Evolution of Porosity and Permeability during Brittle Faulting.

By

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Abstract

Porosity and permeability in rocks are closely related because fluid needs to permeate the effective void space in order for flow to successfully occur. Fundamental relationships have been derived for permeability and porosity as a function of effective stress. Previous studies show that under low temperature and pressure, rocks fail by brittle faulting, usually accompanied by dilatancy and inelastic pore volume increase, resulting in varied porosity and permeability. The variations have also been reproduced in the laboratory and show that the correlation between porosity and permeability is not the same in all rocks. While the porosity and permeability relationship in some rocks are positively correlated, other rocks may be negatively correlated. In Berea sandstone, with initial porosity 21%, permeability reduction is observed during dilatancy just prior to faulting [*Zhu and Wong*, 1997] whereas in the case of Westerly granite, with initial porosity <1%, permeability enhancement is observed during dilatancy [*Zoback and Byerlee*, 1975]. Microstructural observations show that during brittle faulting, dilatancy is as a result of stress-induced microcracking [e.g., *Tapponnier and Brace*, 1976; *Menendez et al.*, 1996]. In Berea sandstone which contains mostly equal dimensional pores, permeability reduction is caused by the decrease in pore size during deformation, whereas the Westerly granite porosity increase is caused by microcracking. I demonstrate that two competing processes control permeability and porosity enhancement in rocks: dilatancy, resulting from microcracking is a porosity-increasing process, and pore closure as a result of stress is a permeability reducing process. The pores in Berea sandstone are modeled as one effective pore and the cracks in Westerly granite as one effective crack. I hypothesize that for a rock containing a network of microcracks and pores, permeability reduction from pore closure is more effective than permeability enhancement due to microcracking. This study will help explain various natural processes that depend on pore fluid pressure such as faulting and earthquakes, as well as economic geology involving the extraction of natural gas.

Introduction

Porosity and permeability are two primary rock properties controlling the flow of fluids in rocks and sediments and are intrinsic characteristics of geologic formations. The use and extraction of natural resources such as groundwater and petroleum is partly dependent on the porosity and permeability of the rock containing the natural resource. Rocks with more closely packed grains have less porosity than rocks with more spaced out grains. Porosity, therefore, is calculated by dividing the total void volume, V_v, by the total volume of the sample, V_t. The porosity of unconsolidated sediments is also a function of the shape of the grains and the range of grain sizes present. Although porosity and permeability are intrinsic rock properties, the amount of stress administered to a rock can affect the effective porosity and, consequently, its permeability. Effective porosity, which is the pore percentage that successfully permit fluid low, can range from less than one percent in crystalline rocks (e.g. granite) to over 20% in some sedimentary rocks (e.g. sandstone). On the other hand, porosity and permeability can also be enhanced through fracturing.

Permeability is a measure of the ease with which fluid will flow through a porous medium under a specified hydraulic gradient. Permeability depends on both the properties of the solid medium and on the density and viscosity of the fluid. Intrinsic permeability, however, depends on the properties of the rock medium alone. For this study I will focus on intrinsic permeability, because it is only affected by the intrinsic rock properties. Studies have shown inconsistencies in porosity/permeability relationships when it comes to different rocks. Although, the close relationship between permeability and porosity exists; there is no one-to-one relationship between porosity and permeability applicable to all porous media [*Bernabe et al.,* 2003]. The reason for the difference in relationship is that, for a given material, not all pores are equally effective in conducting fluid flow. Consequently, two media with the same porosity but different proportions of effective and non-effective pore space must have different permeability values.

Understanding permeability and porosity evolution is important because geologic processes such as earthquakes, faulting and overthrusting depend partly on pore fluid pressure, which in turn depends on the permeability and porosity of the rock. The theory of overthrusting is based on the existence of pore fluids under high pressure near the base of a fault block [*Hubbert and Ruby,* 1959]. The high pressure trapped under the fault block supports the enormous overthrust belt, making thrusting of unusually thick (>10 km) geologic formations possible. Pore fluid pressure also reduces the effective pressure from overburden in rocks. The Mohr's failure criterion shows an important relationship between rock strength and pore pressure. Rock strength is reduced with increasing pore pressure, which eventually causes failure.

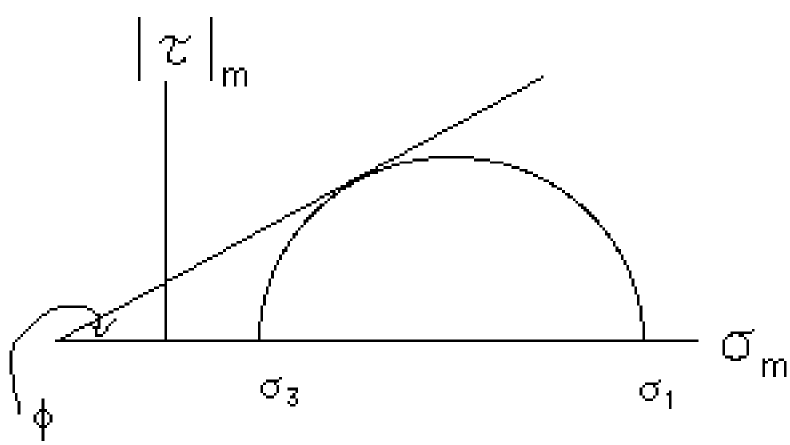


Fig. 1 The Mohr's Failure Criterion at failure. As pore pressure builds up the arc moves in the direction of σ_3. The rock fails once the arc touches the line. σ_3 and σ_1 are principal stresses.

High porosity and low permeability cause pressure buildup and a reduction in rock strength. Rock microstructure is also of great importance in the petroleum and hydrocarbon exploration industry as permeability and porosity of rocks determine the ease of the transport of crude oil from source rocks to trap rocks, and potentially preserve resources with low porosity/permeability seal rocks. A change in the microstructure of a rock would also influence the permeability and porosity. Transport properties of rocks are affected once there are rock microstructural changes. My study focuses on the evolution trends of Westerly granite and Berea sandstone. In particular, I am interested in how microstructural changes that occur during dilatancy cause different permeability and porosity trends in Berea sandstone and Westerly granite during prior to failure.

