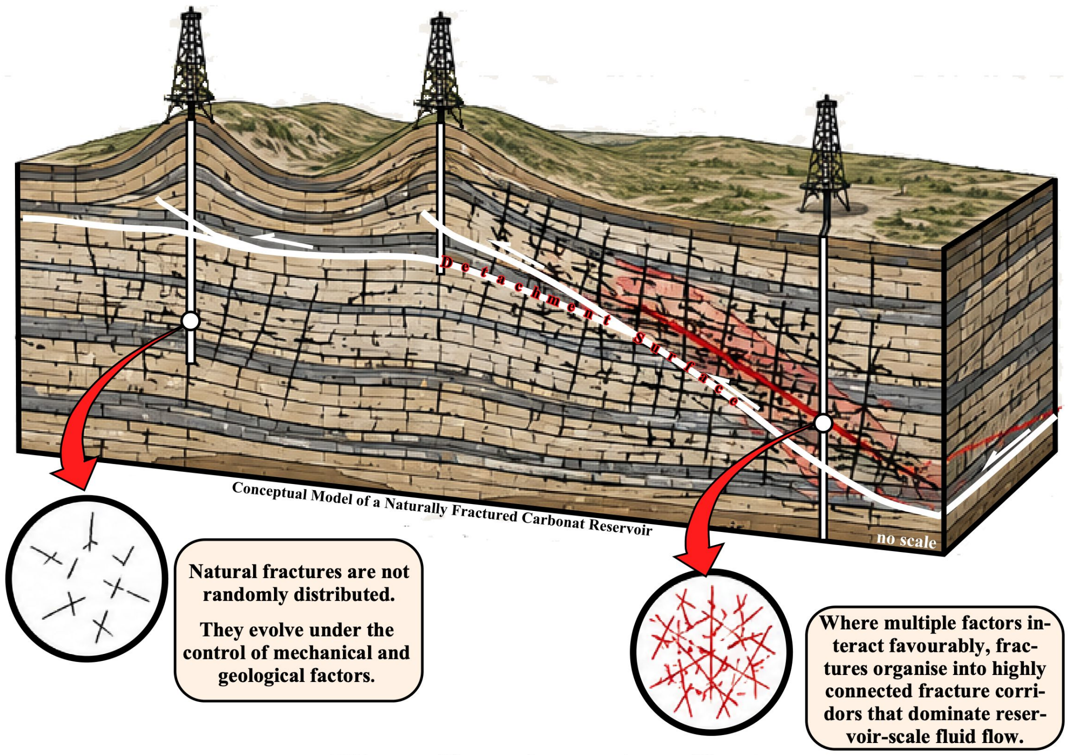
Notes on
Natural Fractured Carbonate Reservoir-Rocks
PART ONE

Aim of this Memorandum

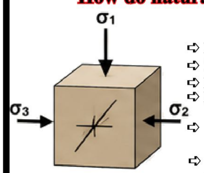
To understand how natural fractures form, why they concentrate, and where they are most likely to occur in several petroleum system, so as to enhance reservoir connectivity, fluid flow, and hydrocarbon recovery.



Three Complementary Parts

Part I- Mechanical Foundation

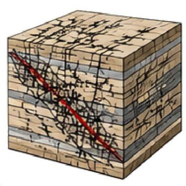
How do natural fractures form?



- Effecftive stresses
- Tectonic regimes
- Faulting ans rock failure
- Fracture initiation, propagation and termination
- Conditions for productive reservoir fractures
- Classification of natural fractures

Part II- Geological Controls

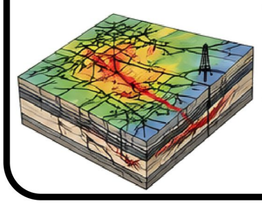
Why do fractures concentrate and evolve into fracture corridors?



- Lithology
- Texture
- Porosity
- Pore-fluid pressure
- Bed thickness
- Structural position
- Deformation history
- Fracture corridors and reservoir connectivity

Part III- Application a Petroleum System

Where are fracture corridors most likely to occur in petroleum system?



- Regional and field-scale structural framework
- Prediction of fracture corridor location
- Identification tools and data-sets
- Impact on well productivity and field development
- Implications for recovery

Integrating Mechanical Principles and Geological Understanding to Identify Fracture Corridors That Control Reservoir Performance and Hydrocarbon Recovery

Ccramez, July 2026

Caption of the cover

This conceptual illustration summarises the central objective and logical organisation of the memorandum "Notes on Natural Fractured Carbonate Reservoir-Rocks." It emphasises that natural fractures are neither randomly distributed nor equally important from a petroleum-reservoir perspective. Instead, they constitute the geological expression of the combined interaction between mechanical processes, geological controls, and tectonic deformation, which together determine whether isolated frac-tures evolve into highly connected fracture corridors capable of controlling reservoir-scale fluid flow.

The central block diagram represents a conceptual naturally fractured carbonate reservoir developed within a thrust-related anticline similar to those encountered in a Fold Belt. The illustration highlights the progressive organisation of natural fractures from scattered background fracturing to highly connected fracture corridors that dominate reservoir connectivity, pressure communication, fluid-flow pathways, well productivity, and ultimately hydrocarbon recovery.

The two enlarged circular insets illustrate this progressive evolution. The first represents a background reservoir containing relatively isolated fractures with limited hydraulic communication. The second illustrates a fracture corridor, where repeated deformation has generated a highly connected fracture network capable of transmitting fluids efficiently over reservoir-scale distances.

The lower part of the figure summarises the three complementary parts of the study. Part I establishes the mechanical foundations of natural fracturing by introducing the concepts of principal stresses, tectonic regimes, rock failure, and fracture development. Part II examines the principal geological controls governing fracture distribution, including lithology, texture, porosity, pore-fluid pressure, bed thickness, structural position, and the development of fracture corridors. Part III applies these concepts to a particular petroleum system, with the objective of identifying the most likely locations of fracture corridors and evaluating their implications for reservoir connectivity, field development, and hydrocarbon recovery.

The central message of this trilogy is that successful development of naturally fractured carbonate reservoirs depends not merely on identifying natural fractures, but on understanding the mechanical principles governing their formation, the geological factors controlling their spatial organisation, and the locations where they evolve into interconnected fracture corridors that dominate reservoir behaviour.

Author's Note

The author was trained within the traditional field-based petroleum geology tradition, in which direct geological observation, field relationships, well and seismic data, and critical interpretation constituted the primary foundations of geological understanding.

Recognising the increasing importance of digital technologies in modern geoscience, the present memorandum was prepared with the assistance of artificial-intelligence tools, particularly ChatGPT Pro.

Artificial intelligence (AI) was used as a support tool for literature review, conceptual exploration, critical discussion, logical consistency checks, and language refinement. It also served as a means of exploring alternative interpretations and testing the internal coherence of geological hypotheses. However, all geological interpretations, hypotheses, conclusions, recommendations, and any remaining errors are the sole responsibility of the author.

The objective was not to replace geological judgement, professional experience, or critical thinking, but rather to combine the insights derived from conventional geological practice with the analytical and exploratory capabilities offered by emerging AI technologies. In this context, artificial intelligence was employed as a knowledge assistant, while the formulation, evaluation and final acceptance or rejection of all geological ideas remained entirely under the sole responsibility of the author.

Table of Contents

1) Executive Summary

Natural fractures constitute one of the most important controls on the behaviour of carbonate reservoirs. Their influence extends far beyond permeability enhancement and may affect reservoir connectivity, pressure communication, well productivity, drainage efficiency, and ultimately hydrocarbon recovery.

This memorandum reviews the fundamental geological and mechanical processes responsible for the generation, evolution, and reservoir significance of natural fractures in carbonate reservoir rocks. Particular emphasis is placed on the relationships between effective principal stresses (σ_1, σ_2, σ_3), tectonic regimes, faulting, folding, rock failure, fracture initiation, fracture propagation, fracture termination, and the development of fracture corridors.

The study demonstrates that natural fractures are not randomly distributed geological features. Rather, they represent the mechanical response of rocks to their stress history. Consequently, understanding the effective stress field constitutes the first step in predicting fracture distribution and reservoir behaviour.

The memorandum further shows that only a small proportion of fractures evolve into hydraulically significant fracture systems capable of controlling fluid flow at the reservoir scale. The most important of these systems are fracture corridors, which commonly provide the principal pathways for fluid migration and hydrocarbon production in naturally fractured carbonate reservoirs.

The concepts developed herein provide the geological framework required to evaluate fracture corridors, reservoir connectivity, and development risks in naturally fractured carbonate reservoirs such as those of the Kurdamir/Topkhana (K/T) petroleum system.

The principal conclusion is straightforward: the critical issue is not merely the presence of fractures, but whether those fractures evolve into connected fracture networks capable of controlling reservoir performance, field development, and ultimately **hydrocarbon recovery**.

2) Abstract

Natural fractures exert a major influence on the performance of carbonate reservoirs by affecting permeability, connectivity, fluid flow, and hydrocarbon recovery. This memorandum reviews the principal geological and mechanical processes responsible for fracture generation and evolution in naturally fractured carbonate reservoir rocks.

The study examines stress, strain, rock deformation, effective principal stresses, tectonic regimes, faulting, rock failure, fracture initiation, fracture propagation, and fracture termination. It further discusses fracture classification, fault-related fracture systems, fold-related fracture systems, and the role of fractures in different reservoir types.

The analysis demonstrates that fracture development is controlled by the interaction between effective principal stresses, rock properties, tectonic processes, and geological history. Although fractures are widespread in carbonate rocks, only a limited proportion evolve into interconnected fracture systems and fracture corridors capable of significantly influencing reservoir behaviour.

The memorandum emphasises that the key objective of fractured-reservoir studies is not merely to identify fractures, but to understand their geometry, connectivity, hydraulic properties, and reservoir significance. These concepts are directly applicable to naturally fractured carbonate reservoirs such as those of the petroleum systems in southeastern Iraqi Kurdistan.

ملخص

تُؤثر الشقوق الطبيعية تأثيرًا كبيرًا على أداء مكامن الكربونات من خلال تأثيرها على النفاذية، والترابط، وتدفق السوائل، واستخلاص الهيدروكربونات. تستعرض هذه المذكرة العمليات الجيولوجية والميكانيكية الرئيسية المسؤولة عن توليد الشقوق وتطورها في صخور مكامن الكربونات المتشققة طبيعيًا.

تتناول الدراسة الإجهاد، والانفعال، وتشوه الصخور، والإجهادات الرئيسية الفعالة، والأنظمة التكتونية، والتصدع، وانهيار الصخور، وبدء الشقوق، وانتشارها، وتوقفها. كما تناقش تصنيف الشقوق، وأنظمة الشقوق المرتبطة بالصدوع، وأنظمة الشقوق المرتبطة بالطيات، ودور الشقوق في أنواع المكامن المختلفة.

يُبين التحليل أن تطور الشقوق يخضع لسيطرة التفاعل بين الإجهادات الرئيسية الفعالة، وخصائص الصخور، والعمليات التكتونية، والتاريخ الجيولوجي. على الرغم من انتشار الشقوق في صخور الكربونات، إلا أن نسبة محدودة منها فقط تتطور إلى أنظمة شقوق مترابطة وممرات شقوق قادرة على التأثير بشكل كبير على سلوك المكمن.

تؤكد المذكرة أن الهدف الرئيسي لدراسات المكامن المتصدعة ليس مجرد تحديد الشقوق، بل فهم هندستها، وترابطها، وخصائصها الهيدروليكية، وأهميتها للمكمن. هذه المفاهيم قابلة للتطبيق مباشرة على مكامن الكربونات المتصدعة طبيعياً، مثل تلك الموجودة في نظام كردمير/توبخانة البترولي في جنوب شرق كردستان العراق.

3) Main Conclusions

1)
Natural fractures are not randomly distributed geological features but the mechanical response of rocks to their stress history.

2)
The effective principal stresses (σ_1, σ_2, σ_3) constitute the primary controls on fracture initiation, orientation, density, connectivity, and reactivation.

3)
Understanding the effective stress field is a prerequisite for predicting fracture distribution, fracture corridors, and reservoir connectivity.

4)
Different tectonic regimes generate different fault and fracture systems; consequently, tectonic analysis represents a fundamental component of fractured-reservoir studies.

5)
Faults and folds commonly generate systematic fracture networks whose geometry may be predicted from structural relationships and effective principal stresses.

6)
Fracture initiation, fracture propagation, and fracture termination collectively determine whether a fracture system evolves into an interconnected fracture network.

7)
Only a small proportion of fractures become hydraulically significant reservoir fractures capable of controlling fluid flow at the reservoir scale.

8)
Fracture corridors represent the most effective expression of fracture connectivity and commonly exert a disproportionate influence on permeability, pressure communication, well productivity, and hydrocarbon recovery.

9)
The behaviour of fractured reservoirs depends on the relative contributions of the rock matrix and fracture systems to total porosity and permeability.

