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Abstract

The behavior of rock joints under various coupled processes is reviewed under four broad categories: (1) hydromechanical (HM) processes, (2) thermohydromechanical (THM) processes, (3) hydromechanical-chemical (HMC) processes, and (4) thermomechanical-hydrochemical (TMHC) processes. The state-of-the-art and possible directions of further research in these coupled processes are discussed. Rock joint behaviors considered include not only dilation, closure, shear and joint propagation, but also changes in flow permeability and chemical sorption and retardation capabilities. These properties are of critical concern in practical considerations of the rock mass as a medium to store and isolate chemical and radioactive wastes. Investigations of coupled processes in two-fracture systems and multi-fracture systems are pointed out as interesting areas for future research. The need to consider coupled processes in borehole testing procedures involving rock joints is emphasized.

1.0 Introduction

By coupled behavior of rock joints, we mean the deformation and propagation, as well as changes in hydraulic and chemical properties of rock joints under various coupled processes. Deformation of rock joints includes dilation, closure and shear. Under shear deformation, faults are created. In the present paper we shall not make a distinction between joints and faults, and shall also refer to them generally as rock fractures. The processes that are usually considered in the study of coupled behavior are thermal, hydrological, mechanical and chemical. Coupling of these processes implies that one process affects the initiation and progress of another, and so under these coupled processes, rock joint behavior cannot be predicted by considering each process independently. An example is the occurrence of earthquakes induced by fluid injection (Healy et al., 1968; Raleigh et al., 1976). Here a hydrological process of injection pressure and fluid flow is coupled with rock mechanics of joint dilation and shear movements. To have a proper understanding of such coupled behavior researchers have to extend themselves beyond their own discipline and to learn from and cooperate with others in related disciplines. Such multi-disciplinary interactions and investigations have been fruitful in opening up new areas of research on rock joints and associated subjects.

From another angle, new areas of research on coupled processes in rock joints are also suggested based on considerations of many important practical problems of current interest. Careful study of these practical problems has pointed to the key role that coupled processes play in their definitions and solutions. The example of earthquakes induced by fluid injection was observed in practical projects in which large amounts of treated waste fluid were disposed by injection underground. This phenomenon is also observed in petroleum reservoir operations. Thus studies of this particular coupled process is needed to ensure the safety of these operations.

Another practical area of much current interest is the isolation of chemical and radioactive wastes by storage in repositories in geological formations. The main transport mechanism of these wastes is by solution in fluid that flows from the repositories to the biosphere through joints and faults in the formation. Thus this problem is intrinsically related to the coupling of the mechanics of rock joint deformation with hydrologic fluid flow and also with the chemical reaction and retardation between solutes and joint surfaces or infill materials. The three-way coupling becomes four-way coupling in the case of radioactive wastes which is also a heat source giving rise to significant temperature gradients near the emplaced waste canisters (Tsang, 1987).

Other practical problems demanding consideration of coupled joint behaviors include hydraulic fracturing and dam stability. Furthermore in hydrologic testing to obtain permeability of rock joints, mechanical deformation may occur and strongly influence the results. Similarly in the estimation of the stress fields by the hydraulic fracturing method, transient fluid flow effects may have to be considered in some cases. Thus the conventional parameter estimation by borehole testing has to be carefully evaluated in light of possible coupled effects to ensure their validity in the presence of fractures.

The purpose of the present paper is to review coupled processes that may occur in rock joints and to point out those coupled processes that require further research. In the next section we shall give an overview of process couplings and the different types of coupled processes. Then rock joint behavior under specific coupled processes will be described and possible future developments discussed. Following this, additional discussions will be given on coupled processes that are yet to be investigated and on certain issues and unresolved questions in this field. A few additional remarks conclude this paper.

2.0 Types of Coupling

Let us focus our attention to four different processes, hydrological, chemical, mechanical and thermal processes. Hydrological processes (H) include fluid flow and tracer transport through a rock joint and transient pore fluid pressure changes due to change of system conditions (such as those occurring during the operation of an injection or pumping well, or the construction of underground space). Chemical processes (C) include dissolution or precipitation of solutes in the fluid, interaction of the solutes with each other forming complexes or colloids, and interaction of the solutes with joint surfaces and joint infill materials. Mechanical processes (M) include dilation, shear, joint propagation, and fracturing at joint tips. Finally thermal processes (T) include changes of temperature and presence of transient temperature gradients.

These four different kinds of processes can be fully uncoupled, i.e., they do not affect each other in any way; or sequentially coupled, i.e., the result or final state of one process affecting another process; or one-way coupled, i.e., the progress of one process affecting the progress of another; or fully coupled, i.e., the progress of one process affecting the progress of another and vice versa (Fig. 1). We call the last two cases coupled processes.

Now considering the four kinds of processes, T, H, C, M, the number of possibilities for coupling two or more processes is $2^4 - 5 = 11$. These eleven types of coupling are shown schematically in Figure 2. Of these, HM, THM, HMC, and THMC are of more importance for rock joints. Examples of HM coupling including stress-flow relationship and role of fluid pressure in fracture initiation and propagation. An example of THM coupling is the effect of changing temperature and pore fluid pressure on mechanical changes of the rock joints, such as those observed in hot dry rock experiments. Examples of HMC coupling include the role of pressure solution or stress corrosion in fracture propagation and dissolution or precipitation of solutes in fluid causing piping or clogging in joints. When these dissolution and precipitation processes are also influenced by temperature gradients present, we have a case of the four-way THMC coupling. These different couplings will be discussed in more detail below.

3.0 Important Coupled Processes in Rock Joints

In this section we will review the more important coupled processes in rock joints listed in the last section and suggest directions for further development. They are discussed in four groups: hydromechanical (HM) processes; thermohydromechanical (THM) processes, hydromechanical-chemical (HMC) processes and thermomechanical-hydrochemical (TMHC) processes. Emphasis will be on those processes whose understanding is relatively less developed.

3.1 Hydromechanical (HM) Processes

Considerable work has been done on stress-flow relationship in single fractures in recent years (Gangi, 1978; Krantz et al., 1979; Witherspoon et al., 1980; Tsang and Witherspoon, 1981, 1983; Walsh, 1981; Barton, 1986; Gale, 1987; Pyrak-Nolte et al., 1987; Zimmerman et al., 1990; Makurat et al., 1990; Erichsen, 1990). These studies emphasized the variable-aperture nature of the rock joints in models for stress calculations. At the same time the observation of the so-called channeling effect for flow and transport observed in a series of field experiments by Neretnieks (1985, 1987), Abelin et al., (1987) and Bourke (1987) brought out the importance of incorporating the effect of variable apertures of rock joints in calculating flow and solution transport. This has stimulated many hydrologic studies (Tsang, 1984; Gentier, 1986; Tsang and Tsang, 1987, 1989, 1990; Brown, 1987; Moreno et al., 1988; Tsang et al., 1988; Pyrak-Nolte et al., 1988, 1990; and Hakami and Barton, 1990).

The picture that emerges from these studies may be briefly described as follows. Rock joints are considered to be two rock surfaces in the rock mass separated by the aperture, b(x,y), whose value may vary with location because of the roughness of these surfaces. The two surfaces may touch or press against each other at various locations where b(x,y) = 0. These are the contact areas or contact points. An example of b(x,y) distribution on a fracture plane is shown in Figure 3. To determine the stress-flow relationship of the rock joint, one needs to calculate the flow rate through the joint under different mechanical stresses. First, mechanical stress-displacement relationship is calculated as the mechanical pressure averaged over the points of contact between the two surfaces that is needed to compress the asperities (Gangi, 1978) or deform the void spaces (Tsang and Witherspoon, 1981). Here asperities are the rock grains that protrude from the mean rock surface (Fig. 4a) and come into contact with the opposite rock surface, and void spaces are aperture spaces between contact points (Fig. 4b). Then, the fluid flow and effective permeability are calculated for the two-dimensional aperture void space defined by b(x,y). Often detailed information of b(x,y) is not available and stochastic method has to be used (Moreno et al., 1988). Within this method one estimates the probability density function of aperture values, defined usually by two parameters and the spatial correlation length which describes the two-dimensional spatial structure of the apertures.