Different rocks have diverse grain arrangements, thus, different percentages of porosity. When stressed to the point of failure, rocks also evolve and respond by different amounts. When a rock is stressed hydrostatically, where there are no shear stresses and the three principal stresses σ_1, σ_2 , and σ_3 are equal, there is uniform compaction.

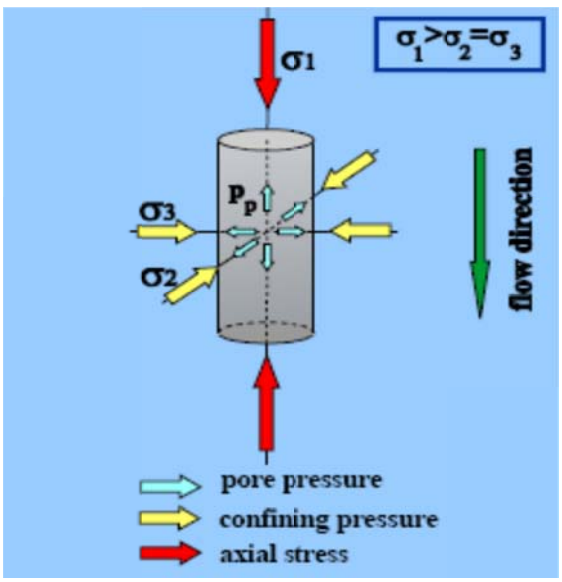


Fig 2: A rock sample stressed triaxially. σ_1 σ_2 and σ_3 are principal stresses. The stress causes brittle failure to occur under room temperature. The pore pressure, Pp acts to oppose th effect of the principal stresses. [Zhu, Wen Lu]

Once the stress increases in one direction- called deviatoric- the rock starts to experience some shear (Fig 2). Prior to brittle failure, the shear results in some microscopic cracks. As the microcracks increase and coalesce, forming larger ones, brittle failure may occur. The stage at which microcracking becomes extensive prior to failure is called dilatancy. When a rock becomes dilatant there is an observed increase in the net porosity of the rock. Because various rocks evolve differently as they become dilatant, porosity and permeability are also influenced variably. Berea sandstone and Westerly granite are structurally different. Berea sandstone with porosity of ~21% is a lot more porous owing to the equidistant pores in between grains. Westerly granite, with porosity of ~1% is a low porous rock and comprises mostly elongate cracks. I follow the observations of *Zhu and Wong* (1999) that assert during dilatancy, in Westerly granite there is an observable enhancement in porosity as well as permeability. However, in Berea sandstone, the porosity increase is followed by a reduction in permeability.

Background

Permeability-porosity evolution is expected to be different under similar conditions in most rocks. This is because porosity is invariant under homothetic transformation. That is, there is uniform, isotropic stretching of pore spaces while permeability is not [*Bernabe` et al.*2003]. Studies have shown that microcracking during deformation, can lead to a significant permeability increase and therefore enhance fluid flow (*Peach, 1991; Fischer and Paterson, 1992*). Although rock deformation may be plastic or brittle, brittle failure is the focus of this study because it involves various stages (in the microscopic level) that adequately demonstrate the dilatancy stage where observable changes in permeability and porosity occur. During brittle failure the following states are critical. Under low temperature and pressure conditions as a stressed rock starts to deform up to its yield point, the rock will undergo elastic deformation. Similar to a rubber band, if the stress is released before reaching the yield point, the rock material will return to its original structure. However, if the applied stress continues, under similar low-temperature and -pressure conditions, once the rock reaches its yield point it will break. This sort of deformation is called brittle failure.

Fig. 3 shows the path of stress a rock takes before brittle failure occurs. At stage I, called the settling stage, the stress is mostly compressive (equal compaction from all directions) and the original pore spaces start to close up. No noticeable macroscopic deformation in terms of new cracks forming is observed when the sample is stressed. This stage is similar to the compacting of a snow ball, in that there may be some volume change as the preexisting pore spaces are closed. Stage II is the Young's modulus stage, in which a preferential increase in stress in one direction, for example, principal stress σ_1, is necessary from this point up to failure. At this point the deformation is linearly elastic, because stress is proportional to strain; there is an equal amount of deformation for comparatively equal amount of induced stress. At stage III the original pores are closed and the rock structure is responding to the increasing stress. At this stage there is ongoing microscopic deformation and the microscopic structure of the rock is changing as emerging cracks start coalescing forming larger cracks. Microscopic response to stress causes changes in grain orientation and result in microcracking and the induced microcracks become extensive with increasing stress. The overall increased pore volume due to microcracking (porosity) is called dilatancy. Henceforth, porosity and dilatancy are used interchangeably. Dilatant microcracks are randomly distributed in samples recovered just before fracture [Brace, 1978]. A study by *His-Ping et al.* (1976) demonstrates that stressed granite showed a dilatants bulge which eventually developed into the fault plane.

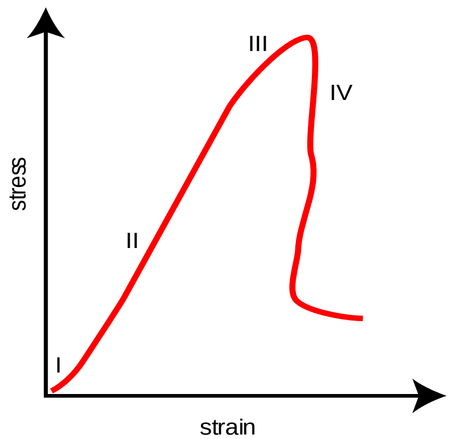


Fig 3 shows the stages a rock sample takes before brittle deformation. 1a stage I, known as pore closure stage, II the Young's modulus stage, III is the dilatancy stage, and IV is when the rock rails. 1b. Shows the three principal stresses that result in failure when rocks are stressed triaxially- σ1> σ2= σ3. *(Zhu, Wen-Lu)*

