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Glacial tectonics: a deeper perspective

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Abstract

The upper 5–10 km of the lithosphere is sensitive to slight changes (< 0.1 MPa) in local stress caused by differential loading, fluid flow, the mechanical transfer of strain between faults, and viscoelastic relaxation in the aesthenosphere. Lithospheric stresses induced by mass and fluid transfers associated with Quaternary ice sheets affected the tectonic regimes of stable cratons and active plate margins. In the latter case, it is difficult to differentiate glacially induced fault displacements from nonglacial ones, particularly if residual glacial stresses are considered. Glaciotectonics, a sub-subdiscipline within Quaternary geology is historically focussed on reconstructing past glacier regimes and, by definition, does not include these effects. The term "glacial tectonics" is hereby suggested for investigations focussed on the past and continuing influences of ice sheets on contemporary tectonics. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Presently, there is a conceptual shift in the geosciences away from increasing specialization, towards more integrative problems at global scales, a shift embodied by the phrase "Earth System Science" (Kump et al., 1999). Simultaneously, technologically driven advances in instrumental and computational techniques are permitting earth scientists to identify and explain synoptic variations in topography, seismicity, and ambient crustal stress that were not recognizable a decade ago. The recent paper by Peltzer et al. (1996) is a case in point; they used synthetic aperture radar (SAR) interferometry to explain the disappearance of transient topographic anomalies at the centimeter scale resulting from the 1992 Landers (California, USA) earthquake, anomalies erased by the in-migration of fluids to 4 km depth. As these conceptual and technical trends continue, the seismotectonic effects of past fluctuations of Quaternary ice sheets are becoming easier to notice and explain. As a result, the role of glaciers in earth deformation is being recognized at a range of spatial scales: from deformation within the ice itself to the reactivation of tectonic faults in response to crustal unloading and viscoelastic relaxation of isostatic anomalies. Broader recognition of the multiple effects of glacial mass transfers is blurring the distinction between the study of tectonics, per se, and the study of "glaciotectonics", which, historically, has been primarily concerned with deformed glacial deposits.

In this paper I show how the physical coupling between glaciation and crustal deformation extends far beyond the decollement between ice and its substrate (i.e. beyond the scope of glaciotectonics), and instead operates up to crustal scales. I begin by reviewing recent research illustrating the sensitivity of the earth's crust to stress differences far smaller than those associated with ice sheets. I then introduce examples of glacially induced, crustal scale deformation from a passive cratonic setting (Fennoscandia) and an active continental margin (Cascadian subduction zone). Next, I explore the basic mechanisms of glacially induced tectonics — effective vertical stress, membrane flexure, and traction at the base of the crust — and how each of these mechanisms is modified by the contrasting tectonic domains associated with compressive, extensional, and transform strain. Finally, I revisit the question of the scope of glaciotectonics.

2. Sensitivity of the Earth's crust

The ambient seismicity in many regions is extremely sensitive to small changes in stress, regardless of cause. For example: Rydelek and Sacks (1999) recently demonstrated that seemingly trivial changes in the confining

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stress (0.1 MPa) are sufficient to nucleate earthquakes; King et al. (1994) proved that fault displacement in one locality can transfer stress to other faults at continental scales; and Pollitz et al. (1998) implicated the aesthenosphere in the transfer of stress across the North Pacific Ocean from the Aleutian Islands to California.

The role of crustal pore pressure in tectonic processes has also been recently clarified. For example: Rojstaczer and Wolf (1992) documented a tenfold increase in baseflow stream discharge following the 1989 Loma Prieta (California, M 7.1) over a radius up to 50 km from the epicenter; Episodic movements on great transform faults (Byerlee, 1993; Sample and Reid, 1998) are toggled by pore pressure variations; Thrust faults within accretionary wedges at continental margins (Bolton et al., 1999) are regulated by hydro-mechanical (valving) processes which partition an otherwise continuous process (subduction) into discrete episodes of deformation. Decollemonts would be mechanically impossible without high pore pressures.