10)
The Kurdamir/Topkhana (K/T) petroleum system is tentatively interpreted as a heterogeneous fractured-carbonate reservoir in which fracture corridors may exert a major control on reservoir connectivity, productivity, drainage efficiency, and recoverable hydrocarbon volumes.

11)
Consequently, the prediction, mapping, and characterisation of fracture corridors should constitute a central objective of reservoir evaluation, development planning, and risk reduction in naturally fractured carbonate reservoirs.

4) Introduction

Natural fractures are particularly important in carbonate reservoir rocks, where they may strongly influence porosity, permeability, reservoir connectivity, and ultimately hydrocarbon productivity.

As illustrated in Figure 1, natural fractures develop in response to the effective principal stresses (σ_1, σ_2, σ_3) acting within the rock mass. These stresses are controlled by the interaction between geostatic stresses (σ_g), tectonic stresses (σ_t), and pore-fluid pressure (σ_p), and therefore evolve continuously throughout the geological history of a basin. Variations in burial depth, tectonic loading, uplift, erosion, fluid migration, or reservoir depletion may significantly modify the effective stress field and thereby influence the initiation, propagation, closure, or reactivation of fractures.

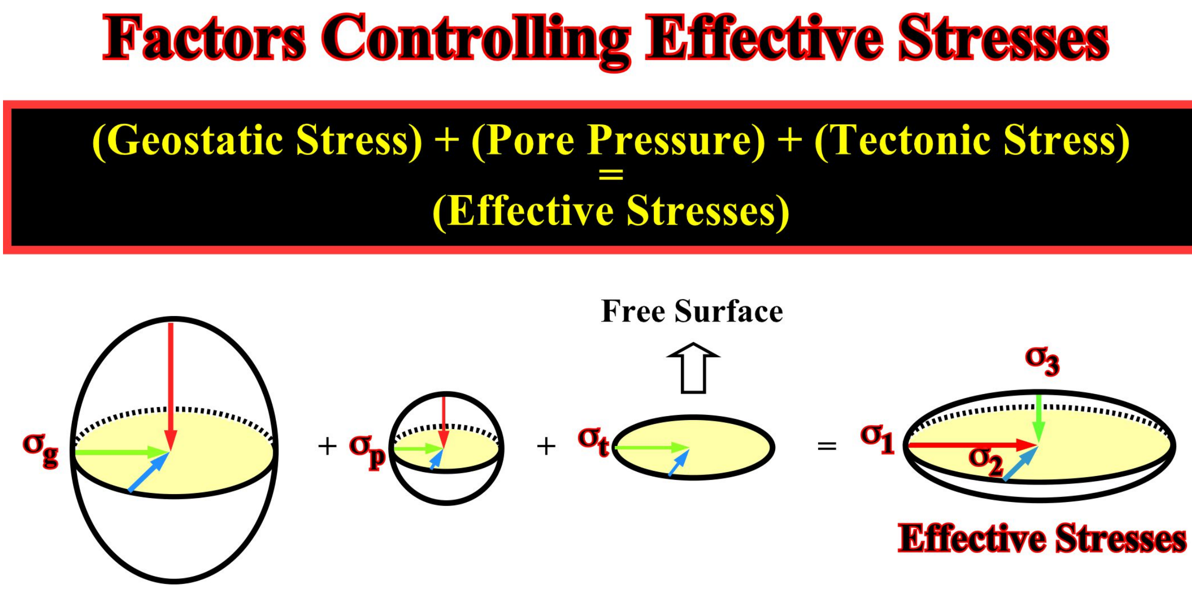


Figure 1- Factors Controlling Effective Stresses and Natural Fracturing. Natural fractures develop in response to the effective principal stresses (σ_1, σ_2, σ_3) acting within the rock mass. These stresses are controlled by the interaction between geostatic stresses (σ_g) generated by the weight of the overlying sediments, tectonic stresses (σ_t) associated with regional deformation, and pore-fluid pressure (σ_p) within the reservoir.

Changes in burial depth, tectonic loading, uplift, erosion, fluid migration, or reservoir depletion may modify the effective stress field and thereby induce the initiation, propagation, closure, or reactivation of fractures. Consequently, natural fractures are not randomly distributed geological features, but rather the mechanical response of rocks to their stress history.

The orientation, density, spacing, connectivity, and permeability of fracture systems depend on the magnitude and evolution of the effective stresses, together with the mechanical properties of the rocks affected by deformation. In carbonate reservoirs, where matrix permeability is commonly low and heterogeneous, natural fractures may become the dominant pathways for fluid migration and hydrocarbon production.

In petroleum system of Iraq, fracture networks and fracture corridors are interpreted to exert a major control on reservoir connectivity, well productivity, drainage efficiency, and ultimately on recoverable hydrocarbon volumes. Understanding the effective stress field is therefore a prerequisite for predicting the distribution of natural fractures and assessing their potential impact on field development.

According to Hunt et al. (2009), several factors exert a major control on the orientation, density, and distribution of fractures within deformed rocks:

1) Rock brittleness,

2) Rock strength,

3) Bed thickness,

4) Depth of burial,

5) Pore-fluid pressure, and

6) Structural position within the deforming structure.

These factors interact during both compressional tectonic regimes (σ_1 approximately horizontal) and extensional tectonic regimes (σ_1 approximately vertical), producing fracture networks with different geometries, orientations, and degrees of connectivity.

The analysis of these parameters requires a basic understanding of stress, strain, rock deformation, rock failure, and fracture development. Therefore for clarity and ease of reading, the present memorandum is subdivided into three complementary parts.

Part I introduces the fundamental mechanical concepts controlling natural fracturing, including effective principal stresses, tectonic regimes, faulting, rock failure, fracture initiation, fracture propagation, fracture termination, the conditions under which fractures evolve into productive reservoir fractures, and the principal classification schemes used to describe natural fractures according to their origin, geometry, displacement, timing of formation, and reservoir significance.

Part II examines the principal geological controls on fracture development, including lithology, texture, porosity, pore-fluid pressure, bed thickness, structural position, and deformation history, and discusses their implications for fracture corridors, reservoir connectivity, and hydrocarbon productivity.

Part III applies these mechanical and geological concepts to a petroleum system of North Ira. Its objective is no longer to explain how fracture corridors form, but rather to determine where they are most likely to occur, how they may influence reservoir connectivity, fluid-flow pathways, well productivity, and hydrocarbon recovery, and how they can be identified and incorporated into reservoir characterisation and field-development strategies.

In naturally fractured carbonate reservoirs such as those of the North Iraq petroleum system, the critical issue is not merely the presence of fractures, but whether they evolve into interconnected fracture corridors capable of enhancing fluid flow, improving reservoir connectivity, and ultimately controlling field performance and hydrocarbon recovery.

5) PART - ONE

Basic Mechanical Concepts controlling Natural Fracturing

5.1) Stress, Strain, and Rock Deformation

Stress (σ) is a vectoral quantity (it has magnitude and direction) defined as force (F) per unit area (A). The unit of measure of stress is Pascals, where 1 Pa= 1 N / m². However, in the Earth's crust they are sufficiently high that they are preferably expressed in MegaPascals (10^6 Pa) or GigaPascals (10^9 Pa).

When acting on a plane, stress (σ) can be subdivided into two components acting along the plane:

(i) Normal stress (σ_n) perpendicular to the plane, and

(ii) Shear stress (τ) parallel to the plane.

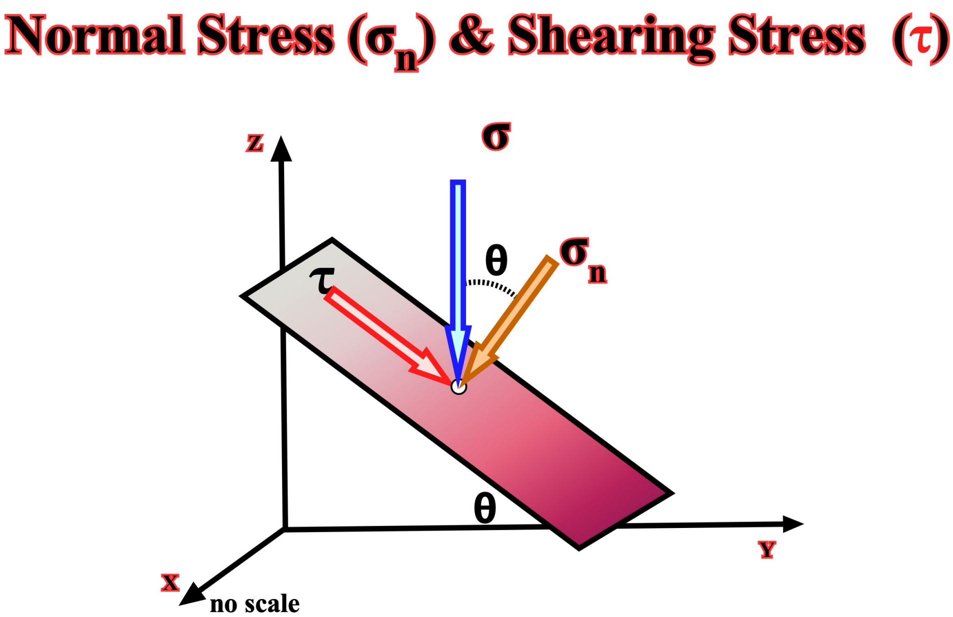


Figure 2- Resolution of Stress (σ) into Normal (σ_n) and Shear (τ) Components Acting on a Rock Surface. Any stress acting on a rock surface can be resolved into two components: (i) a normal stress (σ_n) acting perpendicular to the surface and (ii) a shear stress (τ) acting parallel to the surface. The relative magnitude of these two components depends on the orientation of the surface with respect to the applied stress field.

Normal stress tends to press the rock surfaces together and generally inhibits fracture opening and slip. In contrast, shear stress promotes relative displacement between adjacent rock blocks and may lead to the development or reactivation of fractures and faults when the rock strength is exceeded.

The mechanical behaviour of rocks is therefore controlled not only by the magnitude of the applied stresses, but also by their orientation relative to pre-existing discontinuities and potential fracture planes. The competition between normal and shear stresses determines whether a rock will remain stable, fracture in tension, or fail by shear.

In naturally fractured carbonate reservoirs such as those of the North Iraq petroleum systems, variations in normal and shear stresses may influence fracture initiation, fracture reactivation, permeability anisotropy, and the development of fracture corridors that can significantly affect reservoir connectivity and hydrocarbon production.

Summing up: A fracture may exist within a reservoir-rocks, but whether it remains open, closed, conductive, or sealing depends largely on the balance between the normal and shear stresses acting upon it.

In addition, normal stresses (σ_n) can be positive or compressional, which are generally represented by convergent arrows or by a symbol plus (+) and negative or tensional , which area represented by two arrows in opposite directions or by the symbol minus (-) in each side of the trace of the plane.

Similarly, the shear stresses (τ) can be dextral and sinistral. The dextral shearing stresses are represented, as dextral faults, by two opposite arrows, one above and the other below the plane, indicating that the upper part is displaced to the right. The sinistral shearing stresses are represented, as sinistral fault, by two opposite arrows, one above and the other below the plane, indicating that the upper part is displaced to the left.

Stress, Stress Tensor and Stress Field

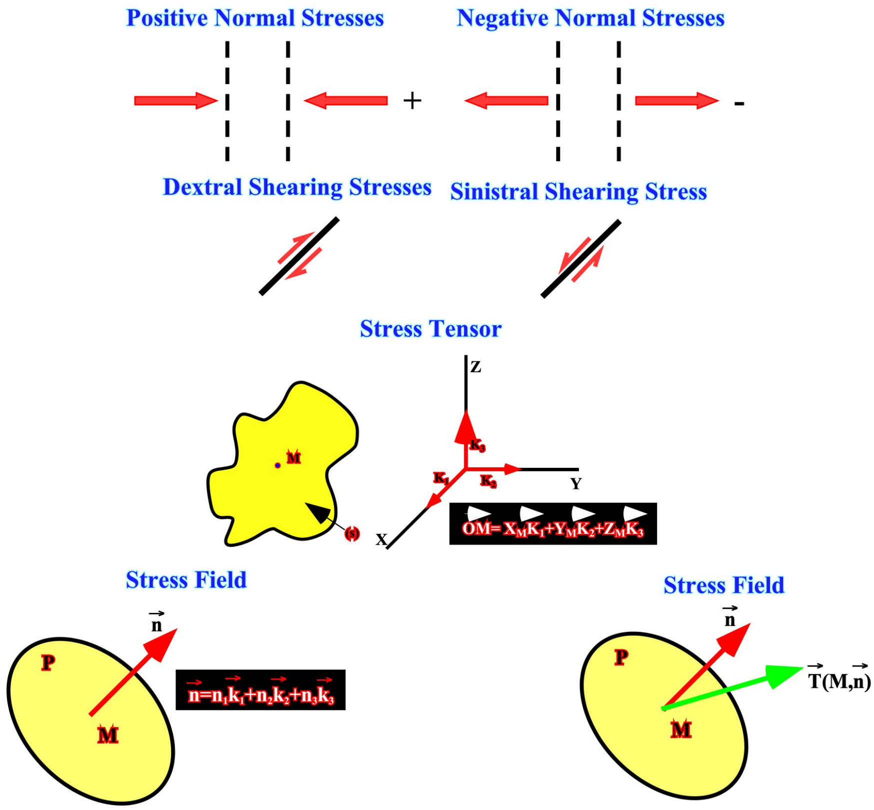


Figure 3- Stress, Stress Tensor and Stress Field. The deformation and fracturing of rocks are controlled by the stress field acting within the Earth's crust. Stress may be defined as the force acting per unit area on an imaginary surface within a rock body. Depending on its orientation relative to the surface considered, stress can be resolved into normal stresses (σ_n), acting perpendicular to the surface, and shearing stresses (τ), acting parallel to the surface.