The bulk of this study occurs at stage III (dilatancy). At the dilatancy stage, increased porosity usually results in a concomitant evolution in permeability. Beyond stage III, up to stage IV, there is coalescence of microcracks, forming microscopic fractures. The microscopic fractures join up into larger macroscopic fractures as the rock experiences brittle failure. Generally, studies show precursory bulging as early as 60% of the fracture stress which is associated with the eventual fault [*Brace, 1978*]. The correlation between dilatancy and permeability at this stage is the focus of this study. During dilatancy the extensive microcracking increases pore volume but, unlike the porosity evolution which increases with increase strain, the permeability does not increase at a uniform rate with increasing strain. Close to peak stress there is an abrupt increase in volume due presumably to accelerated dilatancy, which overtakes compaction [*Brace, 1978*]. This pore volume increase known as dilatancy, is understood as an inelastic increase in volume during deformation under applied triaxial stress and is interpreted as being due to microcracking within the rock with a concomitant increase in void space [*Kwasniewski*, 2007]. *Zoback and Byerlee* (1975) investigated the porosity and permeability of Westerly Granite during dilatancy, and observed a reduction in permeability. Although their results did not precisely show porosity evolution, they indicated that as a sample of Westerly granite was initially stressed the permeability slightly decreased. With further increase in differential stress the samples became dilatant and the permeability correspondingly increased as the differential stress was removed from the sample. Also using low porosity strained calcite samples, *Zang, et al.* (1994) illustrated that under stress, permeability initially jumped about 1 to 2 orders of magnitude for stressed calcite, then gradually increased by about a half to an order of magnitude with further strain and subsequently remained more or less constant. Although, *Zang et al*. showed increased permeability, they still did not consider all induced microcracks as a reason for permeability increase, and only considered connected cracks. *Zhu and Wong* (1997) made an important comparison between low porosity Westerly granite (~1% porosity) and porous Berea sandstone (~21% porosity) and found that permeability and porosity are not positively correlated. Fig 4 shows a plot by *Zhu and Wong* (1997) showing the relationship between permeability and porosity in Berea sandstone and Westerly granite. The first half of the graph shows a reduction in permeability in Berea sandstone as stress increases, up to a certain stage, similar to the dilatancy stage in Fig. 3. When permeability is plotted as a function of porosity they do not track one another in a systematic manner. Before the onset of dilatancy, permeability and porosity were positively correlated. When the samples were loaded to near peak stress, the samples were negatively correlated (*Zhu and Wong,* 1997).

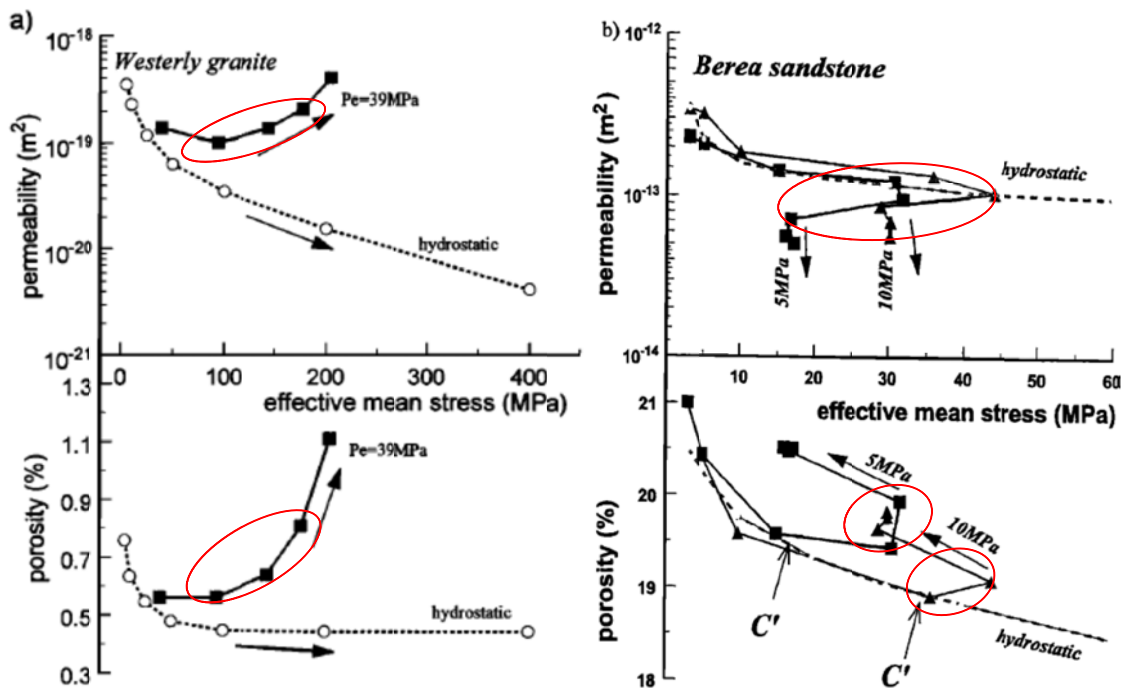


Figure 4a-b: Permeability and porosity as functions of effective mean stress in the brittle faulting regime in Berea sandstone (b) and Westerly granite (a) For reference the data for the hydrostatic tests are shown as dashed curves The effective pressures are as marked and the critical stress states C *, C', and P * are indicated by the open arrows. The plots show positive and negative correlations between porosity and permeability in Westerly granite and Berea sandstone respectively. The highlighted areas show the region of interest (ROI) for this study. It marks the onset of dilatancy in each case. [*Zhu, et al, 1997, Zhu et al, 1999*]

Although the region prior dilatancy is not a focus of this study, it is important to note that some pre existing cracks start to close at this stage resulting in some mechanical compaction and consequently, some decrease in permeability, with increasing effective pressure [*Walsh, 1965*]. This physical grain-relaxation phenomenon that occurs when rocks are stressed has little to do with the rocks becoming dilatant prior to failure. *Zhu and Wong* (1997) investigated the evolution of porosity and permeability in both rocks during dilatancy and their results raised interesting questions. They demonstrated that when a sample of Westerly granite is hydrostatically stressed followed by a triaxial stress, the porosity initially decreases, then increases. There also was a net increase in permeability. In Berea sandstone, however, increased porosity was followed by a decrease in permeability. Overall, the microscopic and macroscopic changes that result in rocks during dilatancy occur differently depending on the rock structure.