Artificial triggering of earthquakes by human activities, now well established, works primarily through the effects of fluid pressure. For example, the injection of petroleum brines, waste-water, and experimental tracers have initiated brittle faulting to a depth of 9 km (Jost et al., 1998). Conversely, the withdrawals of fluids influence seismicity to a minimum depth of 4 km (Gomberg and Wolf, 1999; Segall, 1989). The so-called "delayed" response of reservoir seismicity has been shown to be a consequence of the migration of fluid pressure towards potential asperities on faults, with rupture occurring when a threshold pressure is reached. Dry effects such as crustal loading by water-supply reservoirs (Simpson et al., 1988; Mandal et al., 1998), the extraction of mass from large open-pit mines, and underground explosions are generally less important than fluid effects.

Stress changes caused by human activities are small with respect to those of ice sheets, present or past, which also precipitate and dampen earthquake processes. For example, Johnston (1987) calculated that the East Antarctic Ice Sheet was responsible for a loading stress reaching 59 MPa, although the change in effective stress is much lower. Glaciers, as agents of denudation, are also responsible for permanent mass transfers from highlands to depositional basins, but at a much slower rate than ice loads. The closest analogue to a glacially induced seismicity from fluids was the damaging Koyna (India) earthquake of December 10, 1967 the largest known reservoir earthquake (Mandal et al., 1998). Its main shock was a strike-slip event with a magnitude of 6.2 (Simpson et al., 1988) and a focal depth of less than 5 km, but aftershocks extended to at least 15 km depth in a zone nearly 10 km wide and 30 km long. Carefully instrumented variations in aftershock micro-seismicity indicate that the state of stress in the crust in Koyna was controlled by inter-annual variability between wet and dry years as well as the water level in the reservoir.

Earthquake nucleation processes similar to those beneath the Koyna reservoir — dry loading, poroelastic volume changes, fluid transfers — took place on a much larger scale in the vicinity of former Quaternary Ice Sheets. Although the direct loading and pore pressure effects are most easily understood, the growth and decay of ice sheets were also associated with crustal flexure and aesthenospheric relaxation. Although recognized as important for more than century, the tectonic coupling between ice sheets (the water component of the lithosphere) and the crust (the silicate component) is seldom considered in geologically based reviews of the seismotectonic literature (Yeats et al., 1997; Keller and Pinter, 1996).

3. Contrasting examples

Postglacial fault scarps in northern Fennoscandia are the dramatic surface expressions of faults penetrating the Baltic shield to a depth of about 40 km (Arvidsson, 1996). The most conspicuous, the Parvie Fault in northern Sweden, with a vertical displacement of 10 m and a rupture length of 150 km (Lagerback, 1992; Muir-Wood, 1988) may have generated a deglacial earthquake with an extraordinary magnitude ($Mw = 8.2$). Similar, albeit smaller, faults are known for the Canadian and Siberian shields (e.g. Dyke et al., 1991), in tectonic settings that requires the "externally imposed failure conditions" (Johnston, 1996) caused by glacial loading. Although the Parvie Fault, as well as their counterparts on other shields, was formed during deglacial mass transfers, it remains somewhat active today, as evidenced by continuing micro-seismicity. Ironically, modern seismicity has a glacial heritage.

Building on previous models (Hasegawa and Basham, 1989; James and Morgan, 1990; Johnston, 1987; Mörner, 1980; Muir-Wood, 1988; Stewart and Hancock, 1994) I applied the idea of crustal-scale glaciotectonic deformation to an active plate margin in the Cascadia Subduction Zone, arguing that the tectonic processes in the fore-arc basin of the Puget Lowland were, and continue to be, compromised by the mass and fluid transfers associated with Quaternary glaciation (Thorson, 1996). More specifically, I predicted that a much simpler, preglacial ambient tectonic regime has become partitioned into four discrete time domains, all of which occur sequentially during each glacial cycle:

- A phase of normal background stress in which the direct and delayed effects of glacial mass transfers are insignificant (normal Coulomb failure).
- A phase of mass loading/crustal strengthening in which the combination of ice thickening and isostatic

outflow reduced the deviatoric stresses, contributing to stability.
- A phase of unloading/weakening during early postglacial time associated with significant fault displacements caused by fluid overpressuring and enhanced traction at the base of the crust due to isostatic inflow.
- A recovery phase in which ambient tectonic stresses, supposedly "erased" during the deglacial phase, re-accumulated to background values.