Because of the variable aperture nature of the rock joints, permeability to fluid flow is strongly controlled by regions where b is small (aperture constrictions), and flow has to seek paths of least resistance. This gives rise to high-flow channels as observed by Neretnieks and coworkers (Abelin et al., 1987; Neretnieks, 1987). Tsang and Tsang (1987) pointed out that flow channeling is very sensitive to normal stress, because an increase of stress with accompanying compression of the joint surfaces will proportionally reduce the b values much more at regions of aperture constrictions and in some instances completely close them off (b=0). Thus the flow channeling pattern in the joint plane will be drastically changed. Evidence of such behavior are found in the highly stress-sensitive breakthrough curves of non-reactive tracers that have traveled with fluid through fractures under normal stresses.

Shear stress and fluid flow relationships are investigated by Makurat (1985), Barton (1986) and Makurat et al. (1990). Here the situation is much more complicated. Under low normal stress, shear strain may allow the asperities from the two rock surfaces to "climb on top of" each other, thus opening up the fracture aperture. This is the shear dilation of joints. Permeability increases of orders of magnitudes under shear were measured (Makurat, 1985). On the other hand, under high normal stress or for relatively soft materials, shear force may deform and damage the asperities and the aperture distribution b(x,y) will be drastically changed. Hysteresis effects during cyclic loading may be a result of this phenomenon. Further laboratory and modeling work is needed to establish empirical relationships for different materials and different normal stress conditions (Makurat et al., 1990; Erichsen, 1990).

Another hydromechanical process that has been much studied is that of hydraulic fracturing (Zoback and Haimson, 1983). This has been applied as a means to measure the local stress field, as well as to increase the near-field rock permeability in petroleum and geothermal reservoirs. Fracture mechanics of hydraulic fracturing phenomenon was reviewed by Rummel (1987).

A recent modeling study pointed out an interesting hydraulic pressure build up in a rock joint that may occur during the excavation of a tunnel as a result of undrained response (Noorishad and Tsang, 1990). The modeling study assumes a vertical water saturated joint which intersects the tunnel location. As the tunnel is being excavated in a ten-bench excavation procedure, instantaneous step-wise loading occurs. The stress redistribution compresses the vertical rock joint and the resulting transient fluid pressure in the joint rises to as much as four times the initial in-situ fluid pressure (Fig. 5). Such fluid pressure buildup may have significant effects on the medium permeability near the tunnel. Further studies are needed.

3.2 Thermohydromechanical (THM) Processes

THM processes are found in a number of different situations. One is in the context of the development of hot dry rock geothermal systems (Murphy et al., 1981; Batchelor, 1982; Takahashi and Abe, 1987; Franke, 1988; Parker, 1989; Desroches and Cornet, 1990). An artificial fracture is formed in hot dry rock deep underground by hydraulic fracturing with injection of cold water. This fracture in the hot rock is then used as a heat exchanger surface for extraction of thermal energy from the rock with the injected water. To study such a hydraulic fracturing process one needs to consider the hydromechanical behavior of rock near the injection wellbore. Initially near the wellbore there may be already short fractures or planes of weakness. These may be pre-existing or caused by well drilling operations. Dependent on their stiffness and frictional properties, and the local stress fields, hydraulic fracturing may occur with an increase of injection pressure. It is noted that firstly thermal cracking in addition to hydraulic cracking seems to occur and secondly microseismic events are detected by acoustic receivers during the fracturing process. The latter is particularly interesting in that these microseismic events represent localized fracturing due to the fluid injection and may reflect on local rock properties and local stress field conditions in the heterogeneous rock medium.

A second THM process occurs during hydraulic fracturing of a warm petroleum reservoir with injection of cold water in a water-drive operation. Calculations (Noorishad and Tsang, 1987) show that the difference in temperature between the reservoir and the injected water lowers the injection pressure required for hydrofracturing by as much as 10 MPa (Fig. 6). Such reduction in hydrofracturing pressure was noticed in the field. However, detailed data are not available and laboratory investigations will be helpful to confirm these calculations and study this process in more detail.

A third THM case that has been studied corresponds to the problem of rock joint behavior near a heat source. Let us assume that the heat source is in a borehole intersected by a horizontal water-saturated fracture. Initially when the borehole is drilled, because of the pressure drop at the borehole, water flows from the fracture into the borehole. However, as temperature rises because of the heat source, fracture aperture decreases because of rock thermal expansion and fluid flow eventually is stopped. The calculated results (Noorishad et al., 1984) are shown in Figure 7 and they were confirmed by field observations in the Stripa mine by Nelson et al. (1981).

In general a detailed understanding of rock joint behavior under temperature and pressure gradients is yet to be fully developed. For example temperature gradients may cause local rock grain differential expansion and local cracking. Also, since the thermal expansion coefficient of water (4 x 10^{-4}/°C) is much larger than that of the rock (10^{-5}/°C), a temperature rise may cause an increase in pore fluid pressure. Fluid pressure may transmit large distances and causes triggering of latent seismicity. These phenomena depend on local material properties and stress fields, which are not easy to determine. However they are important if they cause local fracturing that connect existing fractures and thus form a flow path for fluid and chemical transport. This is an area that requires further research.

3.3 Hydromechanical-Chemical (HMC) Processes

The hydromechanical processes related to variable-aperture joints as discussed above (Sec. 3.1) are sometimes found in situations where chemical reactions occur. If dissolution takes place, asperities may be reduced and the aperture distribution b(x,y) will be modified. On the other hand, if precipitation occurs because of chemical reactions, the precipitates may accumulate at aperture constrictions (small b regions) and clog up flow paths. New flow paths will develop. In the extreme case flow may be stopped and local fluid pressure will build up. Dissolution may occur because of the higher pressures and open up the flow paths again. However, the pressure buildup may also cause local fracturing dependent on local stress conditions and joint properties.

Another potential clogging mechanism is the interaction of fluid with joint infill materials. For example, clay can swell upon contact with water of a different salinity (Komornik and David, 1969; Kassiff and Sharon, 1971; Borgesson, et al., 1988). How clay swelling pressures change the local effective stress field and affect the aperture function b(x,y) is yet to be studied. Interaction of joint infill materials with chemicals in the fluid (e.g., the fluid from deep injection disposal of toxic liquid waste) may also result in what is called the chemical piping effect. Thus narrow flow paths through the joint infill materials are created through selective chemical dissolution. In general there has not been much study of the interactions among fluid flow, joint infill materials, stress field across joints and clay swelling pressure, and of their impacts on the joints as potential pathways for fluid leakage.

The channeled flow paths in the rock joints and the possible changes in flow paths due to stress variations or clogging effects may be significant factors in determining the degree of surface sorption and matrix diffusion of solutes. The limited flow paths implies that rock surface areas available for surface sorption and matrix diffusion may be only 10% or 20% of the total fracture surface area. Changing flow paths during the transport will allow new joint surface areas to be available for these processes. Quantitative studies on these factors are lacking.

The phenomenon of pressure solution or stress corrosion (McClay, 1976; Kerrich, 1977; Engelder et al., 1981; Costin and Mecholsky, 1983; Rutter, 1983; Freiman, 1984; Atkinson, 1982, 1984; Meike, 1986) is also a coupled HMC process. This operates at the tip of the joint and causes joint propagation in mode I fracturing. Figure 8 shows a schematic diagram of crack propagation velocity as a function of stress intensity factor, K_I, at the tip for different water pressure present in the rock joint. Thus crack propagation velocity increases with water pressure and with stress intensity. In the figure the early fast rate of crack growth is controlled by the rate of stress corrosion reaction at the joint tip. Then the crack propagation velocity stabilizes to a constant when the crack growth is controlled by the rate of transport of reactive chemical species to the tip or away from the tip. The fast growth at large stress intensity values is due to mechanical rupture and is independent of the chemical effects of the fluid.