Both rocks appear to have followed the same brittle deformation path, with increasing dilatancy through microcracking. Never the less, Westerly granite and Berea sandstone experienced different overall permeability and porosity evolution. Typically, different packing structures almost guarantee different permeability/porosity evolution. In the oil industry, natural resources are extracted from different types of rock formation. In some cases, fractures/

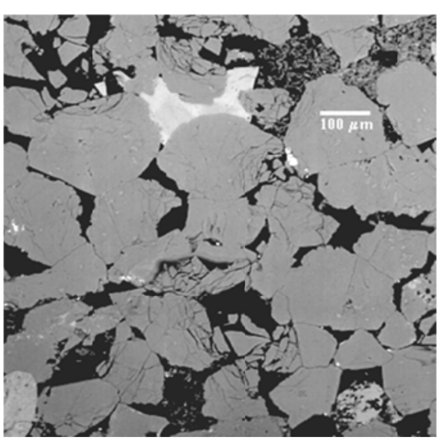
shattering are induced to enhance porosity/permeability of the trap rocks. This research should clearly demonstrate that while fracturing may improve permeability in some locations, it may certainly hamper permeability in other rocks. Understanding the evolution path in rocks with very different packing structures, (e.g. granite and sandstone) also will help explain certain geologic processes including faulting and earthquake occurrence. The reason for this evolution discrepancy is explained in my hypothesis.

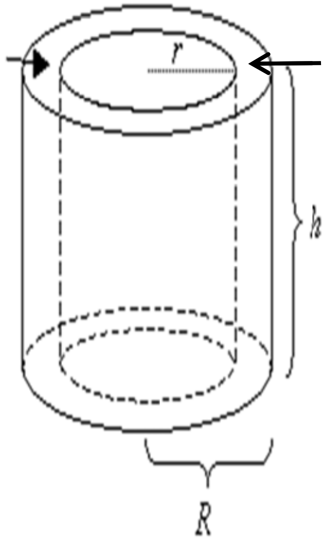
Hypothesis

During brittle faulting, particularly at the dilatancy stage, two competing processes control permeability and porosity in Berea sandstone and Westerly granite. Increased pore volume due to induced microcracking is a porosity-increasing process and closure of pre-existing equal dimensional pores due to stress is a permeability-reduction process. Secondly, for Berea sandstone, porosity increase is followed by permeability reduction, while in Westerly granite porosity increase is followed by increased permeability. Based on these observations, I hypothesize that during dilatancy, the decrease in permeability due to closure of pre-existing pores is more effective in controlling fluid transport properties in Berea sandstone than the increase in permeability as a result of microcracking. In crystalline Westerly granite with pre-existing low aspect ratio microcracks, dilatancy is purely as a result of increased microcracking, and porosity and permeability are both enhanced as a result of increased fracturing.

Method

The above hypothesis will not involve actual laboratory experiments or samples. A number of the background observations that led to my hypothesis, have already been demonstrated by *Zhu and Wong* (1997) and *Zoback and Byerlee (1975*). I will use established mathematical relationships that define intrinsic permeability, k, and porosity, Φ. At this stage of this study, a more effective way of modeling the permeability/porosity relationships for each type of rock (Westerly granite or Berea sandstone) would be to model the pore volumes as one effective pore volume. The pores in Berea sandstone seen in the micrograph in Fig. 5a as the darker areas are assumed to be tiny cylindrical tubes, of cross sectional radius, r and height S. Therefore, based on this assumption, the sum of all the pores in Berea sandstone could be treated as one effective cylindrical tube with cross sectional area radius r and height S (Fig 5b).





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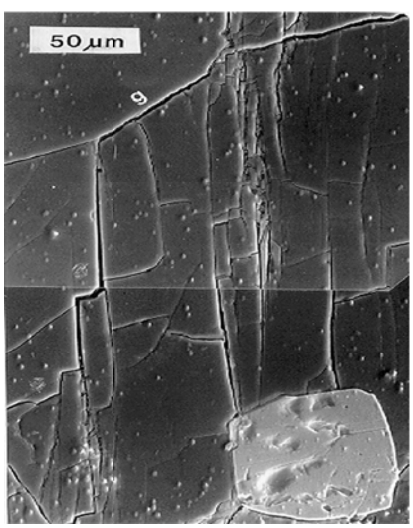
As the Berea sandstone sample is stressed and the cylindrical tube compacts, there is a reduction in cross sectional radius and at the same time the pore volume changes. The change in pore volume is expected to change the permeability of the sample. Similarly, for Westerly granite, all the preexisting pore space could be modeled as one effective elongate crack with spacing *b,* and fixed length and width, *S.* Microcracks are generally high-aspect ratio cracks. This means they are orders of magnitude longer in one dimension than in the other dimension. Fig. 6a shows a micrograph of stressed Westerly granite with high aspect ratio microcracks.