Normal stresses may be either compressive (positive) or tensional (negative), whereas shearing stresses may induce relative displacement between adjacent rock elements. The combined action of these stresses determines whether a rock remains stable, deforms elastically, fractures, or fails by faulting.

Because stress acts in three dimensions, it is represented mathematically by a stress tensor, which describes the complete state of stress at a given point within the rock mass. The stress tensor allows the calculation of the magnitude and orientation of the stresses acting on any plane passing through that point.

When the stress tensor is defined at every point within a geological body, the result is a stress field. Spatial variations in the stress field control the distribution of deformation, fractures, stylolites, faults, and fracture corridors. Consequently, understanding the geometry and evolution of the stress field is fundamental for predicting fracture development and reservoir behaviour.

In the North Irak petroleum system, variations in the regional and local stress fields associated with folding, faulting, burial, uplift, and fluid-pressure changes are interpreted to have played a major role in the generation and reactivation of fracture systems that may significantly influence reservoir connectivity and hydrocarbon productivity.

Summing up: Fractures do not form randomly. They develop preferentially where the stress field concentrates deformation within the reservoir.

5.1.1- Stress Tensor and Stress Field

Stress acting within a rock is generally different in different directions. Therefore, the state of stress at a given point cannot be described by a single value.

To describe completely the state of stress at a point, geoscientists use a mathematical representation known as a stress tensor. The stress tensor contains all the normal and shear stresses acting on an infinitesimal rock element and therefore provides a complete description of the local stress state.

In three-dimensional space, the stress tensor contains nine stress components. Three of these are normal stresses acting perpendicular to the coordinate planes, while the remaining six are shear stresses acting parallel to those planes (Fig. 4).

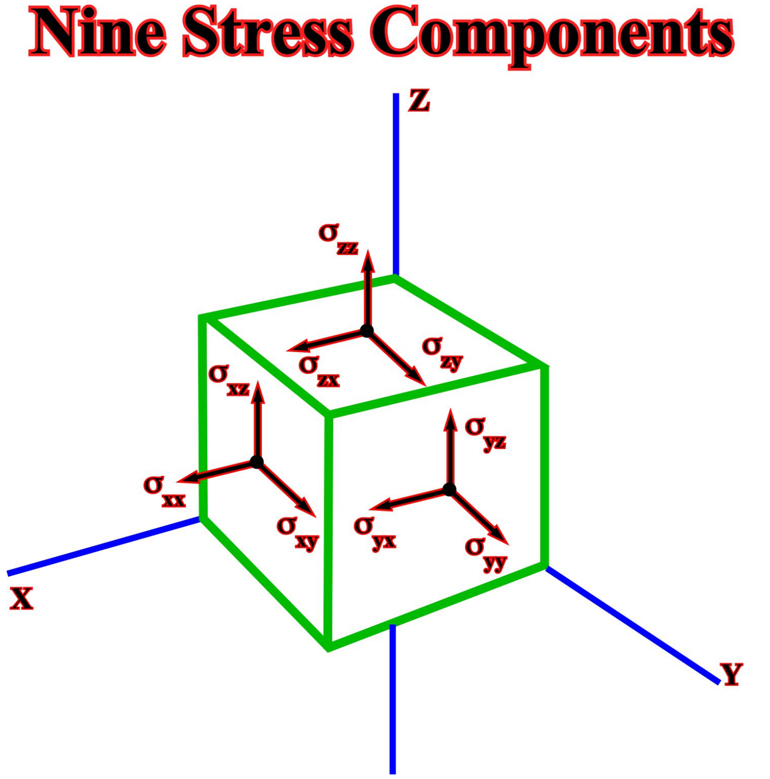


Figure 4- Simplified Representation of the Components of a Stress Tensor. The complete state of stress at a point within a rock can be represented by a set of normal and shear stresses acting in different directions. Together, these stresses constitute the stress tensor, which provides a complete description of the local stress state. From the stress tensor, geoscientists can determine the effective principal stresses (σ_1, σ_2, σ_3), which control rock deformation, faulting, and fracturing.

Once the stress tensor is known at a given point, the stresses acting on any plane orientation passing through that point can be calculated. This makes it possible to determine whether a particular plane is likely to remain stable, open as an extension fracture, fail in shear, or become reactivated as a fault.

When the stress tensor is defined at every point within a geological body, the result is a stress field. Spatial variations in the stress field control the localisation of deformation and therefore influence the distribution of folds, faults, stylolites, natural fractures, and fracture corridors.

5.1.2) Deformation (Rotation, Translation and Strain)

Deformation may be defined as any change in the shape, position, or orientation of a geological body resulting from the application of a differential stress, that is, a state in which the magnitude of stress is not the same in all directions.

Deformation can occur through three fundamental mechanisms:

1) **Rotation** – the pivoting of a rigid body around a fixed axis without any change in its shape.

2) **Translation** – a displacement of a rigid body from one position to another without any change in its shape or orientation.

3) **Strain** – a change in the shape and/or volume of a body resulting from the relative displacement of its constituent particles (Gudmundsson, 2011). Unlike rotation and translation, strain involves an internal deformation of the rock mass.

Depending on the mechanical response of the rock to an applied stress, deformation may be either:

A) Brittle or B) Ductile.

The type of deformation depends on several factors, including the magnitude of the applied stresses, temperature, confining pressure, strain rate, pore-fluid pressure, and the mechanical properties of the rock, particularly those related to (*)Young's modulus and Poisson's ratio.

(*) Young's modulus measures how difficult it is to deform a rock elastically. Poisson's ratio measures how much a rock changes its width when it is compressed or stretched. Together, Young's modulus and Poisson's ratio are commonly used to characterise the mechanical behaviour of reservoir rocks and to evaluate their tendency to deform in a brittle or ductile manner. In general, rocks with a high Young's modulus and a low Poisson's ratio tend to behave more brittly and are therefore more prone to fracturing (relevant on natural fractured carbonate reservoirs).

Brittle deformation occurs when stresses exceed the strength of the rock, leading to the formation and propagation of fractures, joints, and faults. Although brittle failure appears sudden, it is generally preceded by elastic and, in some cases, limited plastic deformation (Van der Pluijm, 2004).

Ductile deformation occurs when a rock undergoes substantial changes in shape without the development of major fractures. Common ductile deformation mechanisms include cataclastic flow, diffusion creep, pressure solution, and crystal plasticity.

The principal differences between brittle and ductile deformation are:

1) **Ductile strain is generally distributed throughout the rock volume, whereas brittle strain is concentrated along fractures and faults.**

2) **Ductile deformation is strongly influenced by temperature, confining pressure, and time, whereas brittle deformation depends primarily on the magnitude of the applied differential stress (Suppe, 1985).**

In petroleum geology, brittle deformation is particularly important because it generates the fractures and fracture corridors that may significantly enhance reservoir permeability and connectivity in naturally fractured carbonate reservoirs.

5.1.3) Effective Principal Stress (σ_1, σ_2, σ_3)

The effective principal stresses (σ_1,σ_2,σ_3) are the three axes of the effective stress ellipsoid (Fig. 1) and represent the stresses responsible for rock deformation. Their magnitudes and orientations result from the combined influence of geosta-

tic stresses (σ_g), tectonic stresses (σ_t), and pore-fluid pressure (σ_p) acting within the rock mass.

Consequently, changes in burial depth, tectonic loading, uplift, erosion, fluid migration, or reservoir depletion may modify the effective stress field and thereby influence the initiation, propagation, closure, or reactivation of natural fractures.

Caveat: In this paper, the term effective stress is used in the geological sense to designate the principal stresses that actually control rock deformation and fracturing.

For petroleum geologists, the most important information derived from the stress tensor is the determination of the three effective principal stresses (σ_1, σ_2, σ_3), corresponding respectively to the maximum, intermediate, and minimum stresses acting at a given point.

The relative magnitudes and orientations of these stresses largely control the initiation, orientation, and distribution of natural fractures within the reservoir. Conventionally:

A) When σ_1 is vertical, the stress regime is extensional, favouring the development of normal faults and associated extension fractures.

B) When σ_1 is horizontal, the stress regime is compressional, favouring the development of folds, reverse faults, and associated fracture systems.

C) When σ_1 and σ_3 are horizontal and σ_2 is vertical, the stress regime is strike-slip, favouring the development of wrench faults and associated fracture networks.

5.1.4) Effective Principal Stress and Tectonic Regimes

The orientation and relative magnitudes of the effective principal stresses (σ_1, σ_2, σ_3) determine the style of deformation that develops within a sedimentary basin. Different stress configurations generate different tectonic regimes and therefore different structural geometries.

In an extensional regime, crustal stretching is accommodated by normal faulting, graben formation, and associated extensional fractures.

In a compressional regime, crustal shortening generates folds, reverse faults, thrust faults, and associated fracture systems. Between these two end-members, strike-slip regimes are characterised by predominantly horizontal movements, producing wrench faults, pull-apart basins, en-echelon structures, and complex fracture networks.

The resulting structural styles may be further modified by the presence of mechanically weak layers such as salt or overpressured shales, which can decouple the deformation of the sedimentary cover from that of the underlying basement.As a consequence, the same regional stress regime may generate markedly different structural geometries and fracture patterns.

Because natural fractures develop in predictable relationships with the effective principal stresses, understanding the tectonic regime provides an important framework for predicting fracture orientation, fracture density, fracture corridors, and reservoir connectivity.

Figure 5 summarises the principal tectonic regimes commonly observed in sedimentary basins and illustrates the relationship between the effective principal stresses and the resulting structural styles.

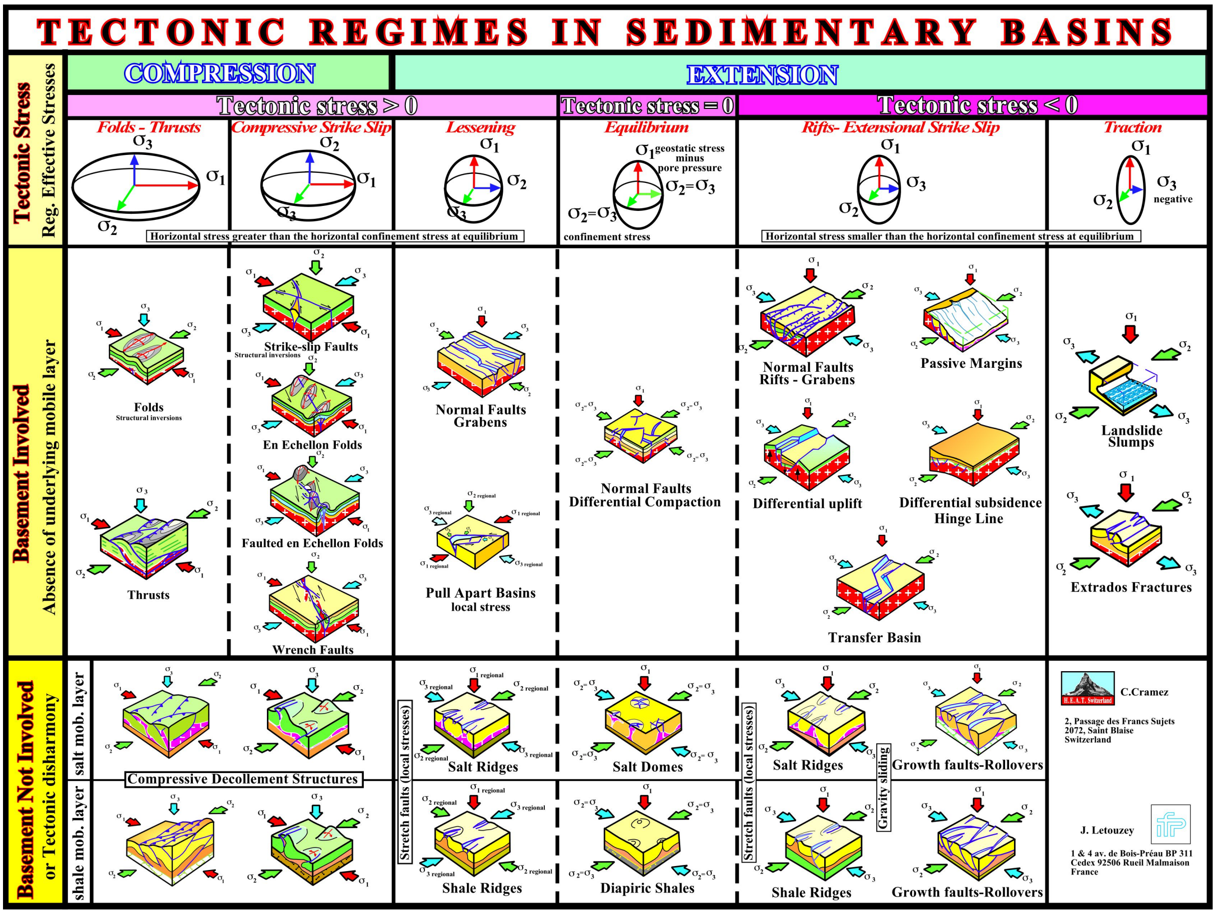


Figure 5- Relationship Between Effective Principal Stresses and Tectonic Regimes in Sedimentary Basins. The orientation and relative magnitudes of the effective principal stresses (σ_1, σ_2, σ_3) control the style of rock deformation and therefore the structural architecture of sedimentary basins. The effective principal stresses correspond to the three axes of the effective-stress ellipsoid and represent the stresses responsible for rock deformation.