The HMC process of pressure solution also causes joint propagation under large compressive stress. The resulting features have been called anticracks (Fletcher and Pollard, 1981; Olson and Pollard, 1989). These anticracks tend to propagate along a plane normal to the direction of maximum compressive stress. This is contrary to tensile fracturing which is usually along a plane in the direction of maximum stress. Thus pressure solution may play a role in forming cross fractures that connect a series of parallel tensile fractures and thus possibly developing a connected flow path. Much work is required to investigate such possibilities in a multiple jointed medium.

3.4 Thermomechanical Hydrochemical (TMHC) Processes

Imposing temperature changes and gradients to the coupled HMC processes described above results in the four-way THMC coupling. The thermal effect could be due to heat sources emplaced in the ground, cold water injection into warm formations, geothermal reservoir evolution under exploitation, and magmatic movements. Temperature effects change chemical reaction rates and causes hydraulic buoyancy flow. Thermohydrologic flow in variable-aperture rock joints under stress has not been adequately investigated.

The four-way THMC coupled processes involve additional parameters so that their analyses are more complex. However their presence in various practical problems demands efforts to understand them to a certain degree.

4.0 Discussion of Additional Coupled Processes in Rock Joints

Having reviewed some of the main coupled processes in rock joints, this section will be devoted to discussions of additional coupled processes that have not yet been sufficiently studied and also to other issues and open questions.

4.1 Flow Permeability and Three Modes of Fracture Propagation

Figure 9 shows three basic modes of fracture propagation: tensile fracturing, mode I; in-plane shear fracturing, mode II and anti-plane shear fracturing, mode III. These three modes of fracturing will result in three rather different flow permeabilities for the rock joint. In tensile fracturing, mode I, there is an increase in values in the aperture distribution b(x,y). The new values of aperture distribution will be directly related to the original distribution b(x,y). On the other hand in shear fracturing, mode II and mode III, the roughness of the two surfaces of the joint could well be physically modified by the shear force, so that there would be much less or even no correlation between original aperture distribution b(x,y) and the new distribution. It has often been assumed that the probability density for aperture b values obeys a lognormal function. Since the three fracturing modes are quite different physical phenomena, the three modes may result in fractures of quite different aperture probability functions. Thus, the different fracturing models may give rise to significantly different flow and transport properties for the rock joint.

Furthermore, the progress of the three fracturing modes may be strongly affected by changing fluid pressures in the joints (e.g., in fluid injection experiments or water drainage in underground constructions). Fluid pressure or pore pressure changes can affect mode I fracturing more than the others, depending on the initial stress condition across the joint and joint friction factors. Research is needed to understand various facets of this coupled hydromechanical process for the different fracturing modes.

4.2 Coupled Processes in Two Rock Joints

An isolated rock joint in the rock mass is usually of little interest in hydrology; however, a series of connected rock joints forming a flow path may be of critical concern. The interaction of two joints situated close to each other is an area of study that may be of significant interest, especially when the interaction causes joints to connect. Segall and Pollard (1980) studied the stress field around two echelon faults. Part of their results are shown in Figure 10. The top of the figure shows the definition of the case under study. Note in particular the magnitude and direction of σ_1 and σ_3. The superscript, ∞, indicates that these are far field tensors. The mean stress in the near field is contoured in Figure 9a and 9b and the maximum shear stress in Figures 9c and 9d. These figures suggest that tensile fracturing, mode I, may be more likely to occur for the case in Figure 9b and that shear failure, mode II, is more likely to occur for that in Figure 9c.

The presence of a temperature gradient and a hydraulic pressure gradient in either joint will alter the stress field between them. Coupling these processes to the considerations of Segall and Pollard will be an interesting area of study.

It has been also observed in the Stripa mine (Abelin et al., 1987) that fluid flow at joint intersections appears to be much larger than that at a location away from the intersection. This may imply that when the two joints are close together the region between them are subjected to increased mean stress or maximum shear stress so that there is a possibility of multiple fracturing. Then the permeability to fluid flow will be significantly increased.

In general, there is a need to develop the capability for estimating two-joint interference phenomena under various coupled processes and relating them to basic rock properties and conditions.

4.3 Coupled Processes in Multiple Joint System

Considerations have been given to the stress field and joint linkages not only in two-joint systems, but also in multiple joint system. Multiple joint formation and the origin of tensile fractures were discussed by Segall and Pollard (1982) and Nur (1982). Mathematical analyses of the formation and stability of a system of parallel cracks and their interaction in the case of high crack densities were given by Kemeny and Cook (1985, 1986). Figure 11 is taken from the more recent work of Martel (1990), which shows four stages of fracture growth and fracture connection in a multiple fracture system. Note the rotation of the imposed stress field in the earliest stage (Fig 11a) to that of the later stages (Fig 11b-d). As a result, the earliest formed fractures become increasingly better connected by new cross fractures as the system develops. The picture was constructed without consideration of coupled hydraulic and thermal effects. Incorporation of these coupled effects in the study and modeling of the formation of fault zones will be a major effort, but may be very significant in considering the rock mass as an isolating medium for the storage of radioactive or chemical wastes.

4.4 Coupled Processes in Borehole Testing Analysis Methods

For the case of rock joints the presence of coupled processes may strongly affect borehole testing results. Analysis methods which do not account for the coupled process may not be valid. An example is fluid injection well test in determining joint permeability (Noorishad and Doe, 1982; Rutqvist et al., 1990). Water is injected into a joint at a given pressure, and the transient flow rate is used to determine the permeability by standard hydrology methods. Even though the injection pressure is only a fraction of the lithostatic pressure, it is sufficient to cause local joint opening (a coupled HM process). The transient flow rate was calculated by Noorishad and Doe (1982) and Rutqvist (1989). Figure 12 shows the modeling results of Rutqvist (1989) in which the initial decrease in flow rate from an instantaneous jump in flow rate follows the usual hydrologic theory of constant pressure test. However, at later times, because of the mechanical opening of joint aperture, the flow rate actually bottoms out and increases.

This anomalous effect however is not found in modeling results for a pulse pressure test (Noorishad, 1985), where because of the transient nature of the injection pressure, no significant aperture change is expected and the flow rate response should follow the conventional hydrological phenomenon.

These examples show the need to review various testing and analysis methods as to their validity in the presence of coupled processes. Tests that are significantly affected by coupled processes may be conveniently used to study these processes.

4.5 Comments on Medium Heterogeneity and In-Situ Stress Field

For many of the coupled processes, the behavior of the rock mass depends strongly on the local material properties and the stress state. The medium typically contains microfractures, joints and other features, and there will be large variations in material properties and stress state. It is difficult if not impossible to determine these local conditions in detail. Yet material weakness at different points in the medium may be critical for some important processes, such as the triggering of latent seismicity due to fluid pressure or temperature gradients.

The problem of addressing such heterogeneities is not simple. Perhaps one approach is to estimate ranges or distributions of the material properties and of the stress field components, and to make use of stochastic methods that have been used to some degree of success in hydrology. New conceptual considerations need to be given to the formulation of the problems, from definition of appropriate medium quantities to definition of observables of interest. Both modeling and field investigations need to be done for systems at different scales, since strong scaling effects can be expected.

Even in the case of single rock joints, two-dimensional heterogeneity and variations of stress field are present because of fracture surface asperities. Stochastic methods have been applied to fluid flow calculations in variable-aperture joints. Perhaps these methods can also be applied to stress deformation calculations, especially in the case of shear phenomenon.