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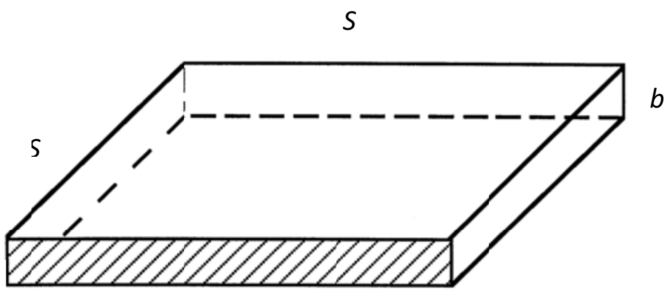
V_c

The total pore volume of the cracks is modeled as one effective crack as shown in Fig. 6a. The permeability equation for elongate cracks with spacing, *b,* and both length and width *S*, is;

$$Kc = b^3/12s \qquad eq.\ 1$$



I make several assumptions at this stage. My first assumption is that all the cracks are high aspect ratio cracks, with fixed length and width (*S*). This is because the cracks are assumed to occur between or around grains with fixed diameters, therefore only the crack opening in between grains (*b*) would change with increasing stress. The second useful relationship is the volume of a cube, considering the assumption that the cracks are one effective crack. Since the cracks are the only pore spaces, then pore volume of the effective crack $V_{\Phi c}$ is given by;

$$Vc = S^2 b \qquad \textit{eq. 2}$$

Incremental changes in pore volume of the crack (with increasing stress) would then be the derivative of volume of the cube. The derivative of the volume yields;

$dV_c = S^2 db$ and rearanging would give ; $db = dVc/S^2$ *eq. 3*

Similarly, if infinitesimal change in porosity results in a corresponding permeability change, then the derivative of *eq. 1* would yield;

$dk_c = (1/12S) * 3b^2 db$ (Where spacing, *S*, remains constant) *eq.4*

Establishing the necessary mathematical relationship requires the assumption that the cylindrical pore tubes in Berea sandstone are perfect cylinders with variable cross-sectional radius, *r*, and fixed length, *S*. Since the sides of the tubes are formed by the surface of the grains around them and the grains are also assumed to have fixed dimensions just as in Westerly granite. Then the lengths of the tubes are also expected to be fixed. When compressed horizontally, as shown by the arrows in Fig. 5b, only the radius of the pore reduces by a small amount, *dr*

For pore volume of cylindrical pore, $Vp = \pi r^2 S$ *eq. 5*
If permeability, *k*, for pores is given by, $kp = r^2/8$, then any small change in permeability is;
$dkp = 2r/8$ *eq. 6*

The corresponding change in pore volume would be $dVp = 2\pi Sr\, dr.$ *eq.7*

Induced microcracking during dilatancy and closure of pre-existing pores are simultaneous events. Therefore, if any small amount of pore volume lost by pore reduction is to be replaced by the addition of a microcrack, then; the porosity change via pore closure is the same as the porosity change via crack emergence. Mathematically, $dVp = dVc$ and

$$2\pi Sr\, dr = S^2 db \qquad \textit{eq. 8}$$

Rearranging gives $r\, dr = S/2\pi\, db$
Because the crack length and width, *S,* are both fixed, and the only change that may occur in the Westerly granite happens along the crack opening, *b*, as the pore volume, V_p closes; corresponding change in the Westerly granite will cause a change in *b*. Hence, removing dV_p results in *db*

$$dkp = r/4\, dr = S/8\pi \qquad \textit{eq. 9}$$

Adding crack volume, dV_c results in

$$dkc = b2/4S\, db \qquad \textit{eq.10}$$

Equations *6* and *7* show the respective relationships between pore permeability, cross sectional radius, crack spacing and crack permeability. The ratio *dkp/dkc* represents the relationship between the changes in pore permeability and permeability of the crack.

If the value of $dkp/dkc = 1$ then there's no net change in permeability. And both variables are equal.

If $dkp/dkc < 1$ then there is an increase in permeability, suggesting that crack permeability enhancement is greater than pore permeability enhancement.

If $dkp/dkc > 1$ then the permeability enhancement via the pores is greater and there is an observed decrease in permeability. I will show that the relationship, *dkp/dkc >1* is the case. Substituting values for dkp and $dkc,$ we have;

$$(S/8\pi\, db)/\,(b^2/4S)\ db \qquad \textit{eq. 11}$$

$\left(\frac{S}{8\pi}\right) * \left(\frac{4S}{b^2}\right)$ and rearranging gives

$$1/2\pi\,(S/b)^2 > 1 \qquad \textit{eq. 12}$$

This final relationship (*eq. 12*) is certainly greater than 1
Eq. 12 could also be rewritten as: $S/b > \sqrt{(2\pi)} = 2.5$ *eq. 13*
or taking the reciprocal, $b/S < 0.399$ *eq. 14*

Equations 12 through 14 verify that the relationship $dkp/dkc > 1$ is valid. Therefore, there is a net permeability decrease as the pre-existing pores in Berea sandstone start to close up.

The above results establish that dkp is much larger than dkc, meaning that permeability transfer through the pores is much effective than through the cracks during dilatancy. A plot of the relationship between porosity and permeability is necessary to further demonstrate my hypothesis. To accomplish this, I establish a different set of mathematical relationships using already known or previously established formulae. The aim is to establish a relationship between pore volume, Vp, of pores and the resulting permeability, kp by closure of the pores. Thus, if a sample of Berea sandstone is stressed and the net porosity is altered, the resulting permeability can be calculated. Because the pore volume change in Berea sandstone is attributed by the emergence of microcracks, I shall also calculate the separate permeability contribution by the cracks. The sum of the crack permeability, kc and the new permeability of the shrunk preexisting pores, kp would yield the net permeability.
Recall that the volume of cylindrical pore, $Vp = \pi r^2 S$ *(eq. 5)* and with increasing stress, infinitesimal change in radius would result in a corresponding change in volume expressed by the derivative given as;
$dVp = 2\pi Sr\, dr$ *(Where, S is constant). (eq.7)*

Rearranging *eq. 7* to solve for *r* would give;

$$r = \frac{2\pi S\, dr}{dVp} \qquad \textit{eq. 15}$$

Also recall from *eq. 1* that the permeability, kp for pores is given by;

$$kp = \frac{1}{8}(r^2)$$

Substituting *r*, in *eq. 15* into *eq. 1* gives the final permeability/ porosity relationship for pores as;

$$Kp = \frac{1}{8}(2\pi S\ dr/dVp)^2 \qquad \textit{eq. 16}$$

With equation 16, any change in pre-existing pore volume could be used as a variable to calculate the corresponding enhancement in permeability.

