PS An Inverse Approach for Relating Seismic Velocity and Overpressure to Permeability and Sedimentation History in Deep Basins*

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Abstract

Pore pressures exceeding hydrostatic ("overpressures") can play an important role in driving fluid flow in the subsurface. Sediments become overpressure mainly by three mechanisms: disequilibrium compaction, because pore fluids cannot be expelled rapidly enough during ongoing sedimentation and compaction, chemical reactions, including diagenesis reactions which release water (smectite converting to illite) and oil and gas formation from kerogen which implies a volumetric increase of the products and thermal expansion of water. In deep basins and thickly sedimented continental margins, extreme overpressures can develop and can play a decisive part in basin evolution and hydrocarbon migration. A range of analytical and numerical techniques has been developed to model patterns of overpressure. Overpressures can also be estimated from remote geophysical observations such as P and S wave velocities, but the resulting estimates can have large uncertainties. These two separate approaches have rarely been brought together. Here, we bring them together by developing a method for estimating overpressure from a disequilibrium compaction mechanism in deep sedimentary basins that satisfies both the geophysical observations and the constraints imposed by physical principles and sedimentation history. The 1D inverse algorithm minimizes the misfit between the observed and the predicted P wave velocity. We have developed a 1D forward numerical method for the calculation of pore pressure in a column of sediment using Athy's law for the porosity evolution with depth and an empirical law for the permeability as a function of porosity. Model output has been used to estimate the P wave velocity in the sediment column by applying a density-P wave relationship. Then, considering a trial P wave profile and the calculated P wave velocity profile, the proposed inverse method has been applied. The methodology has been implemented in a series of synthetic problems allowing a good correlation between the permeability and sedimentation rate inputs in the forward method and the outputs from the inverse method. This inverse approach will be applied to data from the Eastern Black Sea Basin where the P and S wave velocity structure are well known from wide-angle seismic work and the lithology and sedimentation history are constrained by nearby exploration boreholes. The inversion algorithm is a step forward towards a more generalized 2D implementation including other overpressure mechanisms.

An Inverse Approach for Relating Seismic Velocity and Overpressure to Permeability and Sedimentation History in Deep Basins

Case study: the Eastern Black Sea Basin

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1. INTRODUCTION

Pore pressures exceeding the hydrostatic (overpressures) can play an important role in basin evolution and primary hydrocarbon migration in deep basins and thickly sedimented continental margins. From a more practical engineering insight, locating and quantifying overpressures is critical in an exploration drilling campaign in order to drill wells safely and economically. Sediments become overpressured by three mainly mechanisms: stress regime changes, including disequilibrium compaction and tectonic compression, fluid volume changes, including thermal expansion, smectite to illite dehydration and hydrocarbon generation and fluid movement.

Overpressures can be calculated using a range of different approaches but these approaches have rarely been brought together: Here, we present the results of an inverse technique that estimates overpressure from a disequilibrium compaction mechanism that satisfies both, the geophysical observations and the physical constraints imposed by physical principles and sedimentation history.

Four wide-angle seismic lines have been acquired in the Turkish sector of the Eastern Black Sea (EBS) basin (Fig. 1). A low velocity zone (LVZ) was identified en line 1 (Fig. 2) from which overpressures were estimated [1] using the Eaton method [2] and the Westbrook relationship [3].

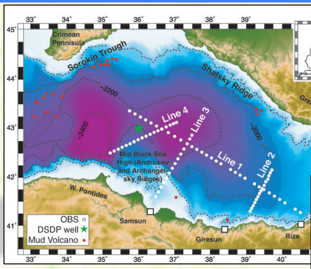

Fig. 1. Map of the EBS basin showing the location of the seismic survey with elevation and bathymetry (after [1]).

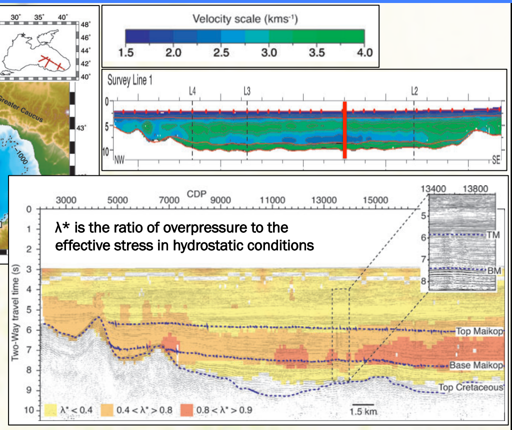

Fig. 2. On the top right, the P velocity structure calculated for Line 1.On the bottom right, a 2D MCS reflection data, near-coincident with Line 1. The seismic profile is overlaid by λ using the pore pressure calculated with the Eaton Method (after [1]).*

2. METHODOLOGY

❑ Forward Model

The equation is formulated in material derivatives (material coordinates) where the reference frame is fixed on the solid grains using a Lagrangian fully compacted coordinate system (FCCS). The FCCS measures a sediment column where all the pores have been removed (zero porosity). The sedimentation rate is also applied in the FCCS.

$$\frac{DP}{Dt} = \underbrace{\left[\frac{K(1-\phi_\chi)^2}{S_t\rho_f g}\right]\frac{D^2u}{D\chi^2}}_{\text{Difussive Term}} + \underbrace{\left[\frac{\phi_\chi}{S_t(1-\phi_\chi)}\beta_m\right]\frac{D\sigma_L}{Dt}}_{\text{Loading Term}}$$

$$u(t=0)=0,\quad u(\chi=\text{top boundary})=0,\quad \frac{du(\chi=\text{bottom boundary})}{d\chi}=0$$

The equation is solved using an implicit finite difference and using four constitutive laws for porosity, hydraulic conductivity, compressibility and viscosity.