5.0 Concluding Remarks

The above discussions may have conveyed the extent of activities in the study of coupled behavior of rock joints and possible directions for further development. While some of the coupled processes are relatively well-known, many are yet to be understood. To approach the rock joint behavior from the direction of coupled processes enables one to identify and focus on some of them that may easily be overlooked. Recent problems of national and international importance, such as disposal of chemical and radioactive wastes, have imposed extraordinary requirements on the stability and isolation properties of rocks. These requirements have motivated the study of a number of new coupled processes, both in the local and the regional scale. Since these processes couple phenomena and information from different disciplines, close interaction and cooperation among researchers in geology, geochemistry, geophysics, hydrogeology and rock mechanics are necessary for a proper scientific investigation program. We hope that the present paper serves its part in stimulating such cooperation and promoting further development in this interesting field of research.

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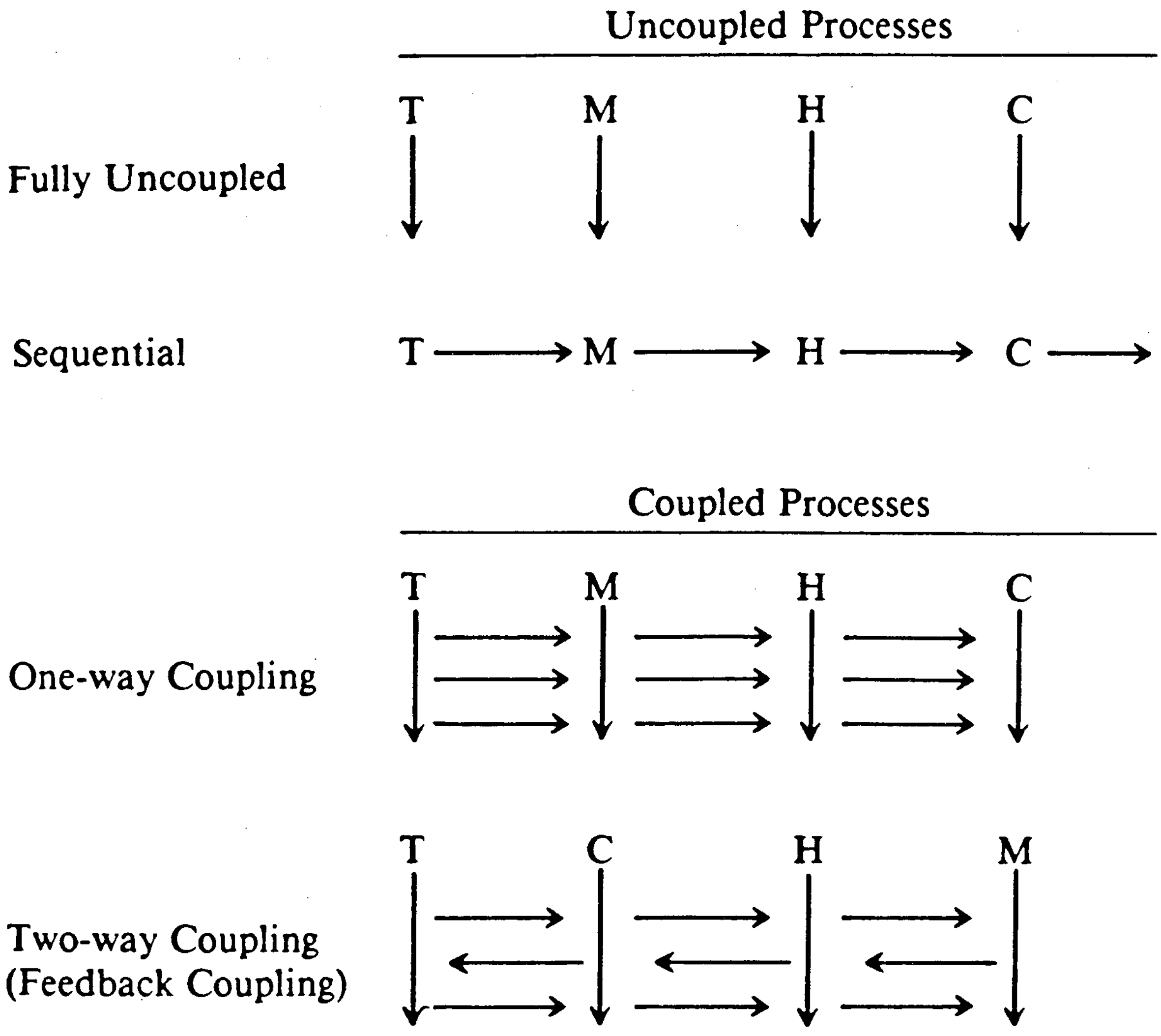

Note: T = Thermal, M = Mechanical, H = Hydrological, C = Chemical.

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Figure 1. Diagrams of uncoupled and coupled processes.

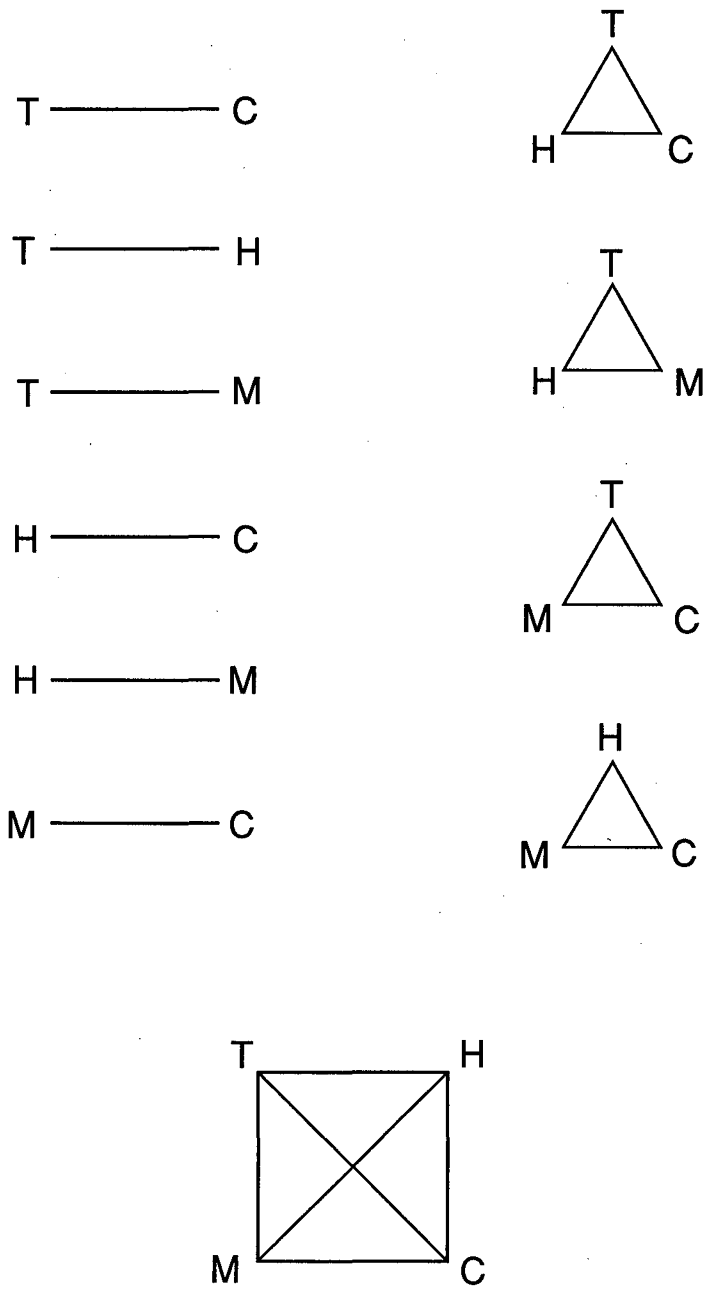

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Figure 2. Types of coupled processes.