For cracks;

Recall that the volume of one effective crack (modeling all induce cracks as one effective crack), Vc is given by

$$Vc = S^2 b$$

incremental change in pore volume of the crack (with increasing stress) would then be the derivative of volume of the cube. The derivative of the volume yields;

$dVc = S^2 db$ and rearanging, $db = dVc/ S^2$ *eq. 17*

Similarly, if infinitesimal change in porosity results in a corresponding permeability change, then the derivative of *eq. 1* would yield;

$dkc = \frac{1}{12S} * (3b^2 db)$ *(eq. 4)* (Where spacing, *S*, remains constant)

Rearranging *eq.4* to solve for *db* then equating *eq.4* and *eq. 17,* we have;

$(dkc * 12S/ 3b^2)$ = (dVc/ S^2) *eq. 18*

Because spacing, S is constant, $S^2 = S$, and can cancel each other out. We can then solve for dkc

as; $dkc = \frac{(dVc*3b^2)}{12C}$

Eq. 19 is the final relationship that relates the change in permeability caused by emerging microcracks and its contribution to a change in porosity. It is important to note that as the Berea sandstone sample is stressed, prior to failure, there would be two ongoing processes -both closure of preexisting pores as well as development of induced cracks. In this case, the total permeability kt becomes the sum of the permeability from cracks and from the pores. That is;

$kt = kp + kc$

To establish a pattern of change in permeability by a change in volume and to plot a curve showing the changes, different values of permeability for changing percentages of pore volume were calculated. In the case of Westerly granite, with starting porosity of 1% I follow the model by *Zhu and Wong* (1999) by increasing pore volume up to 1.5% in 0.1% increments of porosity and calculate the corresponding permeability change in each stage. The starting porosity for Westerly granite is 0.5% porosity and add ten increments of 0.1% each.

For Berea sandstne, the porosity is 21% and as dilatancy sets in, porosity percentage increases as a result of microcracking. Hence, additional pore volume from cracks is introduced as a sepeate variable, ϕc. ϕc increases by 0.5% in each stage , up to a total crack pore volume increase of 5%, while the preexisting pores, Vp shrinks correspondingly by 0.2% in each stage, up to a total of 2% in total preexisting pore reduction. In each case ,the change in permeability caused by a decrease in porosity is calculated as well as the resulting total permeability changes.

Results and Conclusion

The results of this study are consistent with the results stated by Zoback *and Byerlee* (1975), *Peach and Spiers (1996*), and *Zhu and Wong* (1997). Table 1 shows the different results for high porosity Berea sandstone sample with initial porosity of 21%. There is a noticeable porosity and permeability change during dilatancy. As microcracking increases in the Berea sandstone regime, the overall pore volume increases. Nevertheless, there is a reduction in overall permeability as preexisting pore radii, and pore volume reduce. In Westerly granite connectivity between fractures is enhanced as apertures of preexisting cracks are widened [*Tappoiner and Brace*, 1976]. My results also illustrate that in Westerly granite, with initial porosity of 1%, increased triaxal stress up to the point of near failure results in dilatancy and permeability enhancement prior to faulting suggesting that, porosity and permeability are positively correlated. Table 2 shows the relationship between the porosity and permeability changes in Westerly granite. The plot of porosity versus permeability shows this relationship. In Berea sandstone, with initial porosity of 21% increased triaxial stress increases microcracking (this was shown by increasing the microcrack pore volume) and reduces preexisting pores. Overall, the net porosity of the sample increased, but the permeability continued to reduce. This result, so far, is consistent with my hypothesis. Figure 7 shows the porosity/permeability relationship in Berea sandstone. The negative correlation is seen as increasing porosity is followed by a decrease in permeability. For comparison, Fig. 8 shows the onset of dilatancy from *Zhu and Wong, 1997.* Data from the region where dilatancy sets in was taken and plotted to show similarity in my model. However, the reverse is the case for Westerly granite. Fig. 9 shows the positive correlation in Westerly granite. Initial porosity of 1% increases as microcracks are induced. There is also an observed increase in porosity.

This study is critical to the oil and gas industry, earthquake prediction as well as groundwater analysis. Experimental results suggest that prior to an earthquake, the rock mass surrounding the fault should enter the dilatant phase of a material behavior *[Cherry, et al.1975].*

$\Delta\phi_p$ %	$\Delta\phi_c$ %	Φ_{pore} %	Φ_{crack} %	Φ_{total} %	$Radius_{p(m)}$	$k_p(m^2)$	$k_c(m^2)$	Δ Radius	k total
-0.60	1.50	20.40	1.50	21.90	2.101	1.00E-14	0.167	0.000	1.67E-01
-0.80	2.00	20.20	2.00	22.20	2.007	9.00E-15	0.125	0.094	1.25E-01
-1.00	2.50	20.00	2.50	22.50	1.098	2.70E-15	0.100	0.909	1.00E-01
-1.20	3.00	19.80	3.00	22.80	1.073	6.30E-15	0.083	0.025	8.33E-02
-1.40	3.50	19.60	3.50	23.10	1.035	4.50E-15	0.071	0.038	7.14E-02
-1.60	4.00	19.40	4.00	23.40	1.010	5.00E-16	0.063	0.025	6.25E-02
-1.80	4.50	19.20	4.50	23.70	0.887	1.09E-16	0.056	0.123	5.56E-02
-2.00	5.00	19.00	5.00	24.00	0.623	1.13E-16	0.050	0.264	5.00E-02

Table 1: Changes in porosity and permeability in stressed Berea sandstone. Initial porosity of sample is 21% as microcracks emerge and pre-existing pores start to close and the net porosity and permeability is altered.