An attempt to test this hypothesis with field data (Holocene fault displacements) was encouraging, but inconclusive.

Since publication of that paper, the evidence for linking glacial unloading with a transient phase of intense deglacial tectonism has been strengthened. Nearly 40 years ago, Easterbrook (1963) published evidence for an enigmatic emergence and re-submergence of a crustal block near Deming, in northwestern Puget Lowland, during glaciomarine conditions about 12 ka. Owing to the magnitude of the required oscillation (30–70 m), the interpretation of these features remains controversial. Recently, Dragovich et al. (1997) linked these vertical motion anomalies (as well as a concentration of bedrock landslides) to the leading edge of the upper plate of a thrust fault exhibiting both Neogene offset and modern seismic activity. Emergence was likely caused by at least 30 m of localized tectonic uplift during the most rapid phase of deglaciation, an interval when isostatic uplift took place at a rate between 10 and 30 cm yr^{-1} (Dethier et al., 1995), and when the rapid northward flow of a low-viscosity mantle was in phase with the plate convergence direction (10^{18}–10^{20} poise; James et al., 2000).

Tectonically, this uplift can be interpreted as a structural wedge caught between the leading edge of a Quaternary thrust fault and an antithetic reverse fault behind it. The subsequent re-submergence is more enigmatic, but may have been caused by normal faulting and backtilting associated with a subsequent phase of crustal extension associated with continued growth of the uplift dome (Muir-Wood, 2000). Curiously, two other elevated anomalies in uplift profile — Mt. Vernon (Dethier et al., 1995) and Alki Point (Thorson, 1996), also lie on the upper plate of thrusts (Johnson et al., 1999). The amplitudes of the topographic anomalies ($>$ 30 m for Deming on the McCauley Creek Thrust, ca. 22 m for Mt. Vernon on the Devil's Mountain Fault, and ca. 9 m for Strand A of the Seattle Fault) scale with fomer ice thickness and with the magnitude and rate of isostatic uplift.

4. Glacial tectonics

The magnitude of the deglacial uplifts involved in Puget Lowland and the intimate connection between pre-existing tectonic structures and glacially induced deformation, blurs the distinction between tectonics and glacially induced tectonics. Strictly speaking, the glacier itself is a tectonic phenomenon. The base of each ice sheet is

> a rapidly propagating, gravity-driven detachment fault, taking place entirely within the lithosphere. The loss of ice by melting is analogous to un-roofing by denudation … The glacier sole is essentially a slickensided decollement, smeared with fault gouge. The rigid lower plate (the crust) undergoes elastic flexure and changing deviatoric stresses caused directly by the load, and indirectly by the transient decay of the isostatic anomaly and excess pore fluid pressure. (Thorson, 1996, p. 1187)

What separates glacial tectonics from "normal" tectonics is less the physical processes involved or the scope of their influence, but the time scale.

5. Glacial tectonic mechanisms

Kinematically, there are three principal directions in which the forces associated with a change in glacier mass can influence the state of stress of the lithosphere: The stresses can be imposed: vertically through changes in effective stress; horizontally by imparting a shear traction at the top of the crust (conventional glaciotectonics) or at its base (horizontal component of the viscoelastic response in the aesthenosphere); or three dimensionally with respect to volumetric strain and flexure. All of these effects, treated separately below, take place simultaneously, and can overlap in time (Fig. 1).

5.1. Effective vertical stress

Here we consider three limiting cases. In the simplest limiting case, pore pressure effects are absent, allowing the growth of an ice sheet (of infinite width) to create a direct, instantaneous, lithostatic increase in the vertical stress:

$$\Delta\sigma_v = \rho_i \, g \, h_i,$$

where $\Delta\sigma_v$ is the change in vertical stress, ρ_i is the density of ice, and h_i is the ice thickness. This effect is equivalent to the "rapid" reservoir response in induced seismicity directly beneath impoundments. Owing to the Poisson effect, however, the increased vertical stress also causes a proportional (but lower) increase in the horizontal stress, or $\Delta\sigma_H$, reducing the potential deviatoric (i.e. tectonic) stress. The importance of loading diminishes with depth as the stress ratio between pre and post-loaded conditions declines. The principal effects are elastic and instantaneous.