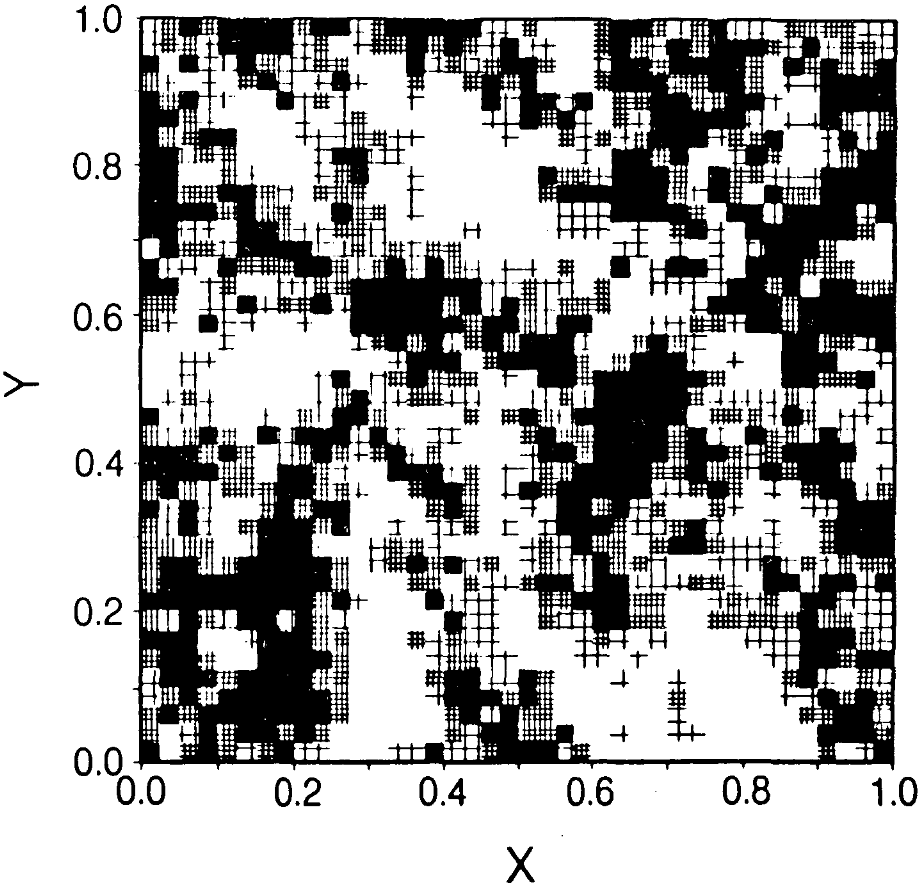

Figure 3. An example of aperture distribution b(x,y) in the joint plane. Large apertures are shown as white spaces and very small apertures as black.

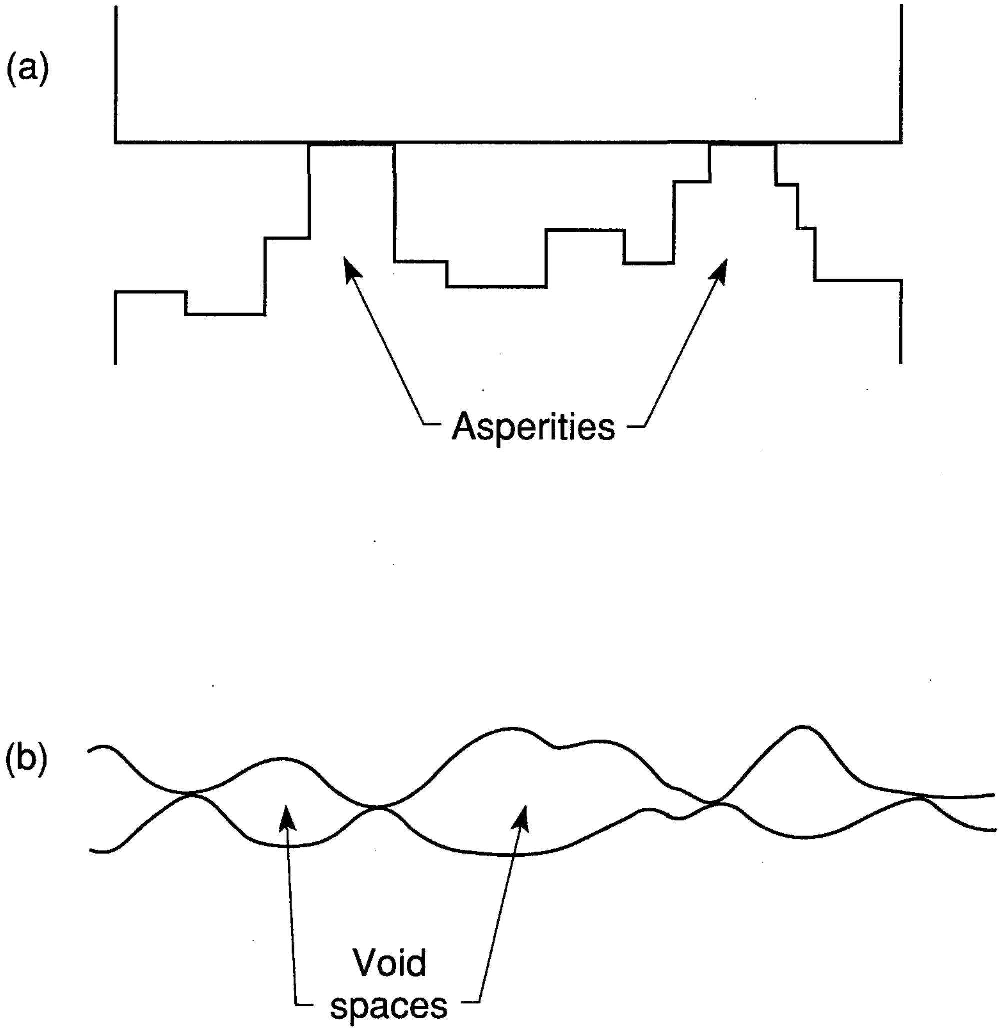

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Figure 4. Models of joint apertures.

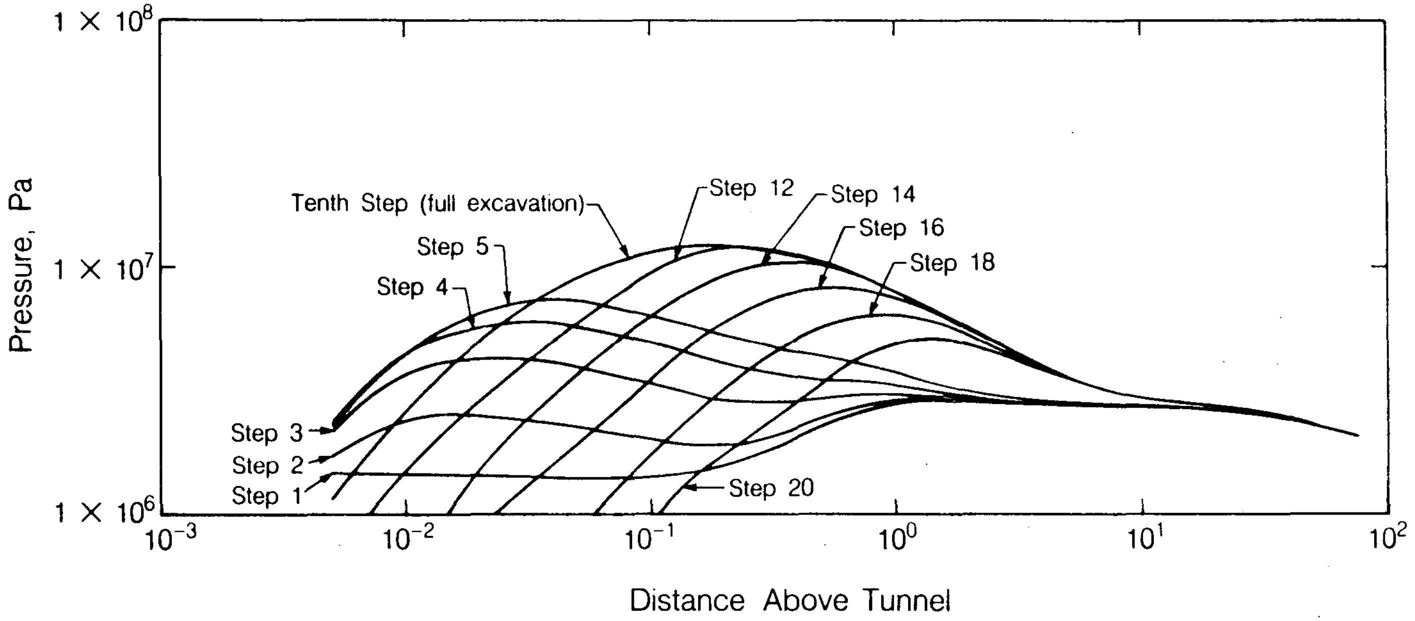

Figure 5. Evolution of the fluid pressure profile inside a vertical fracture intersecting the ceiling of a tunnel during and after excavation. Steps are in time, with the tenth step corresponding to completion of tunnel excavation (from Noorishad and Tsang, 1990).

