Review of the doctoral dissertation « Laboratory measurements and visco-elastic constitutive modeling of rock creep with application to stress prediction in intraplate sedimentary basins » submitted by M Trzeciak to the Institute of Geophysics of the Polish Academy of Sciences, Warsaw.

Introduction.

The Doctoral thesis submitted by Maciej Trzeciak, includes two main parts.

The first one, titled "Viscoelastic modeling of sedimentary rocks" includes three chapters numbered 1 to 3. The first one introduces "Rock deformation and creep", the second one presents "Three-dimensional viscoelastic constitutive models for sedimentary rocks" whilst the third one is specifically centered on "Laboratory data analysis" and corresponds to one of the original contributions of the doctoral thesis.

The second part, titled "Stress distribution modeling in layered, viscoelastic sedimentary basins under tectonic and glacial loads" includes four chapters numbered 4 to 7. The first one introduces the concept of "stress in the lithosphere" whilst the second one proposes a "review of stress prediction methods". These two introductory chapters are followed by two of the main contributions of the doctoral thesis, namely chapter 6 "stress modeling in viscoelastic layered rock formations", and chapter 7 "Baltic basin stress modeling".

The present review proposes first a schematic summary of these various chapters. Then it outlines what is considered to be the main original contributions of the doctoral thesis (already pointed out in the schematic summary by using bold characters for sections considered to include original contributions) and finally it discusses the main points that are considered to be debatable. This report concludes on the excellence of the original part of the work that has been accomplished, and which fully justifies that the "Doctor" title be awarded to Maciej Trzeciak.

Schematic summary of the dissertation.

As pointed out in the dissertation introduction, understanding the stress field that exists in the crustal part of the lithosphere is of relevance to the understanding of both natural phenomena, such as earthquakes, and engineering issues, such as the exploitation of oil and gas or the disposal of nuclear waste. This requires a sound analysis of the geo-mechanical behavior of the crust and the manuscript addresses more specifically that of sedimentary basins.

The **first chapte**r introduces various geo-mechanical aspects of rock deformation and creep. In section 1.1, it addresses linear elasticity (isotropic as well as Transversaly Isotropic materials) and the possibility of separating bulk (or volumetric) deformation and deviatoric deformation, with a discussion of thermodynamically admissible elastic parameters and of conditions of incompressibility. In sections 1.2 and 1.3, the concept of viscous deformation is introduced with the linear viscous (fluid type) constitutive law and the Arrhenius temperature dependent viscosity, as well as the concept of "Rock strength and failure". After outlining differences between brittle and ductile deformation, four different failure criterion are enumerated, namely the Tresca criterion, the Mohr-Coulomb criterion, the Huber – von Mises criterion and the Drucker-Prager criterion. The chapter continues with an introduction to poro-elasticity in section 1.4 with the concept of effective stress and the Biot's poro-elastic constitutive law. In **section 1.5**, various aspects of visco-elasticity are addressed, in which the strain is assumed to be the sum of a time independent elastic component and a time dependent viscous component, with an introduction to Maxwell fluid type models (with exponential relaxation and linear creep), and to Kelvin-Voigt solid type models (with exponential creep and limited stress relaxation). Generalized models, which may contain as many relaxation times as needed, are introduced with either Generalized Maxwell (GM) models in order to deal with *relaxation spectra",* or with Generalized Kelvin-Voigt (GKM) models when considering "*retardation spectra*". This helps to introduce in **sub-section 1.5.2**, viscoelastic models for power law materials, with the "*Retardation spectrum*" approach of GKM models, the "*empirical approach*", in which the power law is directly fitted to experimental data, and the "*Fractional Maxwell approach*" with the notion of "*fractional derivative*" and the associated concepts of α-order fractional derivative of strain and *characteristic time*. In **sub-section 1.5.3 and 1.5.4**, the Boltzmann superposition principle is introduced because it helps to characterize the response of generalized visco-elastic materials to arbitrary loads. This provides a straightforward method to calculate the creep or relaxation function, when the other one is known. The chapter ends up with a discussion of rock creep in section 1.6, with special attention to the various micromechanical mechanisms of creep, namely diffusion and dislocation motion for creep in solids, subcritical crack growth for saturated or partially saturated rocks, poro-visco-elastic effects because of mechanical solid-fluid coupling, and pressure solution because of time dependent mass exchanges between the solid and the fluid phases at localized solid-solid contacts.