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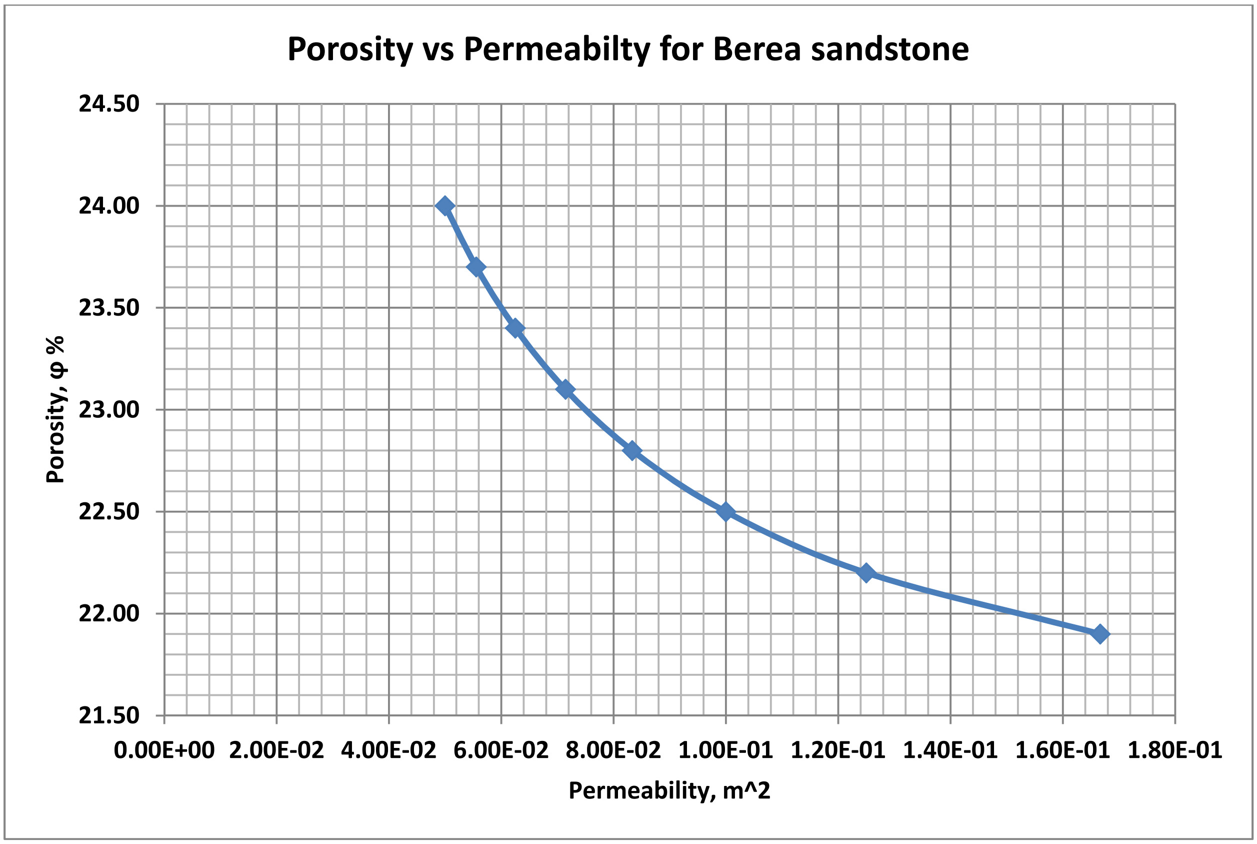

Fig 7: Plot of Total porosity versus permeability in Berea sandstone. As porosity increases as a result of induced microcracks and pre-existing pores are closing, the permeability decrease. The plot shows a negative corelation between porosity and permeability in stresed Berea sandstone. The plot models the plot of the same region done by *Zhu and Wong, 1997* below.

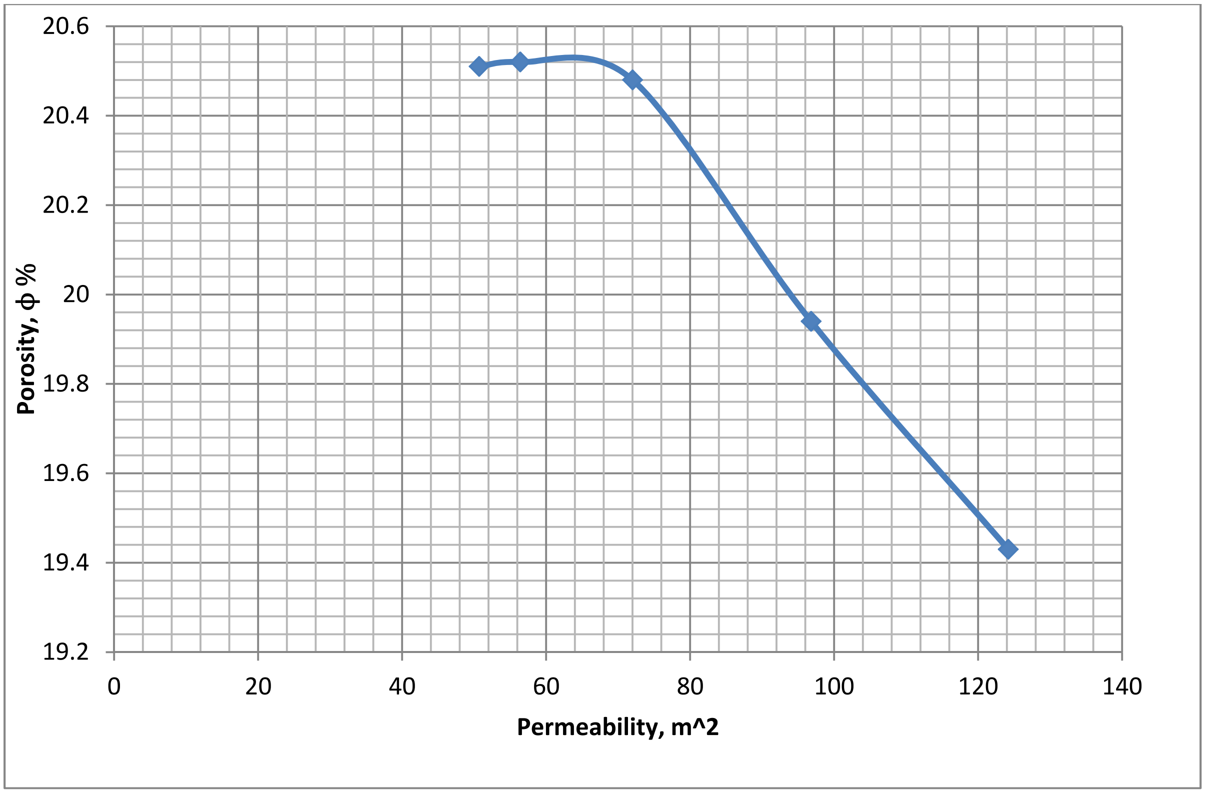

Fig 8: Adapted from Zhu ad Wong 1997, the plot depicts the onset of dilatancy in Berea sandstone. Increased porosity is followed by a decrease in permeability. This plot is modeled by fig 7 above.