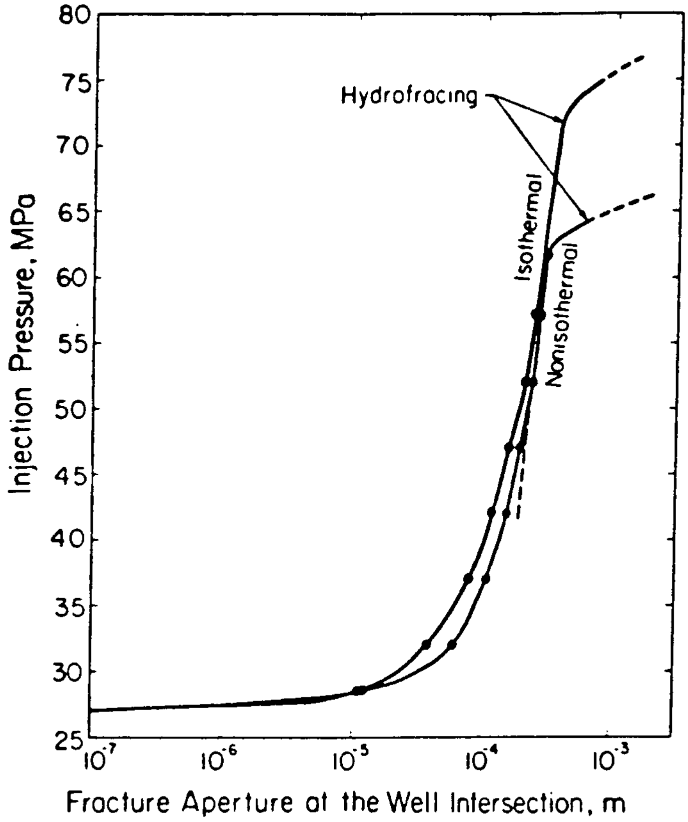

Figure 6. Injection pressure required for hydrofracturing, for isothermal injection and for non-isothermal injection with ΔT = 55°C (from Noorishad and Tsang, 1987).

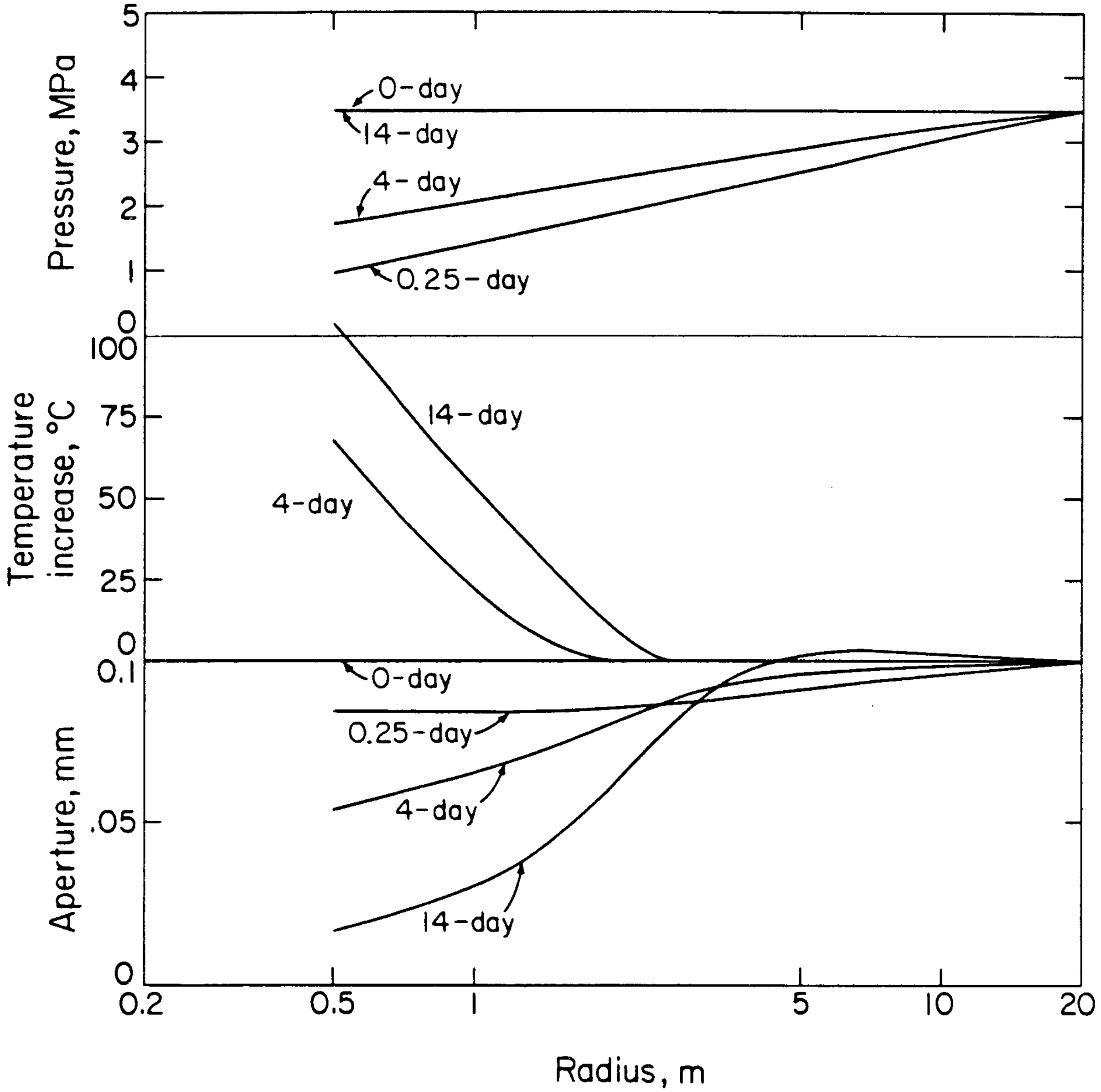

Figure 7. Pressure and aperture profiles in the fracture for various durations, and temperature profiles along the heater midplane (from Noorishad et al., 1984).