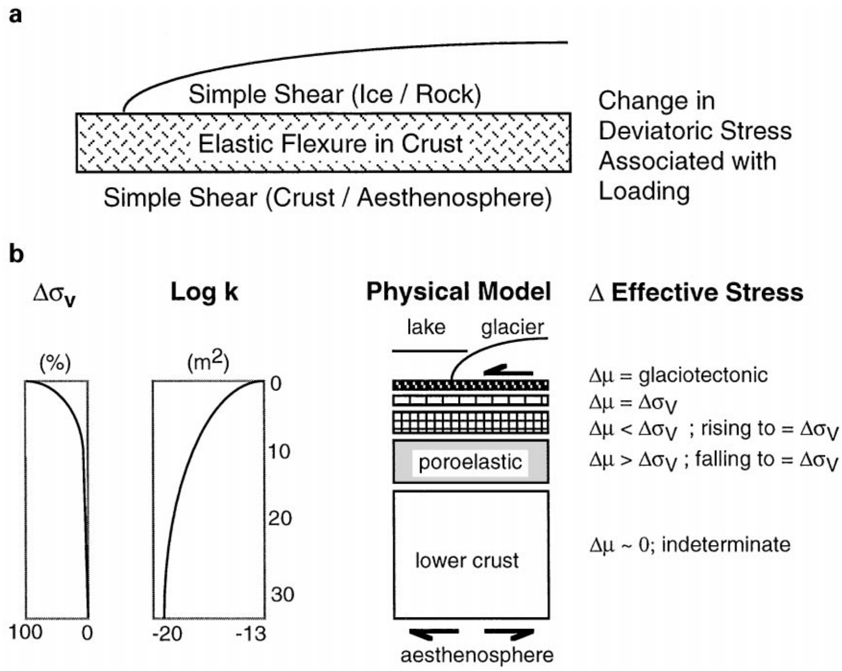

Fig. 1. Schematic diagram showing glaciotectonic domains and processes. (a) Three fundamental processes associated with changes in glacier distribution; elastic effects, vertical stresses, and shear. (b) Idealized physical model for changes in vertical stress during loading. The change in effective stress is determined by changes in pore pressure (μ) and vertical load ($\Delta\sigma_V$), and are reversed and generally more rapid during unloading. Crustal permeability (k) after Manning and Ingebritsen (1999). Change in vertical load with depth is idealized. Top part of the physical model has no scale; the thickness of layers is exaggerated to show differential responses.

In a second limiting case, a wet-based ice sheet is saturated with fluid water to near its surface, and the water has unlimited access to the base in an isotropic crust. In this circumstance, the change in effective vertical stress ($\Delta\sigma_{vE}$) is zero because the increased fluid pressure ($\Delta\mu$) fully compensates the increased vertical load ($\Delta\sigma_v$). Alternatively

$$\Delta\sigma_{vE} = 0 = (\Delta\sigma_v - \mu).$$

This limiting case is realistic for ice-loaded shield areas well inside the glacial margin, where fractures in strong rocks to a depth of several kilometers are open to the surface, and where the high fracture permeability does not restrict the flow of fluids. In these circumstances, changes in the effective vertical stresses remain close to zero because the fluid pressure instantaneously mirrors the changes in load. Changes in horizontal stresses through the Poisson effect remain important.

In cases where the potentiometric surface of fluid water within the ice sheet falls to a level appreciably below the glacier surface, then the effective vertical stress is raised by the proportional decrease in fluid pressure. Conversely, during glacier surges, the potentiometric pressure from meltwater ($\rho = 1.0$ g/cm^3) may exceed the added vertical load of the ice ($\rho = 0.9$ g/cm^3), causing a transient reduction in the effective vertical stress during a time of rapid mass transfer. Thus, micro-seismicity associated with glacier surges (Kamb et al., 1985) likely takes place in the bedrock, as well as within the ice.