When σ_1 is horizontal, the stress regime is compressional, favouring the development of folds, thrust faults, compressional strike-slip faults, and associated fracture systems. When σ_1 is vertical, the stress regime is extensional, promoting the formation of normal faults, grabens, half-grabens, growth faults, rollover structures, and related extensional fractures. Intermediate configurations generate strike-slip regimes, characterised by wrench faults, pull-apart basins, en-echelon folds, and complex fracture networks.

The figure also illustrates the influence of mechanical decoupling associated with mobile layers such as salt or overpressured shales. In such cases, deformation affecting the sedimentary cover may differ significantly from that affecting the underlying basement, resulting in tectonic disharmony and the development of detached folds, thrust systems, salt ridges, shale ridges, diapirs, gravity-driven structures, and structural inversions. Because natural fractures develop in predictable relationships with the effective principal stresses, the determination of the orientation and relative magnitude of σ_1, σ_2, and σ_3 provides a fundamental framework for predicting fracture orientation, fracture density, fracture corridors, and reservoir connectivity. Therefore, the analysis of tectonic regimes constitutes a key step in the evaluation of naturally fractured carbonate reservoirs such as those of the North Iraq petroleum system.

Summing up: Different tectonic regimes generate different fracture systems; consequently, understanding the effective principal stresses is the first step in predcting fracture distribution, connectivity, and reservoir performance.

Before attempting to predict fractures, fracture corridors, or reservoir connectivity, the geoscientist must first establish the tectonic regime and the orientation of the effective principal stresses responsible for deformation.

5.1.5) Effective Principal Stresses and Faulting (Anderson's Theory)

In 1951, E. M. Anderson proposed that the orientation of the effective principal stresses is directly related to the type of faulting developed within the Earth's crust (Figure 6). This influential hypothesis, which has been widely corroborated by field observations and subsurface data, assumes that the effective principal stresses are compressive and ordered such that:

$$\sigma_1 > \sigma_2 > \sigma_3,$$

where

- **σ_1 is the maximum effective principal stress,**
- **σ_2 the intermediate effective principal stress, and**
- **σ_3 the minimum effective principal stress.**

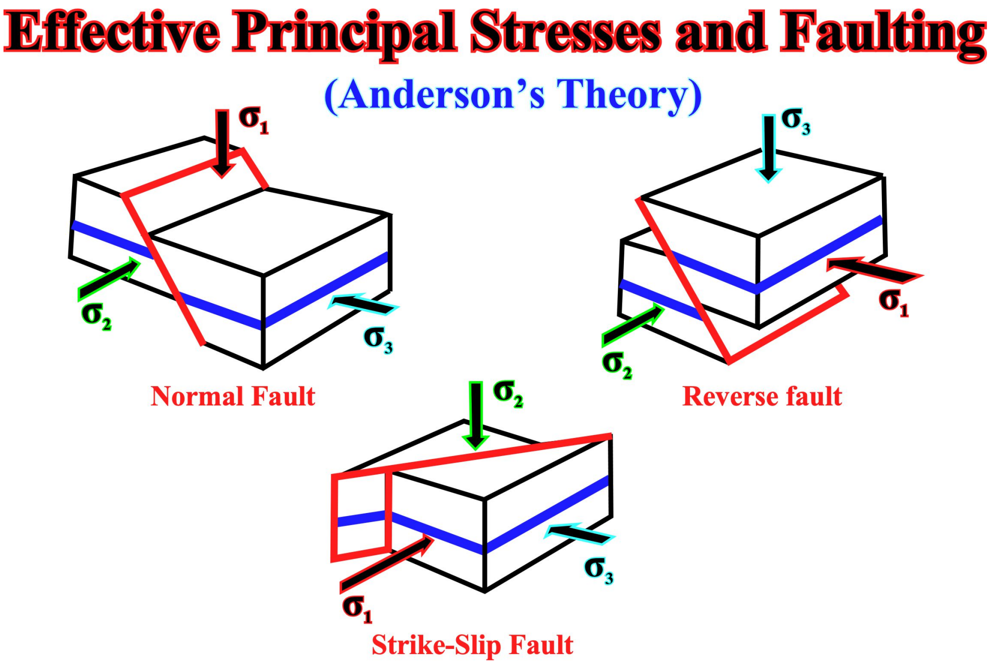


Figure 6- Effective Principal Stresses and Faulting According to Anderson's Theory. The style of faulting developed within the Earth's crust is controlled by the orientation and relative magnitude of the three effective principal stresses (σ_1, σ_2, σ_3), which correspond to the three axes of the effective-stress ellipsoid and represent the stresses responsible for rock deformation.

In an extensional tectonic regime, the maximum effective principal stress (σ_1) is vertical, while the minimum principal stress (σ_3) is horizontal. This stress configuration favours the development of normal faults and associated extensional fractures.

In a compressional tectonic regime, the maximum effective principal stress (σ_1) is horizontal and the minimum principal stress (σ_3) is vertical. This configuration promotes the formation of reverse faults, thrust faults, folds, and associated compressional fracture systems.

In a strike-slip tectonic regime, the intermediate principal stress (σ_2) is vertical, while both σ_1 and σ_3 are horizontal. This stress arrangement favours the development of strike-slip (wrench) faults, pull-apart structures, en-echelon folds, and complex fracture networks.

According to Anderson's theory, the orientation of the principal stresses determines not only the type of faulting but also the orientation and distribution of the associated fracture systems. Consequently, the determination of the effective principal stresses

provides a fundamental framework for predicting natural fractures, fracture corridors, and reservoir connectivity in naturally fractured carbonate reservoirs.

For petroleum geologists, the practical implication is straightforward: different stress regimes generate different fault and fracture patterns, which in turn influence hydrocarbon migration, reservoir compartmentalisation, well productivity, and recoverable reserves.

Following Anderson's theory, different fault types develop under different orientations of the principal stresses. The observation of faults in outcrops, seismic data, borehole images, or geological maps allows geoscientists to infer the orientation of the effective-stress ellipsoid that existed during deformation.

Conversely, if the orientation and relative magnitudes of the effective principal stresses are known, the likely orientation and style of faulting, folding, and associated fracture systems can be predicted. Anderson's theory therefore provides a fundamental link between the stress field and the structural geometry observed in sedimentary basins.

The orientation of the effective principal stresses not only controls the type of faulting but also influences the typical dip of the resulting faults:

(i) In an extensional regime, where σ_1 is the vertical maximum effective principal stress and σ_3 is horizontal minima effective principally stress, normal faults generally develop with dips ranging from approximately 50° to 70°, commonly around 60°. Such faults accommodate crustal extension by allowing the hanging wall to move downward relative to the footwall.

(ii) In a compressional regime, where σ_1 is the horizontal maximum effective principal stress and σ_3 is vertical minimum effective principal stress, reverse faults typically dip between 25° and 45°, whereas major thrust faults generally exhibit lower dips, commonly less than 30°. These structures accommodate crustal shortening by moving the hanging wall upward relative to the footwall.

(iii) In a strike-slip regime, where σ_2 is vertical intermediate effective principal stress and both σ_1 and σ_3 are horizontal, stick-slip faults develop and are generally subvertical, commonly dipping between 70° and 90°. Movement occurs predominantly in a horizontal direction, producing dextral or sinistral displacement depending on the sense of shear.

Although these dip values represent typical geometries predicted by Anderson's theory, actual fault dips may vary according to lithology, pore-fluid pressure, mechanical stratigraphy, tectonic inheritance, and the progressive evolution of the stress field.

5.1.6) Rock Failure

Rock failure may be defined as the condition under which a rock can no longer sustain the stresses acting upon it and therefore undergoes permanent deformation. Failure may occur either by the formation of fractures, by faulting, or by ductile flow, depending on the magnitude and orientation of the effective principal stresses and on the mechanical properties of the rock.

Several theories have been proposed to explain rock failure. Among them, Mohr's theory of failure has proven particularly useful for describing the combined influence of normal and shear stresses on the failure of geological materials.

Mohr's theory is based on two fundamental assumptions:

(i) The state of stress is characterised by three effective principal stresses such that:

$$\sigma_1 > \sigma_2 > \sigma_3$$

where,

σ_1, σ_2 and σ_3 are respectively the maximum, intermediate, and mini-mum effective principal stresses.

(ii) The intermediate effective principal stress (σ_2) exerts only a minor influence on failure compared with σ_1 and σ_3.

According to this theory, rock failure is controlled by both the normal stress acting across a potential failure plane and the shear stress acting parallel to that plane. Failure occurs when the combination of these stresses exceeds the strength of the rock.

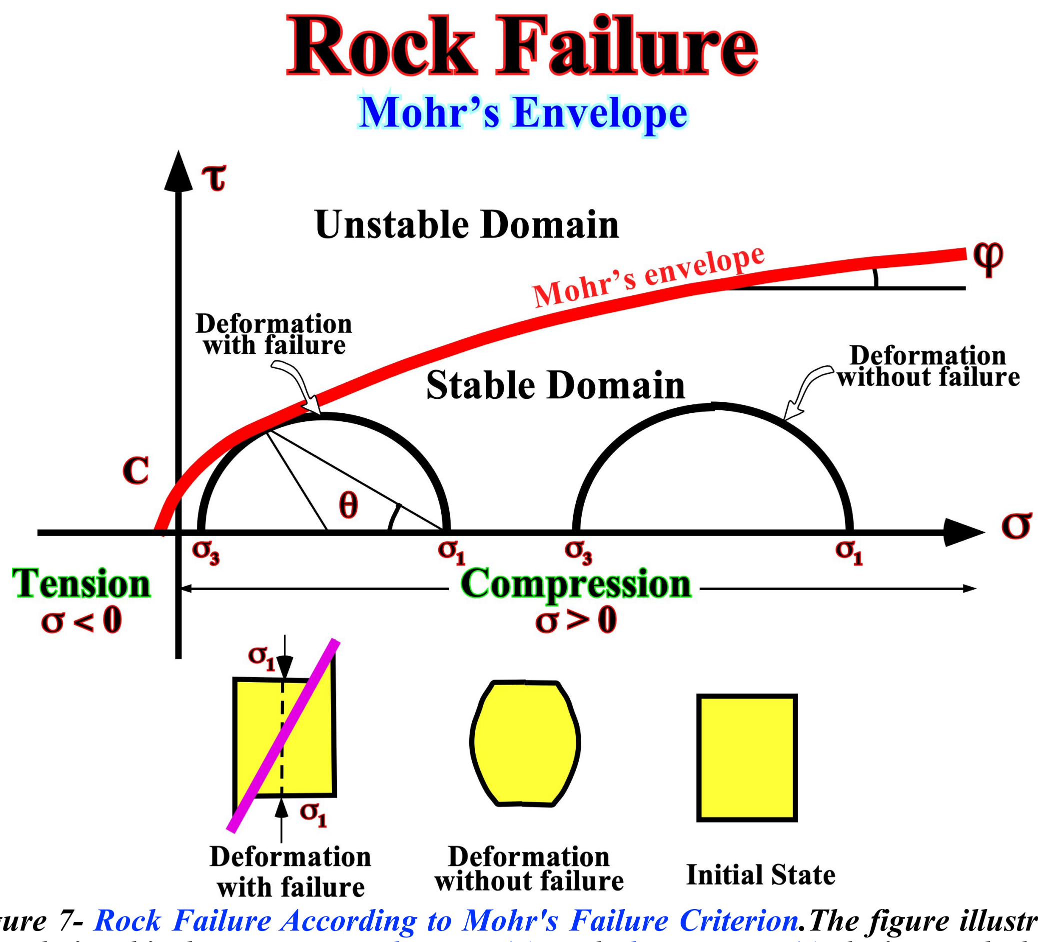


Figure 7- Rock Failure According to Mohr's Failure Criterion.The figure illustrates the relationship between normal stress (σ) and shear stress (τ) during rock deformation. The curved line represents the Mohr failure envelope, which separates the stable domain from the unstable domain. As the differential stress increases, the Mohr circle expands until it touches the failure envelope. At this point, the strength of the rock is exceeded and failure occurs.