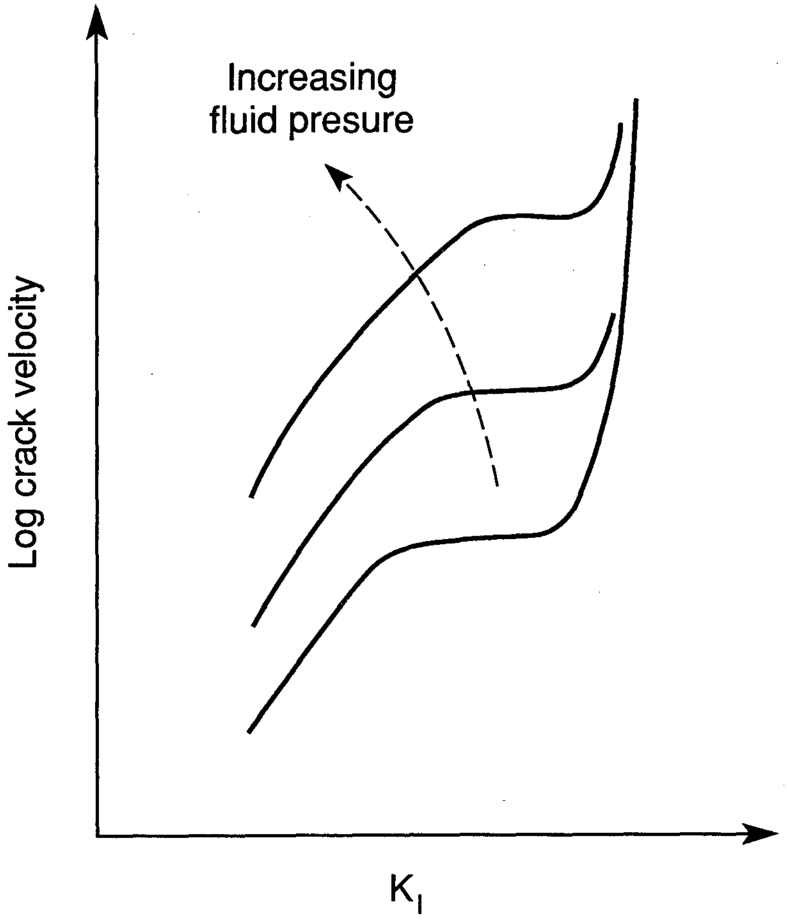

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Figure 8. Crack growth velocity versus stress intensity factor for mode I, due to stress corrosion (adapted from Atkinson, 1984).

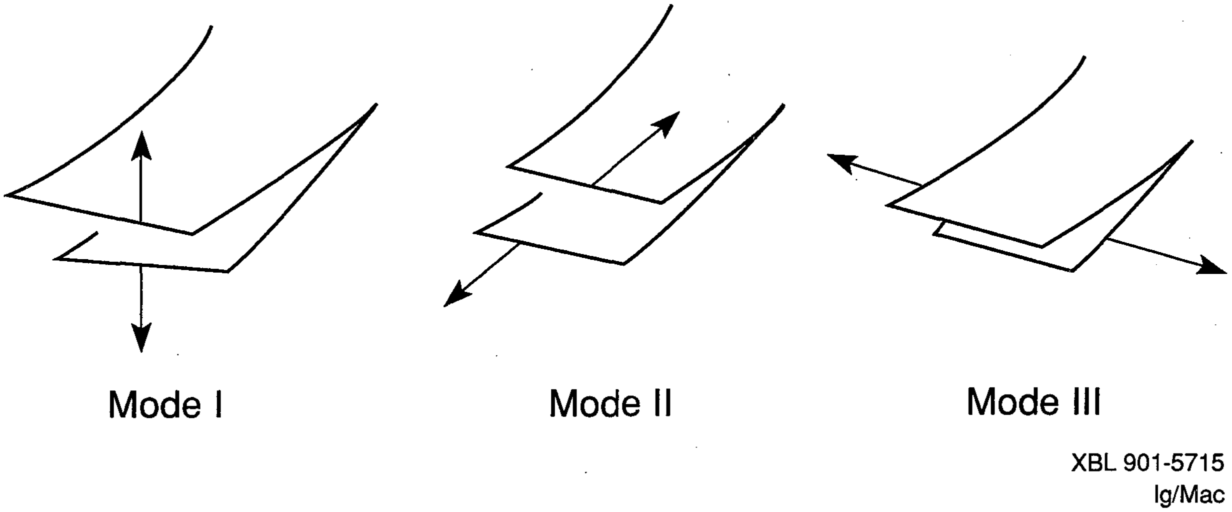

Figure 9. Three modes of fracturing.

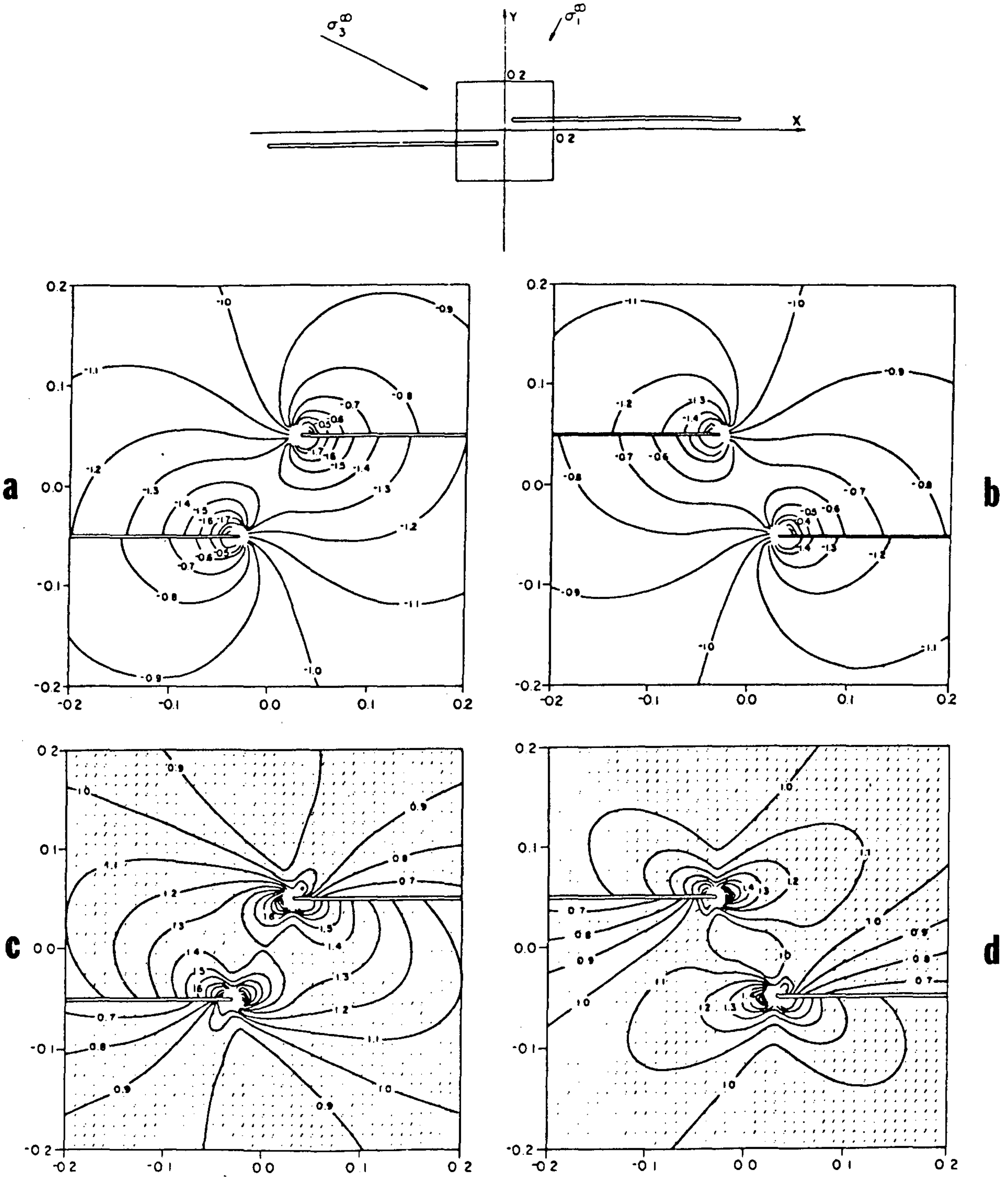

Figure 10. State of stress near echelon discontinuities. Inset illustrates crack geometry, area plotted, and applied stress state. Distribution of mean stress $1/2(\sigma_1 + \sigma_3)$ for (a) left and (b) right step. Contoured values are normalized by far-field mean stress, so that background value is -1.0. Stresses < - 1.0 represent an increase in confining pressure. Distribution of maximum shear stress $1/2(\sigma_1 - \sigma_3)$ for (c) left and (d) right step. Contoured values are normalized by the far-field maximum shear, so that background value is 1.0. Tick marks indicate direction of minimum compression σ_1. In the far field, σ_1 is 60° from the x direction (from Segall and Pollard, 1980).