The **second chapter** is specifically devoted to a presentation of three dimensional viscoelastic constitutive models for sedimentary rocks. The first section is concerned with isotropic materials. The concepts of creep compliance tensor as well as that of relaxation tensor are introduced in subsection 2.1.1, followed by an introduction to time dependent Poisson's ratio in subsection 2.1.2. In **sub section 2.1.3**, the author proposes to assume that the volumetric deformation is elastic and that only the deviatoric component of stress undergoes relaxation and this leads to a discussion in sub-**section 2.1.4** of time-dependent Poisson's ratio in elastically compressible materials. The second section addresses viscoelastic constitutive law for a specific type of anisotropic material, namely materials with Vertical Transverse Isotropy. As for isotropic materials, the volumetric deformation is assumed to be elastic, and a specific method is proposed in **sub-section 2.2.2** for identifying this volumetric deformation through the use of the volumetric distortional decomposition, after the stress has been separated into its spherical part and its deviatoric part. This leads to introducing two fourth order operators, namely the spherical (K) operator and the deviatoric (M) operator, which are used for describing the stiffness matrix of the material as the sum of a purely spherical component, a purely deviatoric component and two mixed components. This sub-section ends up with the formulas used for calculation of the three volumetric-distortional decomposition parameters. In **sub-section 2.2.3** this volumetric-distortional decomposition is used to express in the Laplace domain the VTI anisotropic viscoelastic constitutive law. Its application to time dependent shear moduli is discussed in the final section of the chapter.

Results of chapter 2 are used in **chapter 3** for the analysis of laboratory data produced with rock samples from sedimentary formations of the Baltic basin. After a schematic introduction to the geological setting of the Baltic basin in section 3.1, the rock samples are described in section 3.2 and the experimental procedure adopted for characterizing the elastic and viscous behavior of the samples is described in section 3.3. Experimental results are presented in section 3.4, with special attention to the quasi-static measurements of the Young's moduli (section 3.4.2), the three Poisson's ratios (section 3.4.3) and of the volumetric elastic moduli (section 3.4.4). Then results from ultrasonic measurements are presented in section 3.4.5, followed by an overview of the creep data in section (3.4.6). The chapter ends up with a detailed discussion of experimental data in **section 3.5.** Elastic Anisotropy and its dependence on confining pressure, as observed with quasi-static testing and ultrasonic velocity is discussed **in sub-sections 3.5.1 and 3.5.2**. A power-law creep compliance model is presented in sub-**section 3.5.3**. It starts with a presentation of the Power law fitting approach. Then it proposes three different approaches for determining the Power law viscoelastic parameters and finally discusses the extrapolation uncertainty. **Sub-section 3.5.4** presents and discusses results obtained for the time dependent Poisson's ratio with some attention to its change in sign for some of the samples. This section ends up with the introduction of a simple rock physics model according to the mineralogical composition (**sub-section 3.5.5**).

Chapter 4 is the first chapter of the second part of the thesis, which is devoted more specifically to stress in layered viscoelastic sedimentary formations. The chapter introduces the concept of stress in the lithosphere in section 4.1, and addresses successively the notion of tectonic stress, that of membrane stress linked to the motion of lithospheric plates over a quasi-spherical earth with changes of its radius of curvature with latitude, that of bending stress associated with the bending of a pile of parallel layers, that of topographic stress, and finally that of residual stress. Section 4.2 briefly addresses the issue of stress in sedimentary basins and then section 4.3 lists various methods used for measuring stresses. The chapter ends up with section 4.4 that introduces the concept of stress profile in deep boreholes.

Chapter 5 reviews various methods which have been proposed in the literature for describing stress variations with depth in the crust. After mentioning the original Heim's nineteen century hydrostatic hypothesis and the more recent frictional equilibrium model, it addresses in sub-section 5.3 more specifically layered formations and the laterally constrained, or uniaxial strain, hypothesis. Attention focuses on transversally anisotropic formations as well as to modelling the effect of erosion. Section 5.4 describes the K coefficient empirical method whilst section 5.5 introduces the extended-Eaton model, which considers layered elastic transversally isotropic materials with uniform horizontal strain components at infinity as well as both poro-elastic and thermo-elastic effects. In section 5.6 stress driven elastic models as applied to layered, perfectly bounded, formations with iso-horizontal strain, are discussed. In section 5.7, a Maxwell viscoelastic model is introduced for a layered system with uniaxial strain conditions and loading through gravity with variable vertical load because of erosion effects, as well as through imposed uniform horizontal strain. The model simulates time variations of the vertical stress profile. The chapter ends with section 5.8 on a discussion of viscous relaxation models calibrated on real in situ stress measurements.

Chapter 6 addresses the issue of stress modelling in viscoelastic layered rock formations and **section 6.1** starts with the case of uniform horizontal strain rates for four different materials: linear elastic, linear viscous incompressible, Maxwell, and fractional Maxwell. Then, assuming that the four different models correspond to four different perfectly bounded layers, the model shows how a vertical stress profile would change with time, with the highest stress being supported initially by the viscous layer followed up by a progressive loading of the elastic layer. **Section 6.2** addresses the case of constant tectonic forces applied on a stack of two perfectly bounded layers with the top layer being elastic and the lower layer being either viscous, Maxwell type, or fractional Maxwell. In **section 6.3**, the case of a stress driven viscoelastic model is analyzed as an extension of the stress driven elastic model discussed in section 5.6, with fractional Maxwell rheology for the top and bottom layers and linear elasticity for the central layer. Two cases are considered: uniform horizontal compression and uniaxial exhumation. In the first case the asymptotic solution corresponds to the same compressive stress in all the layers whilst for the second example, in iso-strain conditions, the central layer is progressively loaded. **Section 6.4** ends up the chapter with a discussion of plane strain conditions for elastic and viscoelastic models so as to introduce the last chapter of the thesis on modeling stresses resulting from the glacial rebound in the Baltic basin.