Failure may develop either in tension or compression, depending on the stress conditions. While the Mohr circle remains below the failure envelope, deformation occurs without fracturing. When the circle reaches the envelope, the rock undergoes brittle failure and fractures or faults are generated.

In naturally fractured carbonate reservoirs, this process represents the fundamental mechanism by which fracture systems are created. The orientation, density, and connectivity of the resulting fractures are largely controlled by the effective principal stresses acting during deformation.

In naturally fractured carbonate reservoirs, rock failure is of particular importance because it constitutes the fundamental mechanism by which natural fractures are generated. The resulting fracture systems may subsequently influence porosity, permeability, reservoir connectivity, and hydrocarbon production.

Whether a rock fails in a brittle or ductile manner depends on several factors, including lithology, temperature, confining pressure, pore-fluid pressure, strain rate, and burial depth.

Carbonate reservoirs commonly experience brittle failure during tectonic deformation, producing fractures and faults that may remain open, become mineralised, or be reactivated during subsequent deformation events.

From a geological perspective, two principal modes of brittle failure are recognised:

(i) tensile failure and

(ii) shear failure.

Although both generate fractures, the resulting fracture geometries, orientations, and reservoir implications may be very different.

5.1.6.1) Tensile Failure

Tensile failure occurs when the tensile stresses acting within a rock exceed its tensile strength. Because most rocks are significantly weaker in tension than in compression, tensile fractures may develop even when the overall stress levels are relatively low.

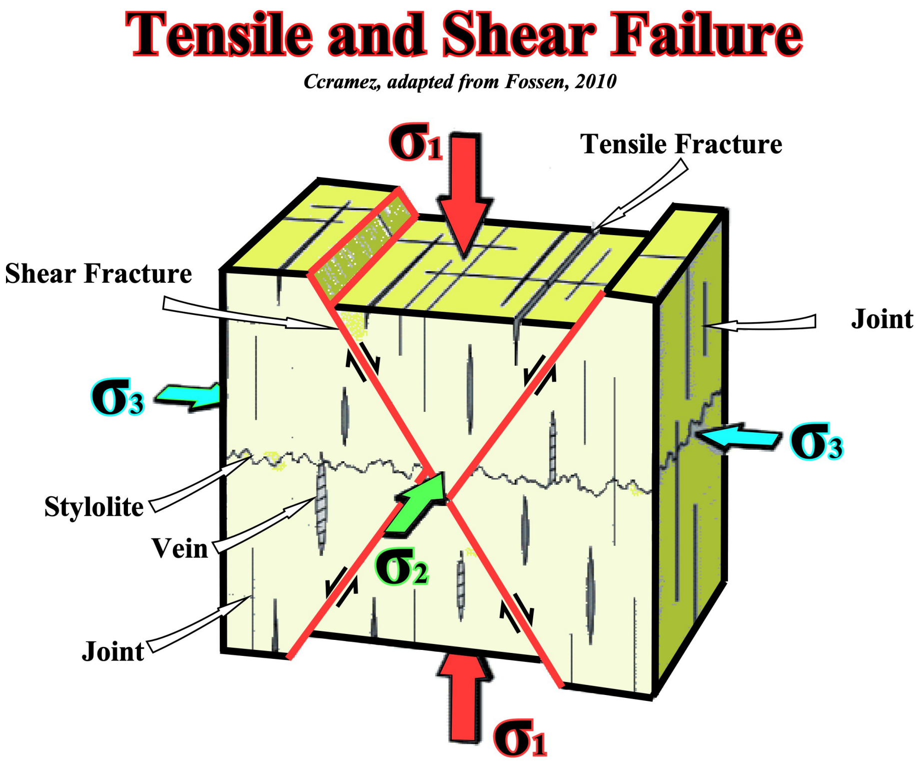


Figure 8- Tensile and Shear Failure in Relation to the Effective Principal Stresses. The figure illustrates the two principal modes of brittle rock failure: tensile failure and shear failure. Tensile failure generates extension fractures, such as joints, veins, and hydrofractures, in which the fracture walls move apart approximately perpendicular to the fracture plane. These fractures commonly develop perpendicular to the minimum effective principal stress (σ_3) and are often highly permeable.

Shear failure generates shear fractures and faults, characterised by relative displacement parallel to the fracture plane. Shear fractures typically develop in predic-

table orientations with respect to the effective principal stresses and may evolve into normal, reverse, thrust, or strike-slip faults depending on the tectonic regime.

The figure also illustrates common fracture-related features observed in carbonate reservoirs, including joints, veins, stylolites (which are not fractures in the strict sense but a pressure-solution surface), and shear fractures. Although both tensile and shear fractures contribute to reservoir permeability, their geometry, connectivity, and hydraulic behaviour may differ significantly. The interaction between these fracture types commonly controls the development of fracture corridors and reservoir connectivity.

Tensile failure produces extension fractures in which the fracture walls move apart approximately perpendicular to the fracture plane. Typical examples include joints, veins, hydrofractures, and many open fractures observed in carbonate reservoirs.

In other words, tensile failure generates extension fractures whereas shear failure generates shear fractures associated with displacement along the fracture plane.

Extension fractures commonly provide the highest permeability because they create open pathways for fluid flow. Consequently, they are often of considerable importance in naturally fractured carbonate reservoirs.

In terms of effective principal stresses, tensile fractures tend to develop perpendicular to the minimum effective principal stress (σ_3) and parallel to the maximum effective principal stress (σ_1).

5.1.6.2) Shear Failure

Shear failure occurs when the shear stresses acting on a plane exceed the shear strength of the rock. Unlike tensile failure, shear failure involves relative displacement of the fracture walls parallel to the fracture plane.

Most faults originate through shear failure. Depending on the tectonic regime and the orientation of the effective principal stresses, shear failure may generate normal faults, reverse faults, thrust faults, or strike-slip faults.

Shear fractures are commonly associated with fault zones and may initially exhibit limited permeability. However, subsequent dilation, dissolution, repeated movement, or fracture reactivation may significantly enhance their capacity to transmit fluids.

Consequently, many productive fracture corridors in carbonate reservoirs are associated with zones of repeated shear deformation, where interconnected shear fractures provide effective pathways for hydrocarbon migration and production.

5.1.6.3) Griffith Cracks and Fracture Initiation

Griffith (1920, 1924) proposed that fractures do not initiate spontaneously within intact rocks, but rather from pre-existing microscopic flaws known as Griffith cracks. These flaws may correspond to grain boundaries, fossils, vugs, pores, stylolites, bedding surfaces, or earlier fractures.

When a rock is subjected to increasing stress, stress concentrations develop at the tips of these flaws. If the local stress exceeds the strength of the rock, a new fracture is initiated may begin to propagate through the surrounding rock mass.

Consequently, fracture initiation depends not only on the magnitude of the applied stresses but also on the distribution, size, and orientation of pre-existing weaknesses within the rock. Larger flaws generally require lower stresses to initiate fracture propagation than smaller flaws.

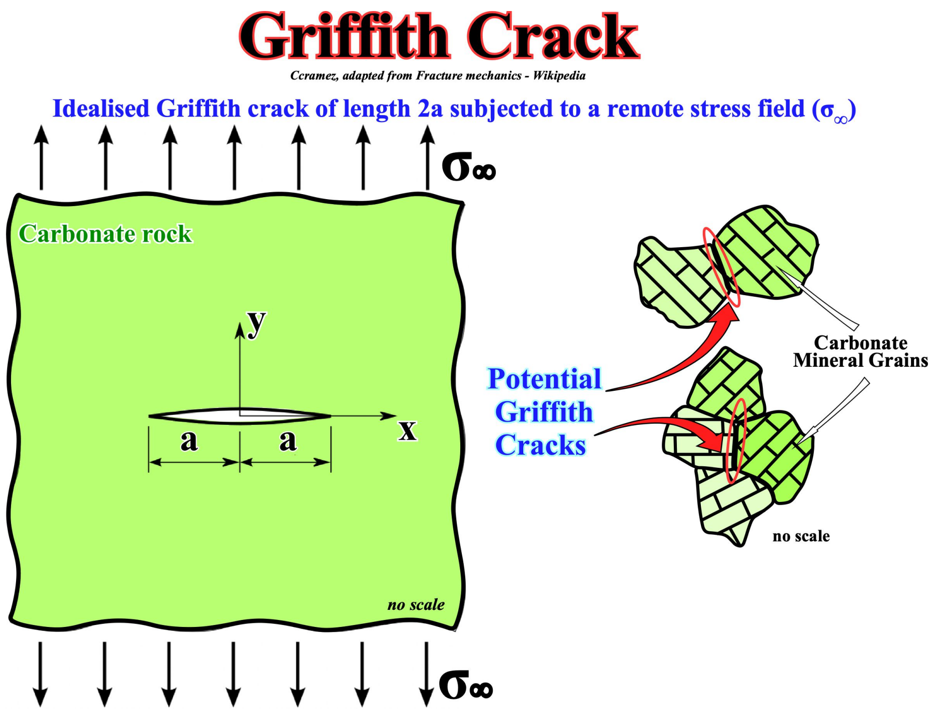


Figure 9- Griffith Crack and Fracture Initiation in Carbonate Rocks. According to Griffith's theory, fractures initiate from pre-existing microscopic flaws or discontinuities known as Griffith cracks. When a rock is subjected to an applied stress field (σ∞), stress concentrations develop at the tips of these flaws. If the local stress concentration exceeds the strength of the rock, fracture initiation occurs and the crack begins to propagate.

The idealised Griffith crack shown on the left consists of a discontinuity of length 2a embedded within a rock mass subjected to a remote stress field. The diagram on the right illustrates how potential Griffith cracks may occur naturally between carbonate mineral grains, at grain boundaries, microcracks, dissolution features, fossils, or other microscopic heterogeneities.

In naturally fractured carbonate reservoirs, fracture initiation commonly begins at such pre-existing weaknesses. Consequently, the distribution of microscopic flaws exerts an important control on the location, orientation, and density of the fracture systems that subsequently develop within the reservoir.

When a rock is subjected to increasing stress, stress concentrations develop at the tips of these flaws. If the local stress exceeds the strength of the rock, a new fracture is initiated may begin to propagate through the surrounding rock mass.

So, fracture initiation depends not only on the magnitude of the applied stresses but also on the distribution, size, and orientation of pre-existing weaknesses within the rock. Larger flaws generally require lower stresses to initiate fracture propagation than smaller flaws.

In carbonate reservoirs, where grain boundaries, fossils, dissolution features, stylolites, and diagenetic heterogeneities are common, suitable fracture-initiation sites are generally abundant. The resulting fracture patterns therefore reflect both the prevailing stress field and the geological characteristics of the reservoir.

Griffith's theory provides a mechanical explanation for why fractures tend to originate at pre-existing weaknesses rather than within perfectly homogeneous rock. It therefore constitutes one of the fundamental concepts of fracture mechanics and natural fracture development.

5.1.6.4) Fracture Propagation

Once initiated, a fracture may continue to grow if the stresses acting at its tip remain sufficiently high. This process is known as fracture propagation.

Fracture propagation is controlled by several factors, including the magnitude of the effective principal stresses, the mechanical properties of the rock, pore-fluid pressure, and the presence of geological discontinuities. In general, fractures tend to propagate in orientations that minimise the mechanical work required for further growth.

According to Griffith's theory, fracture growth occurs because high tensile stresses develop at the tips of pre-existing cracks. As propagation proceeds, the fracture progressively releases part of the stored elastic strain energy accumulated within the rock mass.