The permeability of the Earth's crust, whether sedimentary basins, fractured crystalline basement, and volcanic rocks, decreases systematically with depth, owing to increased confining pressure and the closure of fractures (Fig. 1). Based on studies of metamorphic fluids and heat transport (Manning and Ingebritsen, 1999), the permeability (k) in SK units of "m^2" varies with crustal depth (z, km) in a simple, log–log relationship spanning at least 10 orders of magnitude:

$$\text{Log } k = -14\text{–}3.2 \log z.$$

Log k for sedimentary basins to a depth of 7 km ranges from -12 to -16 m^{-2}. Volcanic rocks and crystalline basement are typically one-to-two order of magnitudes less permeable. Although conceptually straightforward, defining the boundary between meteoric and connate water is difficult in actual practice. The relationship between permeability and depth is least reliable in the shallow crust owing to greater variation in horizontal stress and to lithological heterogeneity.

At some depth, fracture aperture is small enough to limit the permeability, forcing glacially induced pressure changes to take place gradually. The depth at which this transition takes place is not known, but likely ranges widely from about 0.5 km to more than several km. This time-dependent migration of fluids in the shallow crust

(Peltzer et al., 1996) is similar to the "delayed" effect for reservoir seismicity (Simpson et al., 1988) and injection experiments (Odonne et al., 1999), which takes place over time scales of weeks to years. In the glacially induced version of this scenario, changes in fluid pressure of "meteoric water" in the open, but low-permeability crust, will lag each instantaneous increment of load. This will cause an instantaneous rise in the effective vertical stress that will decay as the pressure re-equilibrates. Non-linear changes in the permeability may occur during re-equilibration, possibly through the geochemical effects (stress-corrosion) of infiltrating water (Kisslinger, 1976).

At greater depth, however, where poroelastic effects (Segall, 1989) predominate, connate fluid plays a critical role in supporting the crust. A glacially induced increase in vertical stress ($\Delta\sigma_v$) will be fully compensated by an instantaneous rise in fluid pressure, one that will gradually bleed off through fluid out-migration. This will cause a transient phase during which an initially weakened crust will strengthen, an effect opposite that in the next-higher layer, where the initially strengthened crust will weaken. At even greater depths, fluids are not free to migrate upward, the proportional change in hydrostatic pressure diminishes, and anisotropy plays a critical, and largely unknown, role in modulating the effects of the ice load.

Near the edge of the glacier, however, the effects will be more complicated. Disregarding fluid effects, the differential weighting on either side of a glacier margin will be felt immediately as the crust is elastically compressed below the load, with no compression beyond it. When fluid effects are considered, the differential stresses are greater because the glacier imparts a new hydraulic gradient on the system. Seepage pressures, particularly near the ice margin, may also influence the ambient stress. Membrane flexure of the crust during isostatic compensation will cause radial compression and extension beneath the ice load and in the forebulge domain, respectively, deformation that will affect crustal permeability.

5.2. *Horizontal traction; top and bottom*

Drag forces at the glacier–bed interface are controlled by the effective overburden stress (ice thickness reduced by fluid pressure), the viscoelastic properties of the ice, and the frictional properties (Mohr–Coulomb) of the boundary. Three limiting cases can be visualized. In the first case, thick ice is frozen to a flat, crystalline bed; horizontally flowing ice and the stationary bed form an ideal simple shear couple limited only by the slow rate of ice deformation; in this case, the shear on the rock is trivial. In the second case, the ice moves continuously above a very weak, deforming bed, which fully compensates the shear stresses. As before, negligible shear is propagated downward to the lithosphere. In the third case the ice is frozen (or frictionally bonded) to its bed near the margin, with groundwater outflow taking place beneath the ice–bed interface in strata where the permeability is limiting. In this circumstance, the frictional bond between the glacier and its bed (whether rock or unconsolidated sediment) is stronger than in deeper materials, even that of jointed bedrock. The traction associated with the advancing ice can thus be transferred downward into the crust, with displacement along faults, both brittle or ductile, taking place to a depth of up to several hundred meters, and involving intact slabs of the lithosphere at the kilometer scale (Aber, 1988). The depth and behavior of such effects are controlled primarily by the strain rates being applied. Thrusting at the ice margin, which leads to the familiar push moraines and imbricate ridges, is conceptually similar to the behavior at accretionary wedges of subduction zones.

