we found a way to avoid the nested delta-beta loop construction resulting in an order of magnitude reduction of the computational time: the number of required calls for the forward solver is reduced now from "hundreds" to "tens". Such a small number of inverse solver iterations opens the possibility of fully dynamic inverse modeling, a research direction we pursue independently [8](for further details and updates see http://www.geology.ethz.ch/sgt/staff/yura).

References

1. McKenzie, D.P. (1978) Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett. 40, 25-31.
2. Kooi, H. (1991) Tectonic modelling of extensional basins - the role of lithospheric flexure, intraplate stress and relative sea-level change. PhD thesis, Vrije Universiteit, Amsterdam, The Netherlands, 183 pp.
3. Kooi, H. and Cloetingh, S. (1992) Lithospheric necking and regional isostasy at extensional basins 2. Stress induced vertical motions and relative sea level changes, J. Geoph. Res., 97, 17573-17591.
4. van Balen, R.T., Podladchikov, Y.Y. and Cloetingh, S. (1998) A new multilayered model for intraplate stress-induced differential subsidence of faulted lithosphere, applied to rifted basins. Tectonics 17(6), 938-954.
5. Poplavskii, K.N., Podladchikov, Yu.Yu. and Stephenson, R.A. (2001) 2D inverse modeling of sedimentary basin subsidence. J. Geophys. Res. Vol. 106 , No. B4 , p. 6657-6672.
6. White, N. (1994) An inverse method for determining lithospheric strain rate variation on geological timescales. Earth Planet. Sci. Lett., 122(3-4), 351-371.
7. van Wees, J.D., Stephenson, R.A., Stovba, S.M. and Shymanovskyi, V.A. (1996) Tectonic variation in the Dniepr-Donets Basin from automated modelling of backstripped subsidence curves. Tectonophysics 268: (1-4) 257-280.
8. Kaus, B. and Podladchikov, Yu.Yu. (2001) Forward and reverse modeling of the three-dimensional Rayleigh-Taylor instability. Geophys. Res. Lett. Vol. 28 , No. 6 , p. 1095-1098.