❑ Inverse Model

The inverse model is solved by calculating a large number of forward models. An objective function H, is minimized varying the parameters P_k, surface porosity, compaction factor, sedimentation rate and a empirical factor controlling the evolution of intrinsic permeability with porosity, using Powell's algorithm [4]. The differences between the observed and calculated P velocity and density profiles, and the depths of the present day layer boundaries are minimized until the error is below an imposed tolerance.

$$H = \underbrace{\left[\frac{1}{N}\sum_n^N\left(\frac{Vp_n^{obs}-Vp_n^{cal}}{\sigma_n^{Vp}}\right)^2\right]^{1/2}}_{\text{Misfit Velocity Term}} + \underbrace{\left[\frac{1}{N}\sum_n^N\left(\frac{\rho_n^{obs}-\rho_n^{cal}}{\sigma_n^{\rho}}\right)^2\right]^{1/2}}_{\text{Misfit Density Term}} + \underbrace{\left[\frac{1}{L}\sum_l^L\left(\frac{Zb_l^{obs}-Zb_l^{cal}}{\sigma_l^{Zb}}\right)^2\right]^{1/2}}_{\text{Misfit Layer Boundary Depth Term}} + \underbrace{\frac{W_k}{L}\sum_l^L \log P_k}_{\text{Parameters Positiveness Term}}$$

3. SYNTHETIC MODEL RESULTS

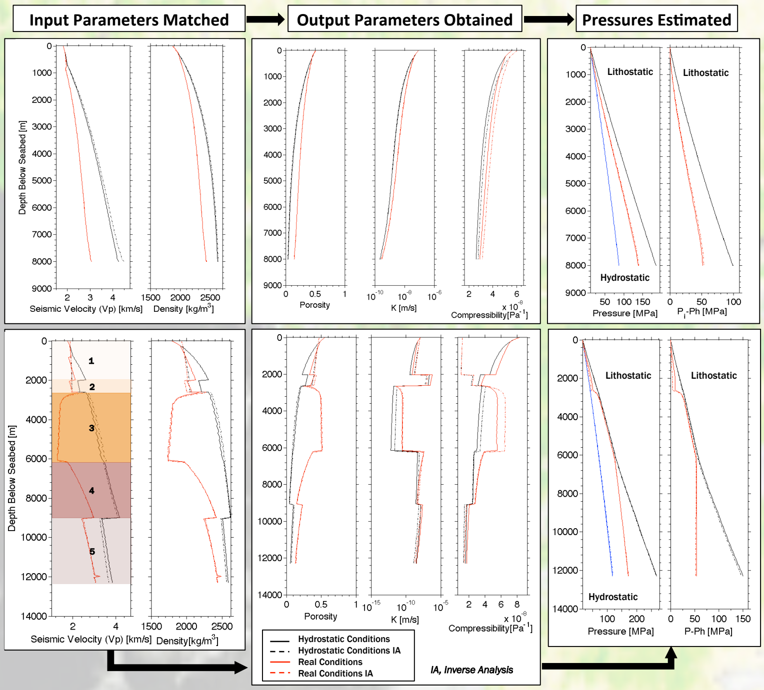

Fig. 3. A 1D plot showing the results of the inverse problem for two synthetic cases: at the top, considering just 1 layer (4 parameters), and at the bottom considering 5 layers (20 parameters). The parameters in both synthetic cases have been chosen randomly. The forward problem results are shown as solid lines and the inverse problem as dashed lines

4. EBS BASIN RESULTS

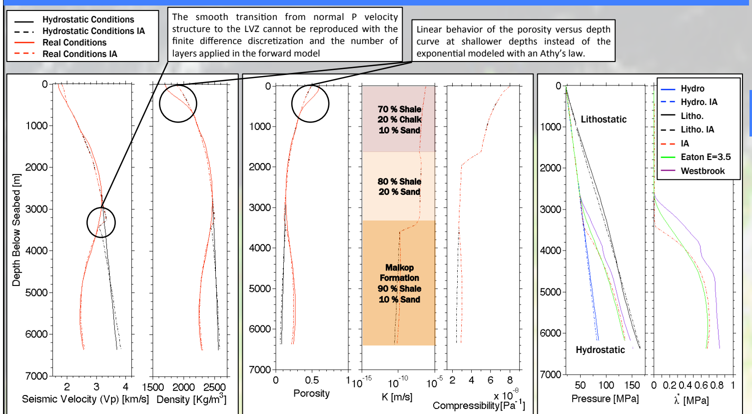

Fig. 4. A 1D plot showing the results of the inverse analysis for the sedimentary structure at 250 km offset along Line 1 (red line Fig. 2). In solid lines the results of the observed and estimated data [1] and in dashed lines the results of the inverse problem.

5. CONCLUSIONS

- The inverse analysis has successfully been applied to two synthetic cases and to observed data from the EBS basin.
- The hydraulic conductivity has been obtained from P seismic velocity data.
- Although some of the parameters recovered with the inverse analysis are different to the ones imposed in the synthetic models (Fig. 3 compressibility plots), the errors in P velocities, densities and present day thickness are small. This suggest a trade off between parameters.
- The results from the inverse model in the EBS basin suggest that the observed LVZ is linked to overpressures developed by a disequilibrium compaction mechanism. The overpressures would have been generated and controlled by the low hydraulic conductivity 10^{-11} m/s (Fig. 4) and the relatively high sedimentation rate 0.31 m/ka of the Maikop Formation.
- The overpressures obtained with our model are similar to the ones obtained with the Eaton method with an exponential factor of E=3.5 and the Westbrook relationship (Fig. 4).

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