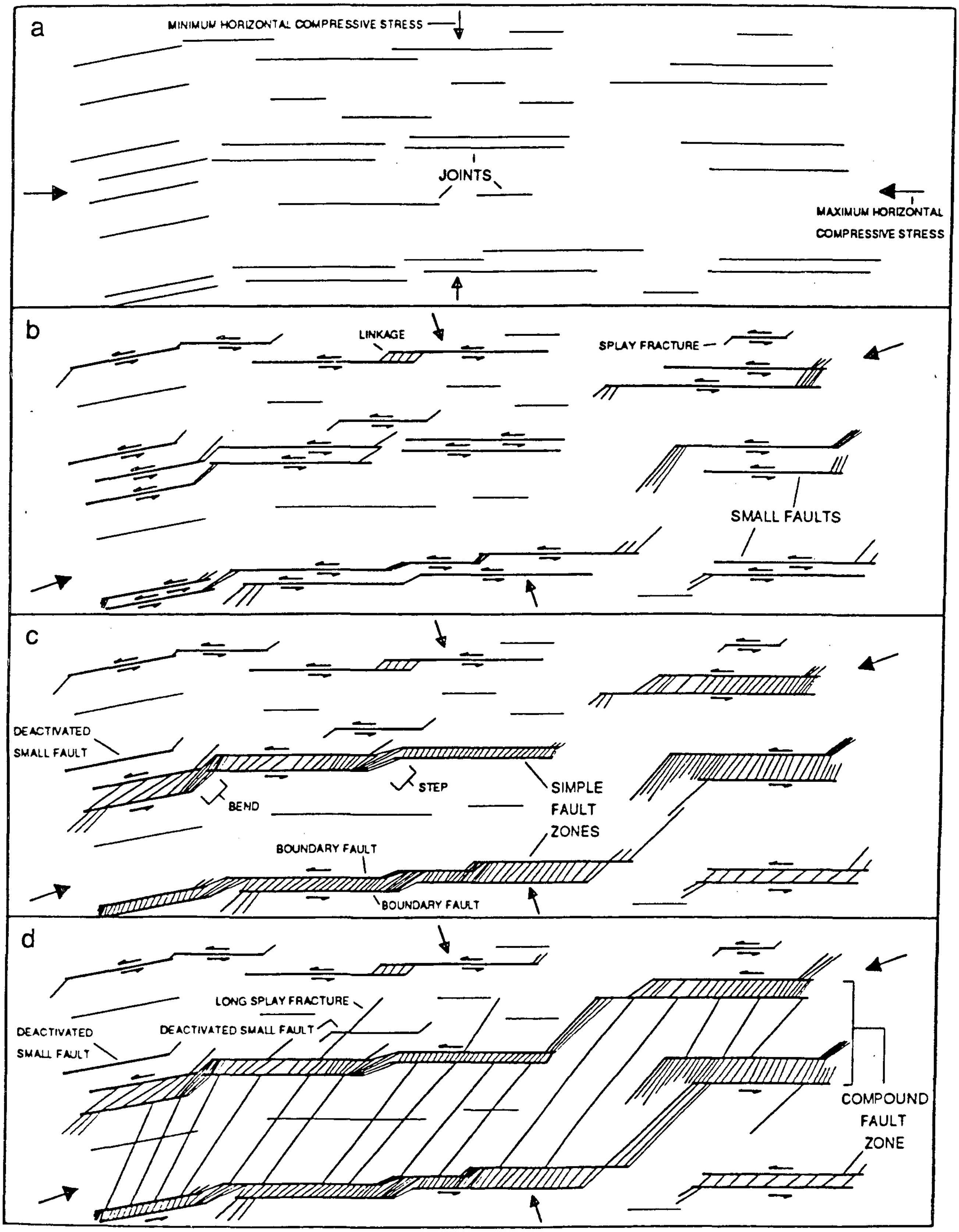

Figure 11. Multiple fracture system. Four stages in the development of fault zones (from Martel, 1990).

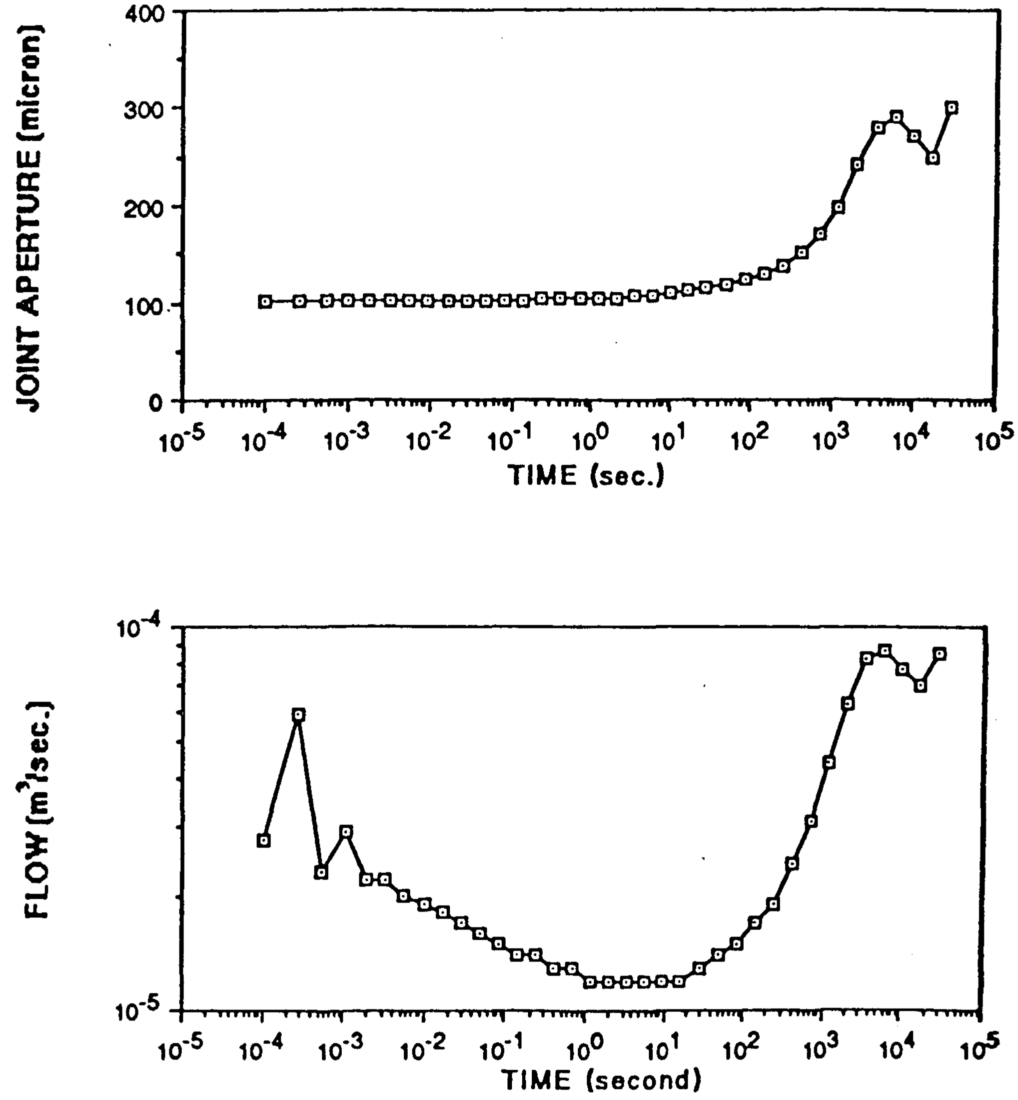

Figure 12. Calculated joint aperture and flow (measured at well wall) as a function of time for a constant head injection test (from Rutqvist, 1989).

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