Modeling of the stress field in the Baltic sedimentary basin is discussed in **Chapter 7**. After a brief review of the main stress provinces of north-western Europe in section 7.1, a simplified vertical profile of the sedimentary Baltic basin is provided in section 7.2. **Section 7.3** starts with a summary of the most resent glacial loading history and the proposition that the maximum horizontal principal stress is directed perpendicular to the glacial front with no strain in the perpendicular direction so that a two dimensional layered model may be proposed. In **sub-section 7.3.1** the initial stress field that existed prior to glaciations is discussed and assumed to be strike slip with horizontal principal stress differences equal to 20 MPa at a depth of 2.8 km. **Sub section 7.3.2** discusses the effect of glacial loading alone with two different models. The first one assumes that the layers are elastic and perfectly bounded, whilst the second one considers fractional Maxwell viscoelastic materials. The fractional Maxwell viscoelastic model is found to predict always higher differences between stiff and compliant layers as compared to the elastic model. Further, because glacial unloading is much faster than glacial loading, the viscoelastic response is closer to the elastic response and the relaxed viscoelastic layers develop tension. **Sub-Section 7.3.3** presents results of the total stress model, i.e. the superposition of the initial state of stress with that resulting from glacial loading.

The manuscript ends up with a summary of what are considered important results namely that the frictional equilibrium principle does not apply to the Baltic basin and that vertical stress profiles reflects both the time dependent properties of the various geo-materials involved by the profile as well as by the bounding conditions at interfaces between the various layers.

From my own perspective on the characterization of stress fields in the upper crust and more specifically that in sedimentary basins the original part of the doctoral thesis concerns the consideration of visco-elasticity, with the correlative issue on time constants. Nearly all the papers that discuss direct stress measurements consider only elastic models and try to correlate plate tectonic considerations with results from the stress measurements. This dissertation demonstrates very efficiently that this type of analysis is simply erroneous. In addition the dissertation relies on excellent laboratory measurements for the characterization of some aspects of the visco-elastic behavior of shales an these data ae likely to become classical references.

I appreciated more particularly the effort to separate effects of the spherical component of stress from that of the deviatoric component as well as the idea of time dependent Poisson's ratio, and I was happy to note that author has pointed out the role of pressure solution as a time dependent source of deformation.

Interestingly, in my 2017 paper with Vincent Magnenet, published in the Journal of Geophysical research (Magnenet V, F.H. Cornet and C. Fond; 2017. Present-day non-tectonic sources of stress in the Paris Basin sedimentary formation; *J. Geophys. Res.-solid earth*, **122**, pp 9313-9327) we also consider pressure solution as a source of time dependent deformation which may be modeled as an effect on the Poisson's ratio for a privileged direction associated with the preferential orientation of fractures. In our model, pressure solution results in a loss of volume that affects the void ratio of the fracture volumes with preferential orientations. It would be interesting to discuss how such a model may be accounted for with the fractional Maxwell models introduced by authors.

I was very pleased to observe that author had read my paper with Y. Wileveau on stress measurements in the Paris basin, but he has not observed that these measurements outline some local decoupling between the various layers. Indeed, in table 1, a 40° rotation of the maximum horizontal principal stress direction principal directions may be observed at the interface between oxfordian limestone and Callovo-oxfordian clay stone. This rotation outlines the existence of a local loss of bound between the two layers, which cannot be observed if only iso-horizontal strains are considered. In fact, as proposed by Magenet et al. in their discussion, a simple way to introduce non-iso horizontal strain is to consider small lateral variations in the geo-mechanical characteristics of the sedimentary material, as suggested also by Cornet and Roeckel

(G.J.I., 2012) for another discussion of the stress field in the Paris Basin, at the same location but with results from a number of vertical boreholes distant a few km from each other.

And this will conclude my report. I have been very pleased by this exploration of the role of visco-elastiity on the stress field observed in sedimentary formations. But in the process, author has raised very important and yet unanswered issues, such as reconciling the time constants of laboratory experiments with those of geological processes. This is the demonstration that his work is a real contribution to science and that author has opened perspectives, which I hope he will further explore in the not too far future.

I am very pleased to recommend that the title of doctor be awarded to Maciej Trzeciak.

Francois Cornet

Professor emeritus, Strasbourg University.

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F. H. Cornet