Φ_{crack} %	$\Delta\phi_c$ %	Φ_{crack}	kc	b
1	0.00	1.00	0.08	1.00
	0.10	1.10	0.11	1.10
	0.20	1.20	0.14	1.20
	0.30	1.30	0.18	1.30
	0.40	1.40	0.23	1.40
	0.50	1.50	0.28	1.50
	0.60	1.60	0.34	1.60
	0.70	1.70	0.41	1.70
	0.80	1.80	0.49	1.80
	0.90	1.90	0.57	1.90

Table 2: Changes in stressed Westerly granite sample are shown. The initial porosity of the sample is 1%. Changes in crack volume as a result of stress increases the total prosity in each case.

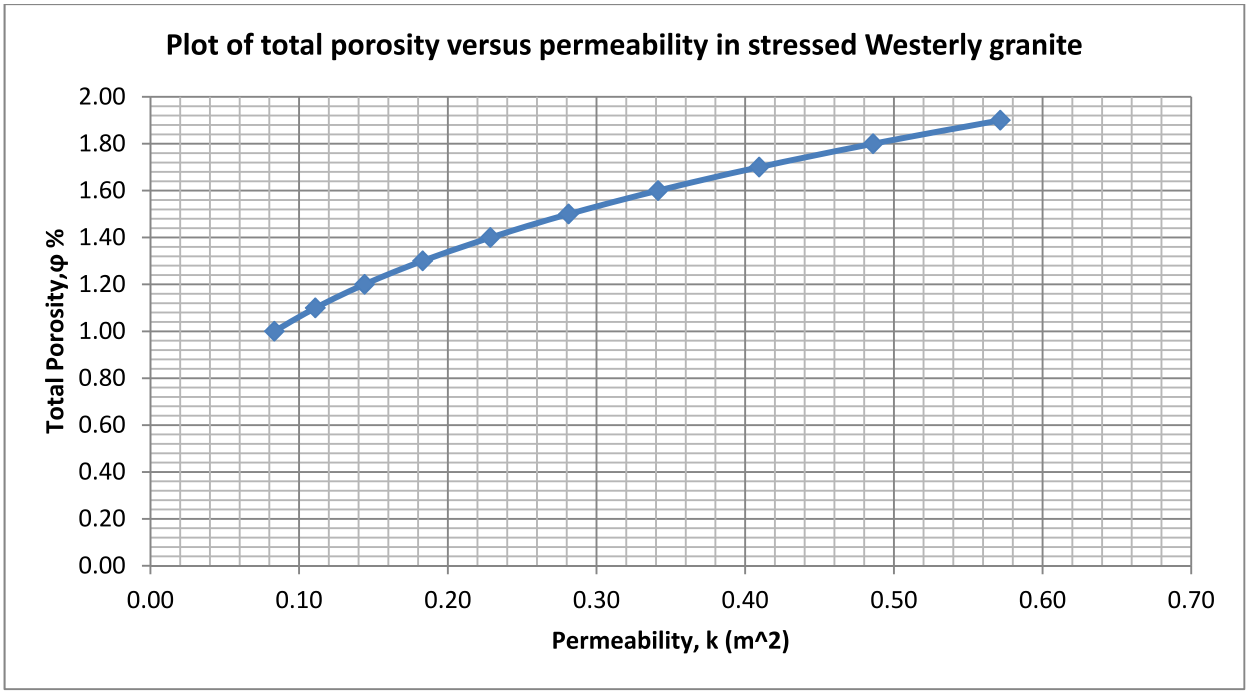

Fig 9: Plot of total porosity versus permeability in stressed Westerly granite. A net porosity increase is observed as the rock is stressed, giving rise to an increase in permeability. Porosity and permeability are positively correlated in Westerly granite.

Discussion:

It is important to consider the configuration of the induced microcracks as they occur. While a large number of microcracks are developed and propagated parallel to the direction of maximum principal compressive stress with the maximum microcrack propagation may occur in this zone (*Marek*, 2007), other networks are possible. Depending on the network model, total permeability could be lower or greater based on connectivity of the pores and cracks. One of the stages of this study that was not attainable due to time constraint would aim to account for different microcrack arrangements. Mathematical relationship could be established between porosity and permeability in a case of multiple cracks, taking into account the different arrangements of the crack: parallel, serial, or random.

For the sandstone, since there are no new pores being created, there will not be need to consider different network arrangement of the pre existing pores, but the induced microcracks shall be calculated taking into account all three arrangements.

Fig. 8 shoes the region where dilatancy sets in from figure 4b. Fig. 7 is a graphical representation of my data. Clearly, it is not exactly as that of Zhu and Wong, 1997. The difference could be ascribed to the assumptions I made during the model. Firstly, the effective pore volume induces possible oversimplification in the pore volume. While my model ensures all porosity contributes 100% to permeability, in real life that isn't the case. Microcracks have high connectivity and turtuosity. In fact, not all pores or cracks are effective in transmitting fluid. My model assumed all porosity is effective, but not all porosity is effective. Effective porosity of a porous medium is defined as the part of the pore volume where the water can transmit fluid. In naturally porous systems such as subsurface soil, where the flow of water is caused by the composition of capillary, molecular, and gravitational forces, the effective porosity can be approximated by the specific yield, or drainage porosity.

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