A second type of horizonally–directed shear takes place at the base of the rigid crust through the effect of horizontal flow within the asthenosphere (James and Morgan, 1990). Traditionally, studies of glacioisostasy have focussed on the vertical component of motion and on crustal flexure (Mörner, 1980), but the horizontal flow between the forebulge and the subglacial depression, can be quite rapid, up to a meter per year. Recent geodetic investigations in the western US confirm that viscoelastic relaxation in the aesthenosphere after major earthquakes (Rydelek and Sacks, 1999) raises the strain along other, distant faults. Similarly, horizontal isostatic motions during loading and unloading must enhance or diminish the horizontal components of regional stress (Muir-Wood, 2000).

5.3. *Three-dimensional flexure*

Mechanical loading is has been reviewed by Turcotte and Schubert (1982). Slab loads, line loads, point loads, end loads, and embedded loads all create flexures of the lithosphere, the size and shape of which are governed largely by the effective rigidity of the crust, which, is sensitive to the third power of membrane thickness. The physics of the process are independent of the composition of the load, whether glacier ice, crystallized lava, or a sedimentary accumulation. Hence, the familiar "moat-forebulge" profiles of volcanic islands, foreland basins, and glacial margins are similar. Importantly, membrane flexure includes zones of convexity where the crust is radially dilated, and zones of concavity where it is radially compressed. Radial and tangential extension on the forebulge, and radial compression beneath the ice sheets took place during the loading hemicycle; the reverse took place, and with higher strain rates, during deglaciation, a process that continues today.

6. Complications

6.1. *Ambient crustal stress*

In the previous discussion, I made the simplifying assumption that the ambient lithospheric stress was isotropic. Lithospheric stress, however, varies continuously and heterogeneously in response to plate motion, topographic loading, exhumation, and the mass transfer of water during ice ages. Generally speaking, the state of crustal stress can be classified into one of three categories:

In a compressive, or thrust regime, the principal stress (σ_1) is horizontal and the minimum stress (σ_3) is vertical. Increased effective vertical stresses stabilizes the system by reducing the deviatoric stress. Conversely, a reduction in effective vertical stress pushes the system towards instability. Fluid injection often produces earthquakes with focal solutions consistent with at least a component of reverse faulting (Jost et al., 1998) because the effect of fluid injection is to raise the pore pressure, which reduces the effective vertical stress. In an extensional, normal fault regime, σ_1 is vertical and σ_3 is horizontal. Increasing the effective vertical stress helps destabilize the system, whereas reducing the vertical stress stabilizes it. Fluid extraction (Gomberg and Wolf, 1999) increases vertical stress by reducing the pore pressure, and is thus often associated with normal faulting (Amelung et al., 1999). In a strike slip regime, where σ_1 and σ_3 are both horizontal, an increase in the effective stress stabilizes the system through the Poisson effect; pore pressure is especially important in regulating strike slip faults.

Although there are broad tectonic domains where the ambient stress is relatively uniform, local stresses are often highly heterogeneous at a variety of scales (e.g. Mueller et al., 1999). Additionally, most faults have an oblique component of motion involving two of the idealized regimes above.

6.2. Glacial history

The tectonic effects of Quaternary ice sheets are unique because their effective loads can change rapidly, more than several orders of magnitude faster than the processes of mountain building and erosion. Although the stresses are lower than for lithospheric forces, the stress gradients and strain rates can be significantly higher, causing brittle rupture where ductile failure might have otherwise occurred. Also, unloading is usually much more rapid than loading, reversing many of the effects described above. Importantly, the effects of loading and unloading work in opposite directions, allowing the possibility for glaciers to trigger episodes of rupture regardless of ambient stress. They push and pull.