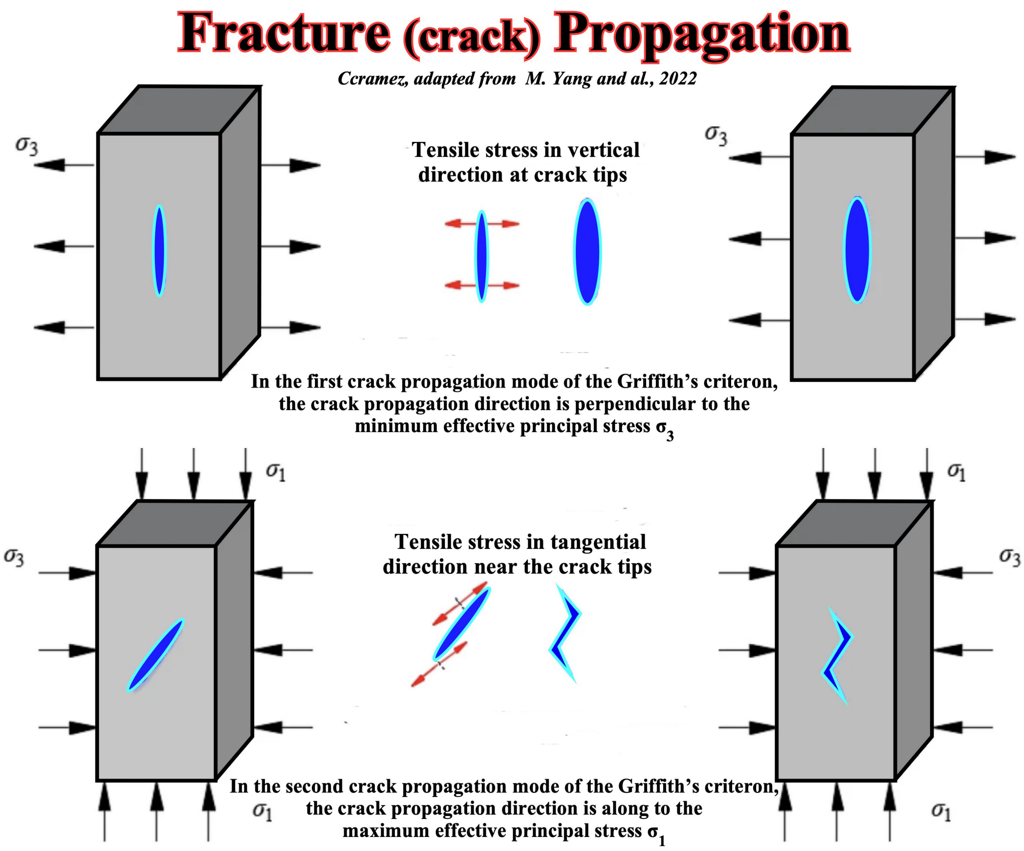


Figure 10- Fracture Propagation According to Griffith's Theory. Once a fracture has been initiated, continued propagation depends on the development of stress concentrations at the fracture tips. Griffith's theory predicts that these local stress concentrations may exceed the strength of the surrounding rock, allowing the fracture to grow progressively through the rock mass.

The upper example illustrates a fracture propagating perpendicular to the minimum effective principal stress (σ_3), a configuration commonly associated with extension fractures. The lower example shows an inclined Griffith crack subjected to compression, where local tensile stresses develop near the crack tips and promote fracture growth approximately parallel to the maximum effective principal stress (σ_1).

As fractures propagate, they may interact with neighbouring fractures, faults, stylolites, bedding surfaces, and other geological discontinuities. Such interactions *may progressively generate interconnected fracture networks and, ultimately, fracture corridors capable of significantly enhancing reservoir permeability and connectivity.*

In naturally fractured carbonate reservoirs, fracture propagation is therefore a key process controlling fracture length, fracture density, reservoir connectivity, and hydrocarbon productivity.

As fractures grow, they may connect with neighbouring fractures, faults, stylolites, dissolution features, or bedding surfaces, progressively forming larger fracture networks. Such connectivity is particularly important in carbonate reservoirs because it may significantly increase permeability and facilitate fluid flow over large distances.

The ultimate size, geometry, and connectivity of a fracture system depend not only on fracture initiation but also on the ability of fractures to continue propagating through the rock mass. Consequently, fracture propagation constitutes a critical step in the evolution from isolated fractures to interconnected fracture corridors capable of influencing reservoir performance.

5.1.6.5) Fracture Termination

Not all fractures continue to propagate indefinitely. Fracture growth commonly ceases when a fracture encounters a mechanical or geological barrier. This process is known as fracture termination.

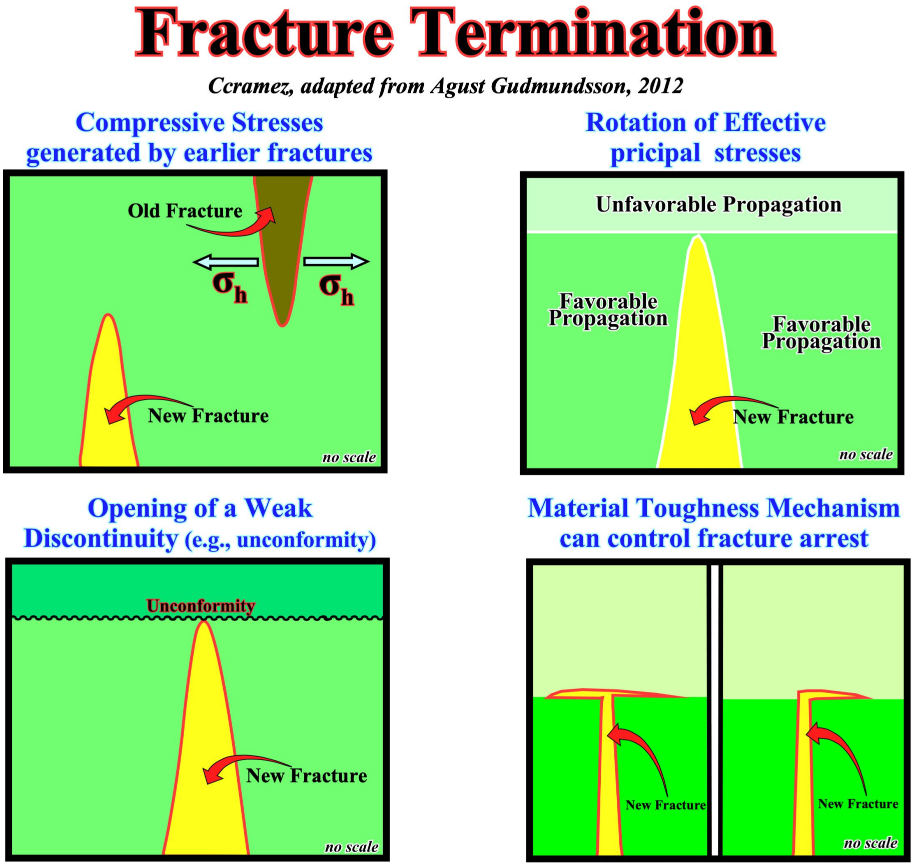


Figure 11- Common Mechanisms of Fracture Termination. A propagating fracture does not necessarily continue growing indefinitely. Fracture growth may cease when the fracture encounters mechanical, stratigraphic, or stress-related barriers that inhibit further propagation.

The examples illustrated include: (i) compressive stresses generated by earlier fractures that create local stress barriers; (ii) local rotations of the effective principal stresses that change a favourable propagation direction into an unfavourable one; (iii) opening or activation of a weak discontinuity, such as an unconformity or bed-

ding surface, which absorbs the propagating fracture; and (iv) contrasts in material toughness between adjacent rock layers that arrest or deflect fracture growth.

These termination mechanisms exert a fundamental control on fracture length, spacing, and connectivity. Consequently, they strongly influence the development of fracture networks and fracture corridors, as well as their ability to transmit fluids within naturally fractured carbonate reservoirs.

Common fracture-termination mechanisms include:

a) Compressive stress barriers generated by earlier fractures, faults, or local stress concentrations.

b) Mechanical or lithological barriers associated with changes in rock strength, brittleness or mechanical stratigraphy.

c) Weak discontinuities, such as bedding surfaces, unconformities, stylolites, or other stratigraphic interfaces that absorb or redistribute stresses.

d) Local rotations of the effective principal stresses, which may change a favourable propagation direction into an unfavourable one.

e) Material-toughness contrasts between adjacent rock layers, which may arrest or deflect fracture growth.

Fracture termination exerts a major control on fracture length, spacing, connectivity, and ultimately on the hydraulic behaviour of fracture systems.

Therefore, fracture termination plays an important role in determining whether a fracture system evolves into an interconnected network capable of transmitting fluids efficiently.

In carbonate reservoirs, fracture termination commonly occurs at stylolites, marl inter-beds, shale-rich intervals, tight cemented layers, or mechanically weak bedding surfaces that act as barriers to fracture growth.

Such barriers may compartmentalise the reservoir and significantly influence fluid flow, pressure communication, and hydrocarbon recovery

5.1.6.6) Why Some Fractures Become Reservoir Fractures

Although natural fractures are widespread in carbonate rocks, only a small proportion become economically significant reservoir fractures.

To contribute effectively to reservoir performance, fractures must satisfy several conditions:

(i) they must remain open or be capable of reopening during subsequent deformation events.

(ii) they must possess sufficient aperture to transmit fluids, and

(iii) they must form interconnected networks capable of linking different portions of the reservoir.

Many fractures fail to meet these conditions because they become cemented, sealed by mineral precipitation, terminated by mechanical barriers, or remain isolated from neighbouring fractures. Such fractures may have little or no influence on reservoir permeability or fluid flow.

Conversely, fractures that remain open and interconnected may progressively evolve into fracture corridors capable of transmitting large volumes of hydrocarbons. These fracture corridors commonly exert a disproportionate influence on reservoir connectivity, well productivity, pressure communication, and hydrocarbon recovery.

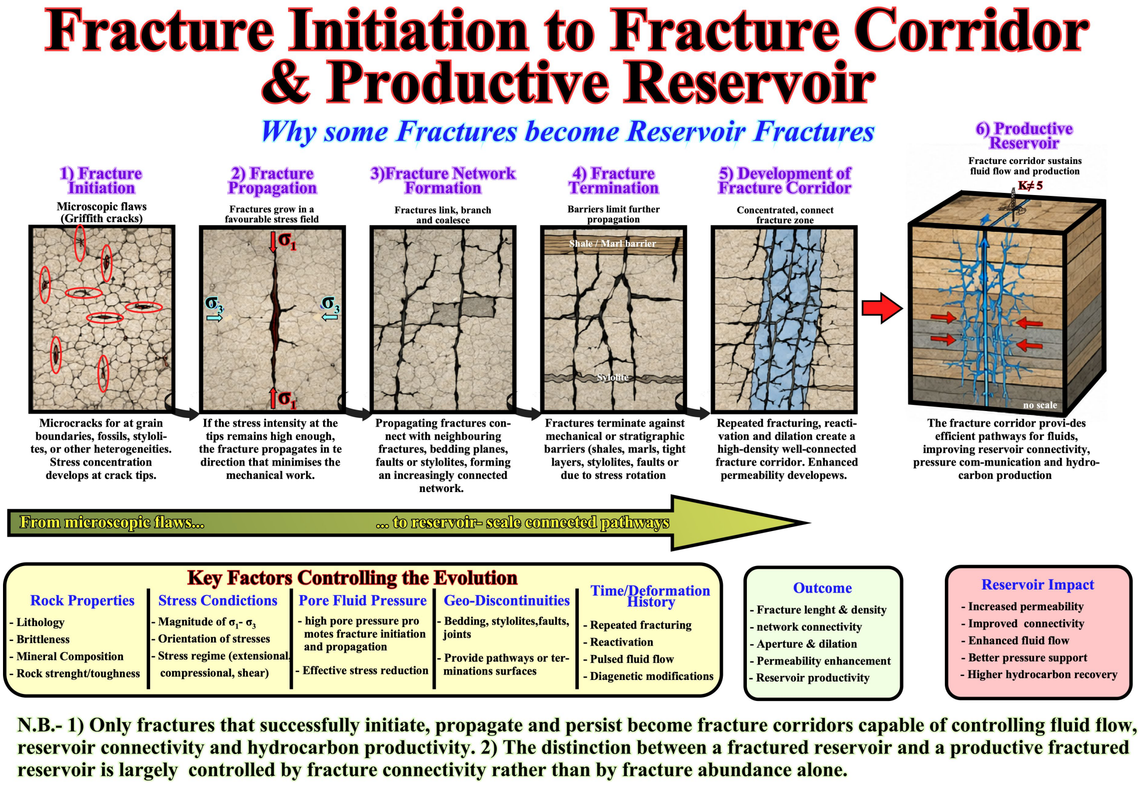


Figure 12-Evolution from Fracture Initiation to Fracture Corridor and Productive Reservoir. The figure illustrates the progressive evolution of a fracture system from microscopic flaws to reservoir-scale conductive pathways. Fracture development begins with the initiation of micro-cracks at pre-existing weaknesses such as grain boundaries, fossils, stylolites, dissolution features, or other heterogeneities. If the stress intensity at the crack tips remains sufficiently high, fractures propagate and progressively connect with neighbouring fractures, faults, bedding surfaces, and other geological discontinuities.

As fracture propagation continues, interconnected fracture networks may develop. However, many fractures terminate against mechanical, lithological, or stratigraphic barriers and therefore never become hydraulically significant. Only those fractures that remain open, continue to propagate, and establish effective connectivity can evolve into fracture corridors.

Repeated fracturing, fracture reactivation, dissolution, and local dilation may further enhance the connectivity and permeability of these corridors. At the reservoir scale, fracture corridors commonly provide the most efficient pathways for fluid flow and may therefore exert a major control on pressure communication, hydrocarbon migration, well productivity, and hydrocarbon recovery.

The figure also highlights the principal geological factors controlling this evolution, including rock properties, stress conditions, pore-fluid pressure, geological discontinuities, and deformation history. Consequently, only a small proportion of all fractures ultimately become productive reservoir fractures capable of significantly influencing reservoir performance.

