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Tectonic pressure: Theoretical concepts and modelled examples

Neil S. Mancktelow

Geologisches Institut, ETH Zürich, CH-8092 Zürich, Switzerland

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Abstract

Pressure variation due to deformation is an intrinsic property of fracture and flow in all materials, including rocks under geological conditions. Strong gradients occur at rheological boundaries (due to inclusions, layers, channels, shear zones, boudin necks, etc) and these gradients are instrumental in driving local pore fluid and/or melt flow during deformation. The pressure distribution in deforming rocks is not static, but changes in space and time. A clear and relevant natural example is the variation during buckle folding of strong layers embedded in a weak matrix. Local pressure gradients and magnitudes can therefore change without any associated change in depth. The magnitude of tectonic pressure is determined by a non-dimensional pressure parameter, reflecting geometry and position, and a scaling factor, with units of stress (Pa), given by the strength of the rock. Brittle fracture places an upper limit on rock strength. For Mohr–Coulomb yield, the tectonic overpressure is equal to the effective vertical load (or "lithostatic pressure"− pore fluid pressure) in the case of plane strain crustal shortening. Deep seismic failure in relatively dry rocks, as recorded by pseudotachylytes developed under lower crustal or even eclogitic conditions, is therefore direct evidence for significant tectonic pressure. For viscous materials, tectonic pressure scales linearly with flow stress, or alternatively with the effective viscosity and strain rate. Typical tectonic pressures related to folds, boudins, or strong inclusions are of order 1–2 times the maximum shear stress that the strong material can support. However, even geologically weak materials (e.g. effective viscosity 10^{19}–10^{20} Pa s) can develop very significant tectonic pressures (on the order of many 100's of MPa to several GPa) when the flow is confined, such as during extrusion or convergent channel flow between strong walls, as has been proposed for active subduction zones. The maximum overpressure in this case is limited by the strength of the confining walls, which do not have to be unrealistically strong (or rigid) for the development of significant tectonic pressures.

Keywords: Tectonic pressure; Overpressure; Deformation; Flow; Fracture; Tectonic stress

1. Introduction

In the earth sciences, pressure is often assumed to be a well-defined variable dependent on depth and density according to the equation $p_l=\rho_{av}gz$ (ρ_{av} is the average rock density from surface to depth z; g is the acceleration due to gravity), where p_l is referred to as the "lithostatic pressure". This relationship, known in fluid dynamics as Pascal's law or principle, is attractive because it allows pressure estimated from geobarometry (usually based on the metamorphic mineral assemblage) to be directly converted to depth and thereby integrated into tectonic models of burial, deformation and exhumation. However, Pascal's law is only strictly valid for an incompressible fluid at rest, in which there are no shear stresses and normal stress is isotropic. This is not a realistic model of the dynamic earth and all rheological models for deformation of natural rocks imply a state of stress that is not isotropic but described by a second order tensor, involving components of shear and normal stress that vary with direction. As considered more

E-mail address: neil.mancktelow@erdw.ethz.ch.

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thoroughly in Sect. 3, pressure p is in this case defined as the isotropic part of the stress tensor, which is an invariant quantity equal to the mean normal stress. Volume change is directly related to pressure through a material constant (the compressibility), which for rocks is on the order of 10^{-11} Pa^{-1} (e.g. Turcotte and Schubert, 1982). A relatively large pressure change therefore causes only a very small volume change, which is in general elastic and recovered on unloading. It follows that the pressure history through geological time can only be estimated indirectly, from the preserved mineral assemblage and its chemistry or from deformation structures, in particular if these involve a pressure-sensitive rheology (e.g. brittle fracture).

When the value of mean stress is greater than the lithospheric value given by Pascal's law, the difference has been referred to as "tectonic overpressure" (e.g. Rutland, 1965). Although tectonic overpressure has received the most attention, the opposite case, namely "tectonic underpressure", is equally possible and may be crucial in the development of some common deformation structures (e.g. boudins developed by extensional fracture), as will be discussed below. Tectonic underpressure could also be important on a larger scale, providing the hydrodynamic suction force that prevents detachment of the subducting plate from the overriding plate in the lower part of subduction channels (Jischke, 1975). It has also been proposed that such hydrodynamic suction may be responsible for back-arc spreading during slab roll-back (e.g. Hassani et al., 1997).

In natural systems, there will always be a component of tectonic pressure reflecting the state of stress and therefore indirectly the strain, strain rate and boundary conditions, often locally provided by some geometric constraint (e.g., on a large scale, the boundaries of a subduction channel or, on a small scale, the walls of a boudin neck). The unanswered questions concern its potential magnitude and whether effects directly attributable to tectonic pressures are preserved in the geological record. That very significant tectonic pressures can be maintained, at least on the small scale, is apparently well established from the study of Parkinson and Katayama (1999). They present Raman microspectroscopy evidence that ultrahigh-pressure conditions can be preserved at the surface in coesite inclusions within zircon and garnet. However, evidence for or against tectonic overpressure is more typically equivocal, because geological markers that directly record depth, rather than the assumed proxy, pressure, are almost invariably lacking.

The whole debate over possible geological effects of tectonic pressure has unfortunately become rather polarized. There is no doubt that pressure is fundamentally determined by the depth of burial and that tectonic pressure effects represent a perturbation on this basic gradient. However, it is also obvious that every high-pressure experiment is an example of tectonic overpressure, and overpressure values on the order of 10's of GPa are now readily attained in the laboratory. Indeed, as already pointed out by Jamieson (1963) many years ago, experimental rigs for investigating metamorphic reaction or rock deformation at high pressure (e.g. Tullis and Tullis, 1986) have several generic characteristics that could be directly relevant to natural conditions:

(i) overpressured samples do not have to be particularly strong and in many high T and high P experiments are in fact rather weak — indeed the surrounding pressure medium that maintains the confining pressure is specifically chosen to be very weak (e.g. argon gas, oil, talc, molten salt) so as to maintain a near hydrostatic pressure;
(ii) high pressure is attained as the result of confinement within a stronger pressure vessel, with the geometrical arrangement intensifying the pressure to values considerably in excess of the ultimate strength of the material from which the pressure vessel is constructed (e.g., in the rigs considered by Jamieson, 1963, three to nine times the normal compressive strength of the carbides used);
(iii) the volume of the confined material is small compared to that of the pressure vessel.

As discussed and modelled below, confinement or extrusion between stronger plates, which need not be rigid, can indeed lead to strong local pressure enhancement for assumed rheologies and geometries that are conceivable during natural rock deformation.

The debate about "tectonic overpressure" has typically concentrated on the potential magnitude, mainly because the discussion has been tied to the question of formation and exhumation of (ultra-) high pressure rocks (Brace et al., 1970; Ernst, 1971; Mancktelow, 1993, 1995; Green, 2005). As will be argued here, high overpressures on the order of many hundreds of MPa are certainly conceivable for highly constrained flows and for strong rocks, especially those strong enough to still fail in a brittle manner. However, the controversy about potential magnitudes tends to overshadow a wider discussion of common deformation structures, such as blocky boudinage, pressure shadows, pressure solution, veining on the outer arc of buckle folds, reaction textures, etc, that clearly develop as a result of spatial variation in tectonic pressure. It should also be recognized that it is the gradient in tectonic