6.3. Coupled effects

Given the three basic directions of applied stress, the three fundamental stress domains, the heterogeneity of local stress within the crust at a variety of scales, and the asymmetric history of ice sheet loading and unloading, glaciotectonic stresses will be complex. Additionally, the effects can either amplify or diminish one another. For example:

- The creation of a forebulge may contribute to radial jointing, which may increase crustal permeability, which may decrease the pore pressure beneath the ice margin, which may steepen the ice profile, which may cause even greater flexure, etc.
- Aesthenospheric outflow caused by ice loading may enhance or diminish stresses of tectonic origin, depending on the ambient direction of plate convergence. For example, deglaciation of the Cordilleran Ice Sheet near Kodiak Island in southern Alaska may have enhanced and reduced the rate of plate convergence on the southern and northern flank of the former ice sheet, respectively.
- The rate of de-weighting caused by ablation may exceed the rate at which excess pore pressure can drain towards the surface, leaving the crust weaker than it would be under normal conditions. In thrust and strike-slip domains, this may lead to a deglacial interval of heightened seismicity.
- Fault displacement triggered by a rise in pore pressure may be a self-limiting phenomenon through the effect of stress dilatancy, in which crustal porosity is increased through microfracturing.
- Above the onset of poroelastic effects the crust (excluding normal fault regimes) is instantaneously strengthened by vertical loading, then weakened back to initial conditions by the in-migration of fluids. The opposite happens where poroelastic effects predominate; the crust is weakened, then strengthened. Both of these effects can take place simultaneously in different superimposed crustal layers, concentrating stress in subhorizontal boundaries between these zones.
- The permeability of the shallow crust is highly variable, hence the effects of changing glacial loads will be felt differentially; delayed pressure effects will continue to influence local stresses until re-equilibration, long after the ice has disappeared.

7. Conclusion

The tectonic setting of *passive* continental margins is usually characterized by a thick granitic crust, greater uniformity in ambient stress, and low strain rates (10^{-16} yr^{-1}). In such a setting — for example in Fennoscandia (Arvidsson, 1996), the British Isles (Sissons and Cornish, 1982), and the North American Craton (Adams and Bell, 1991; Andrews, 1991; Oliver et al., 1970) — glacially induced stresses are superimposed on the regional field, but may actually be the dominant factor controlling seismicity and crustal motion at the time scale of 10^3–10^4 yr (Mörner, 1991). In contrast, the tectonic setting of *active* continental margins is characterized by high strain rates (10^{-14} yr^{-1}), crustal-scale anisotropy, and the dynamic effects of plate flexure and buoyancy. In this type of setting — for example, in Cascadia (Mathews et al., 1970; Clague, 1983; Thorson, 1996), glacially induced stresses and subduction work simultaneously at Quaternary time scales. In the former case of passive margins, ice sheets modify an existing tectonic regime. In the latter case, they must be considered part of it.

Glaciotectonics, as conventionally defined, "…involves structural deformations of the upper horizon of the lithosphere caused by glacial stresses" (Van der Wateren, 1995). This definition specifically excludes deformation within the ice itself, and crustal-scale effects because the primary research objective of glaciotectonics, is the reconstruction of past glacier regimes from field observations, especially those associated with deformation of unconsolidated materials at and below the glacier sole, and with marginal thrusting at scales of 10^{-2}–10^{3} m. The academic territory of glaciotectonics is clearly defined as subdiscipline within Quaternary geology. I recommend continued use of the term in this narrowly restricted sense. A new term, however is needed, one that encompasses the deformation in the shallow crust caused by ice–bed traction, and the crustal-scale deformation described in this review. For now I suggest the following candidate terms, arranged in order of increased simplicity: glacio-seismotectonics, glacio-seismicity, glacially induced tectonics, glacial tectonics, or simply tectonics. Although tempted to adopt the last candidate for its simplicity, the term "glacial tectonics" seems an acceptable compromise between focus and breadth. The actual practice of glacial tectonics has a long pedigree. I recommend adoption of this term to help focus an important, coalescing subdiscipline within geology, one that straddles the boundary between glaciology and tectonics.

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