Consequently, the key issue in naturally fractured carbonate reservoirs is not simply the presence of fractures, but whether those fractures form connected and conductive networks at the reservoir scale. Understanding why certain fractures evolve into productive reservoir fractures therefore represents one of the central objectives of fractured-reservoir studies.

From a petroleum-geology perspective, fracture corridors represent the most effective expression of fracture connectivity because they concentrate deformation, permeability, and fluid flow into relatively narrow zones that may dominate reservoir performance.

5.2) Classification of Fractures

Because fractures are geological features, they can be described in terms of their geometry, morphology, orientation, distribution, kinematics, and origin. Consequently, several classification schemes have been proposed to organise their description and facilitate their interpretation.

As a result, a wide variety of fracture classifications can be found in the geological literature, each reflecting the particular objectives of the author or the specific aspect of fracturing being investigated. Despite this diversity, a broad scientific consensus exists regarding two fundamental approaches to fracture classification:

(i) Generic Classification, based primarily on the geometry and displacement characteristics of fractures; and

(ii) Genetic Classification, based on the geological processes and mechanisms responsible for their formation.

These two approaches are complementary rather than mutually exclusive. The generic classification describes what the fracture is, whereas the genetic classification attempts to explain how and why the fracture formed. Together, they provide a useful framework for understanding fracture development and evaluating the potential impact of fractures on reservoir behaviour.

In naturally fractured carbonate reservoirs, both classifications are important. The generic classification provides information about fracture geometry, connectivity, and fluid-flow characteristics, whereas the genetic classification helps reconstruct the stress history and deformation processes responsible for fracture development.

5.2.1) Generic Classification

The generic classification of fractures is based primarily on the relative displacement of the fracture walls across the fracture plane. According to this classification, fractures can be subdivided into two fundamental categories: extension fractures and shear fractures.

a) Extension fractures are characterised by a displacement perpendicular to the fracture plane, such that the fracture walls move away from one another. They are commonly generated by tensile failure and include features such as joints, veins, hydro-fractures, dykes, and sills.

Because extension fractures may remain open, they often constitute highly effective pathways for fluid migration and hydrocarbon production. Consequently, they are often among the most permeable fracture types encountered in naturally fractured reservoirs.

b) Shear fractures are characterised by a displacement parallel to the fracture plane, such that the fracture walls slide past one another. They are generated by shear failure and commonly evolve into faults.

The principal types of shear fractures include normal faults, reverse faults, thrust faults, and strike-slip faults.

Although shear fractures may initially exhibit limited permeability, repeated movement, dilation, dissolution, or reactivation may significantly en-hance their hydraulic conductivity.

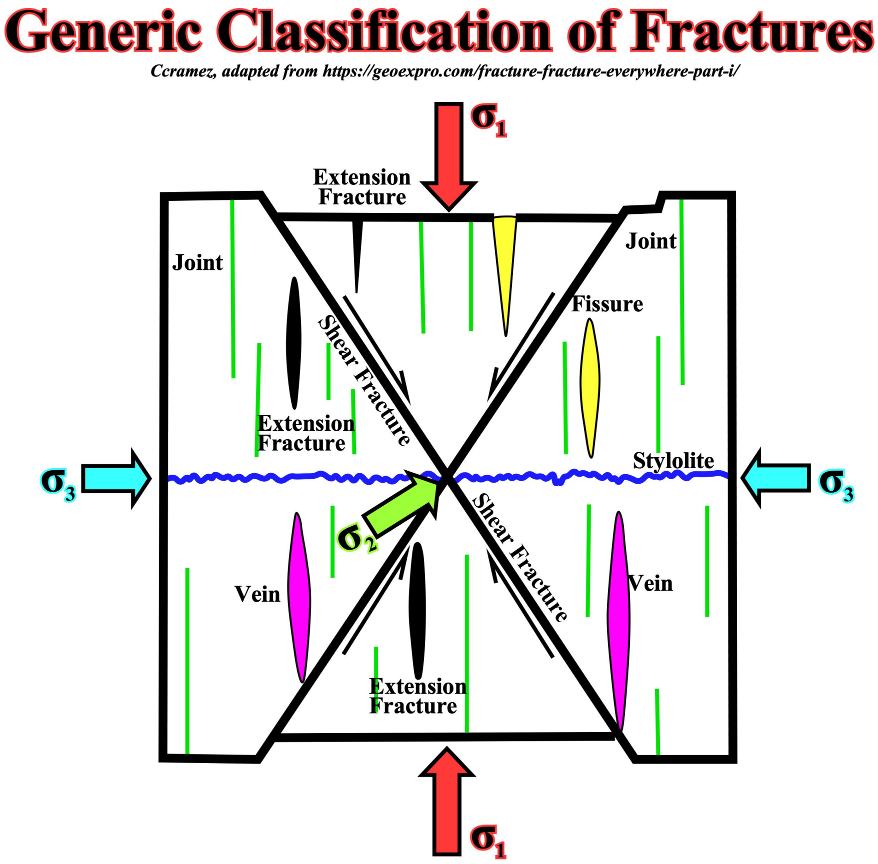


Figure 13- Generic Classification of Fractures Based on Relative Displacement Across the Fracture Plane. The generic classification subdivides fractures into two principal categories according to the relative displacement of the fracture walls. Extension fractures are generated by tensile failure and are characterised by wall separation perpendicular to the fracture plane. Typical examples include joints, fissures, veins, hydro-fractures, dykes, and sills.

Shear fractures are generated by shear failure and are characterised by displacement parallel to the fracture plane. They commonly evolve into faults and fault-related fracture systems.

The figure also illustrates the relationship between fracture geometry and the effective principal stresses (σ_1, σ_2, σ_3). Extension fractures typically develop perpendicular to the minimum effective principal stress (σ_3), whereas shear fractures develop along preferential shear planes determined by the stress field.

Stylolites are also shown for comparison. Although stylolites are not fractures in the strict sense, they are important pressure-solution discontinuities commonly encountered in carbonate reservoirs and may influence fracture propagation, reservoir compartmentalisation, and fluid flow.

From a petroleum-geology perspective, the distinction between extension and shear fractures is fundamental because these fracture types commonly display different permeabilities, connectivities, and reservoir implications.

The distinction between extension fractures and shear fractures is particularly important in petroleum geology because the two fracture types commonly exhibit different geometries, permeabilities, and degrees of connectivity. In naturally fractured carbonate reservoirs, extension fractures frequently provide highly conductive flow pathways, whereas shear fractures commonly control the development of fracture corridors and fault-related permeability systems.

5.2.2) Genetic Classification

The genetic classification of fractures is based on the geological processes responsible for their formation. Rather than describing the geometry of a fracture, it seeks to explain the origin of the stresses or deformation mechanisms that generated it.

According to Nelson (2001), the principal genetic categories of fractures include:

5.2.2.1) Tectonic Fractures

Tectonic fractures are associated with regional or local tectonic deformation and commonly occur in systematic networks related to folds, faults, and regional stress fields. Because they often form interconnected fracture systems, tectonic fractures are of particular importance in the petroleum industry, where they may provide significant permeability within low-porosity carbonate reservoirs.

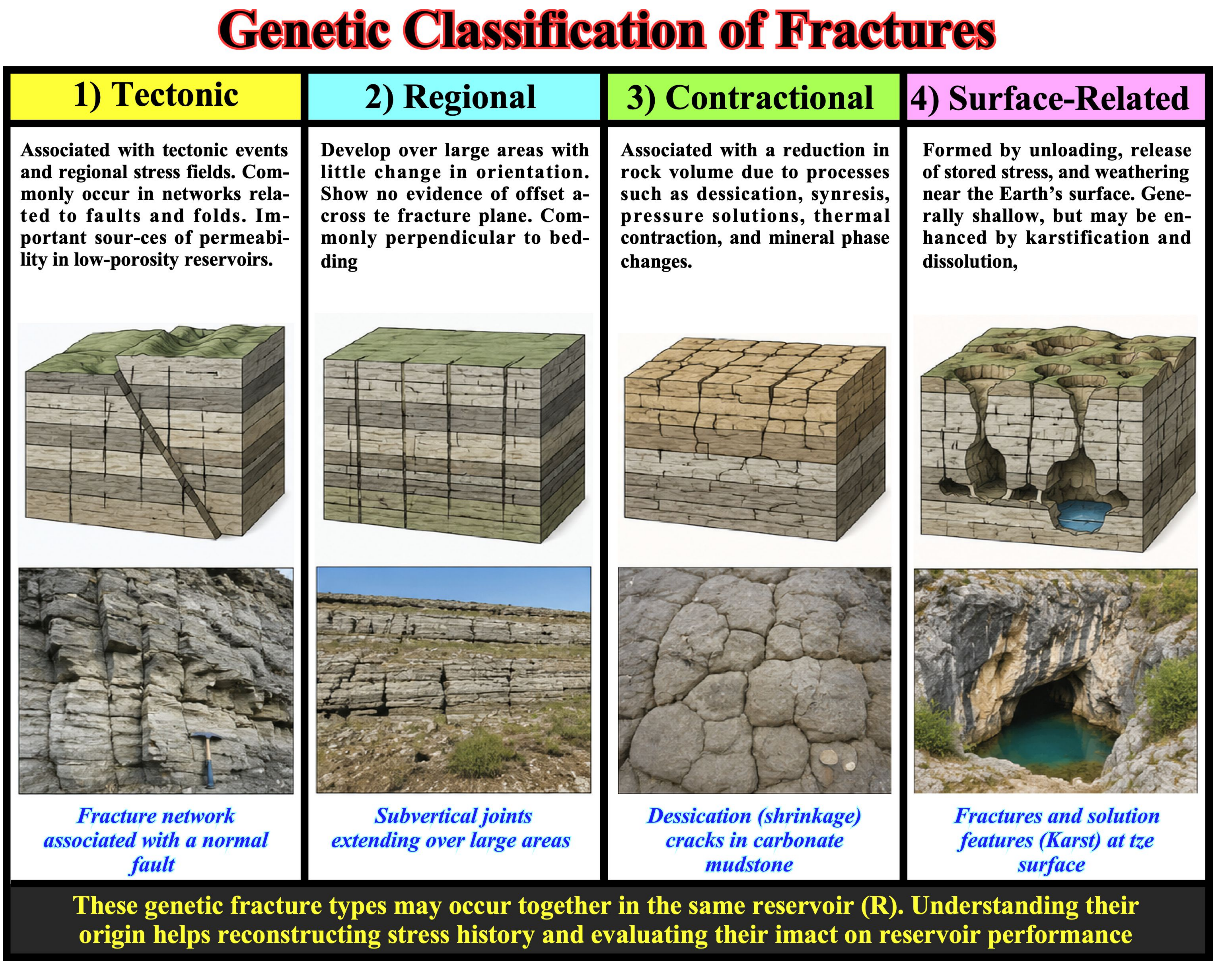


Figure 14- Genetic Classification of Fractures Based on Their Origin. The genetic classification of fractures is based on the geological processes responsible for their formation rather than on their geometry or displacement characteristics. According to this classification, four major fracture categories can be distinguished.

Tectonic fractures are generated by regional or local tectonic deformation and commonly occur in systematic networks associated with folds, faults, and regional stress fields. They are particularly important in naturally fractured reservoirs because they may form highly connected fracture systems capable of enhancing permeability and hydrocarbon production.

Regional fractures develop over large areas of the Earth's crust and commonly maintain relatively constant orientations over considerable distances. They generally exhibit little or no observable displacement and are frequently oriented approximately perpendicular to bedding surfaces.

Contractional fractures are associated with a reduction in rock volume resulting from processes such as desiccation, syneresis, pressure solution, thermal contraction,

mineral phase transformations, and diagenetic compaction. Depending on their degree of connectivity, they may locally influence reservoir permeability.

Surface-related fractures develop as a result of unloading, stress release, weathering, dissolution, and near-surface deformation. Although generally of limited significance in deep hydrocarbon reservoirs, they may become important where karstification and dissolution generate secondary porosity and permeability.

These genetic fracture types are not mutually exclusive and may occur together within the same reservoir. Understanding their origin helps reconstruct the geological and tectonic history of a reservoir and provides valuable information for evaluating fracture connectivity, reservoir behaviour, and hydrocarbon productivity.

5.2.2.2) Regional Fractures

Regional fractures develop over large areas of the Earth's crust and commonly maintain relatively uniform orientations over considerable distances. They generally show little or no observable displacement across the fracture plane and are often approximately perpendicular to bedding surfaces. Their origin is commonly attributed to large-scale crustal movements and regional stress fields.

5.2.2.3) Contractional Fractures

Contractional fractures are associated with a reduction in rock volume resulting from processes such as desiccation, syneresis (spontaneous contraction of unconsolidated, water-saturated fine-grained sediment, resulting in the expulsion of pore water and the formation of shrinkage cracks under permanently submerged conditions), pressure solution, thermal contraction, mineral phase transformations, and diagenetic compaction. Under favourable geological conditions, such fractures may locally enhance reservoir permeability and fluid flow.

5.2.2.4) Surface-Related Fractures

Surface-related fractures develop as a result of unloading, stress release, weathering, or near-surface deformation. Although they generally have limited importance in deep hydrocarbon reservoirs, they may become significant where karstification, dissolution, or near-surface fluid circulation has enhanced secondary porosity and permeability.

The genetic classification is particularly useful because it provides information about the geological history of a reservoir and the deformation processes responsible for fracture development. Combined with the generic classification, it provides a more complete understanding of fracture geometry, origin, connectivity, and potential reservoir significance.

The generic classification describes what a fracture is, whereas the genetic classification explains how and why it formed. Both classifications are complementary and are commonly used together in fractured-reservoir studies.

5.3) Fractures Associated With Faults

Faults rarely occur as isolated structures. Their formation and evolution are commonly accompanied by the development of associated fracture systems that may extend considerable distances away from the principal fault plane.

As displacement accumulates along a fault, deformation is progressively distributed within the surrounding rock mass, generating a variety of secondary structures including extension fractures, shear fractures, fracture swarms, splays, relay ramps,

linkage zones, conjugate fractures, and fault-damage zones. The geometry and distribution of these structures depend on the type of faulting, the mechanical properties of the rocks, the magnitude of displacement, and the prevailing stress field.

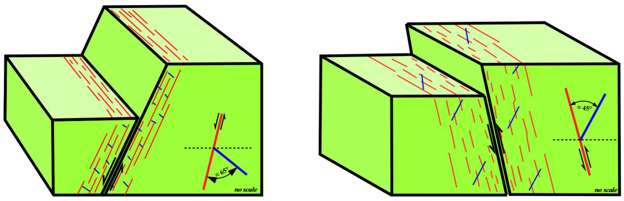
The zone surrounding a fault, commonly referred to as the fault-damage zone, is often characterised by fracture densities significantly higher than those observed in the surrounding undeformed rock. Consequently, fault-damage zones may constitute important pathways for fluid migration and hydrocarbon production.

As neighbouring fractures and faults interact, they may progressively become connected through relay zones, splays, and linkage structures, eventually forming larger fracture networks and fracture corridors. These corridors commonly represent zones of enhanced permeability and reservoir connectivity.

Shear Fractures Associated with Faulting

Fractures Associated with Individual Faults

Ccramez, adapted from https://people.wou.edu/~taylors/es406_structure/TM_chap3_fractures.pdf



Schematic Fault and Fracture Network Types

Ccramez, adapted from D.C.P. Peacock et al.,, 2016

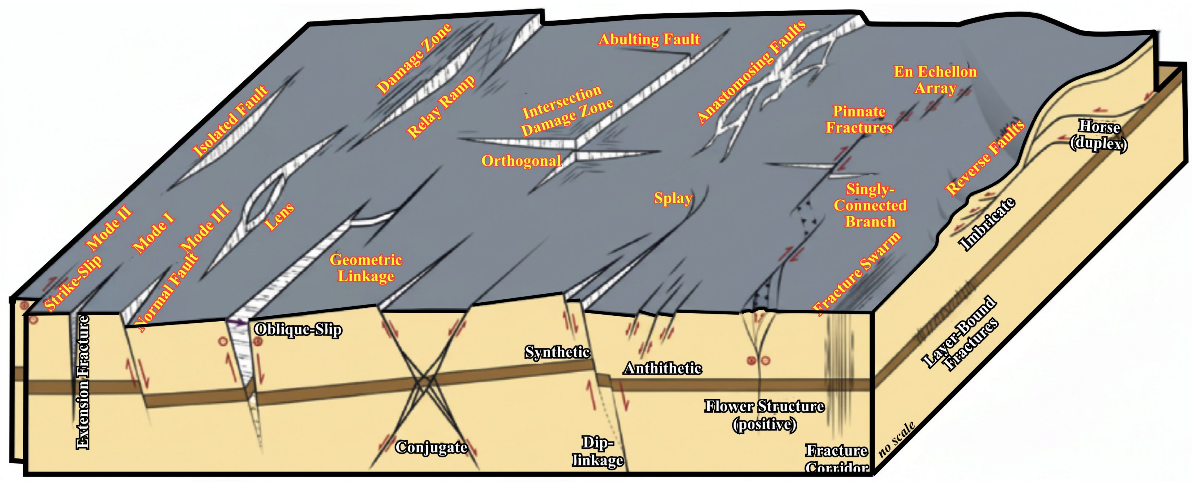


Figure 15- Fractures Associated with Faults and Development of Fault-Related Fracture Networks. Faulting is commonly accompanied by the development of numerous secondary fractures and deformation structures that together form complex fault-related fracture networks.The principal fault-related structures illustrated in this figure include: 1) Damage Zone — a highly fractured volume surrounding a fault plane, generally characterised by fracture densities significantly higher than those of the surrounding rock. 2) Relay Ramp — a transfer zone between two overlapping fault segments that commonly concentrates deformation and fracturing. 3) Splay Fault — a secondary fault that branches away from a major fault. 4) Synthetic Fault — a subsidiary fault that dips in the same direction as the main fault. 5) Antithetic Fault — a subsidiary fault that dips in the opposite direction to the main fault. 6) Conjugate Faults or Fractures — paired structures formed under the same stress field, typically intersecting at characteristic angles. 7) Dip Linkage — the connection of fault segments along their dip direction. 8) Geometric Linkage — the connection of initially isolated fault segments to form larger fault systems. 9) Abutting Fault — a fault that terminates against another fault. 10) Anastomosing Faults — inter-

connected fault networks that split and rejoin, forming braided fault patterns. 11) En Echelon Array — a set of overlapping fractures or faults arranged in a step-like pattern. 12) Pinnate Fractures — small subsidiary fractures that branch from a larger fault or fracture at a low angle. 13) Fracture Swarm — a dense concentration of subparallel fractures developed within a limited zone. 14) Flower Structure — a characteristic structure associated with strike-slip faulting, formed by diverging fault splays. 15) Horse (Duplex) — a fault-bounded block located between overlapping thrust or strike-slip faults. 16) Layer-Bound Fractures — fractures restricted to a particular mechanical or stratigraphic layer. 17) Lens — an isolated fault-bounded rock body developed between overlapping fault segments. As fault displacement increases, many of these structures interact and become connected, generating progressively larger fracture networks. In naturally fractured carbonate reservoirs, such networks may evolve into fracture corridors, which commonly represent zones of enhanced permeability, fluid flow, reservoir connectivity, and hydrocarbon productivity. Consequently, the petroleum significance of a fault is often determined not only by the fault plane itself, but also by the associated damage zone and surrounding fracture network.

In naturally fractured carbonate reservoirs, fault-related fracture systems are therefore of particular importance because they may exert a major control on fluid flow, pressure communication, compartmentalisation, well productivity, and hydrocarbon recovery.

From a petroleum-geology perspective, the critical issue is not simply the presence of faults, but whether the associated fracture systems act as conduits, barriers, or mixed-flow systems within the reservoir.

5.4) Fractures Associated With Folds

Folding is commonly accompanied by the development of systematic fracture networks generated by the stresses and strains associated with layer bending and shortening.

As deformation progresses, different fracture sets may develop in different parts of the fold, depending on local curvature, layer orientation, mechanical stratigraphy, and the magnitude of the effective principal stresses.

Because folded strata are continuously rotated during deformation, fracture orientations are commonly described using a local orthogonal coordinate system a, b, c, in which:

- ➡ **b-axis is parallel to the fold axis,**
- ➡ **a-axis lies within the bedding plane and is perpendicular to the fold axis, and**
- ➡ **c-axis is perpendicular to the bedding plane.**

Fractures associated with folds may therefore be classified according to their orientation relative to the a, b, and c axes. In many folded carbonate sequences, fractures tend to occur in systematic sets that can be recognised and correlated throughout the fold structure.

The distribution of these fracture sets is not random. Certain fracture orientations are preferentially developed:

a) on fold limbs (fracture sets 1 and 5 in Figure 16),

b) whereas others are concentrated near fold hinges where curvature and strain are greatest (fracture sets 2 and 4, in Figure 16, tend to occur preferentially on convex portions of folds where curvature and extensional strain are greatest).

Consequently, fold-related fracture systems commonly display predictable spatial relationships with fold geometry.

Fractures Associated with Folds

Ccramez, adapted from https://people.wou.edu/~taylors/es406_structure/TM_chap3_fractures.pdf

Stereographic Projection shows thr orientations of the coordinate system, the bedding where is not horizontal (dotted great circles) and the fractures (solide great cercles).

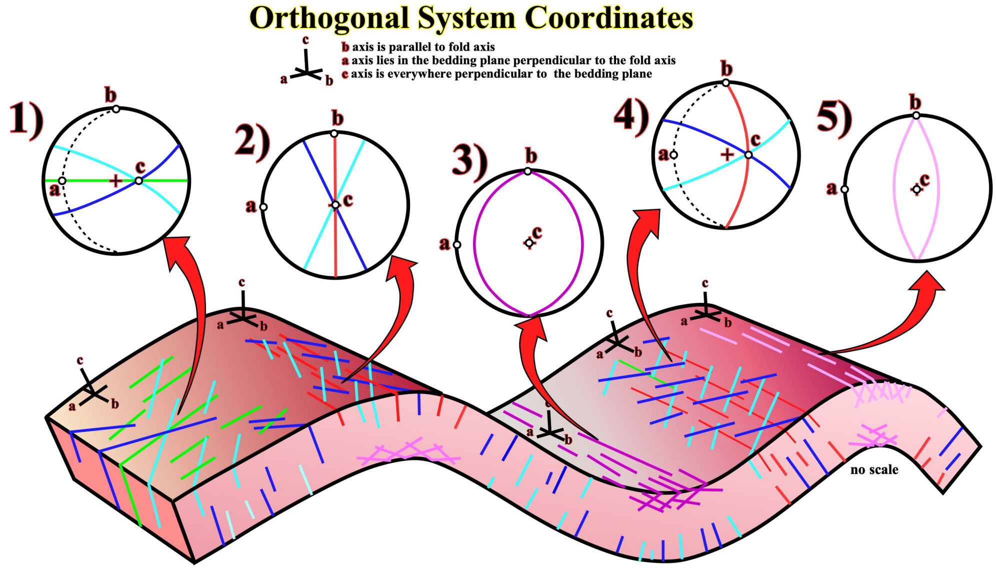


Figure 16- Principal Fracture Sets Associated with Folded Strata. The figure illustrates several common fracture sets associated with folding using a local orthogonal coordinate system in which the b-axis is parallel to the fold axis, the a-axis lies within the bedding plane and is perpendicular to the fold axis, and the c-axis is perpendicular to the bedding plane. The stereographic projections illustrate the orientations of bedding (dashed great circles) and fracture sets (solid great circles).

Fractures parallel to the ac plane and bc plane are referred to respectively as ac fractures and bc fractures. These fractures are commonly interpreted as extension fractures generated during folding.

The fracture sets illustrated as 1, 2, and 4 are all approximately perpendicular to bedding. In sets 1 and 2, the ac and bc fractures respectively bisect the acute angle between two associated oblique fracture sets. In set 4, the bc fractures bisect the obtuse angle between the associated oblique fractures.

The inclined fractures illustrated in sets 3 and 5 are parallel to the fold axis (b-axis). Those of set 3 form a low angle with bedding and are commonly developed on strongly curved concave fold surfaces. Those of set 5 form a high angle with bedding and are particularly common on fold limbs.

Fracture sets 1 and 5 are commonly observed on fold limbs, whereas sets 2 and 4 tend to occur preferentially on convex portions of folds where curvature and extensional strain are greatest. Set 3 is most frequently associated with strongly curved concave fold surfaces.

It is generally interpreted that all of these fracture sets may develop during folding. The ac and bc fractures are commonly interpreted as extension fractures, whereas the oblique and inclined fractures are commonly interpreted as shear fractures generated by layer-parallel shortening and fold-related deformation.

The systematic distribution of these fracture sets demonstrates that fold geometry exerts a major control on fracture orientation, density, and connectivity. Consequently, fold-related fracture systems may provide valuable information for predicting fracture corridors and reservoir connectivity in naturally fractured carbonate reservoirs.

In naturally fractured carbonate reservoirs, fold-related fractures are particularly important because they may form interconnected fracture networks and fracture corridors capable of significantly enhancing reservoir permeability and connectivity. The prediction of fracture orientation and density from fold geometry therefore constitutes a fundamental aspect of fractured-reservoir analysis

Although folding may generate a wide variety of fracture orientations, most fold-related fracture systems can be grouped into a limited number of principal fracture sets that display systematic relationships with the effective principal stresses and the geometry of the fold.

Under a compressional tectonic regime, the maximum effective principal stress (σ_1) is generally oriented perpendicular to the fold axis, whereas the intermediate effective principal stress (σ_2) is commonly parallel to the fold axis. The minimum effective principal stress (σ_3) tends to be oriented approximately normal to the folded bedding surfaces, particularly near fold hinges.

This stress configuration commonly generates three principal fracture families:

1) **Longitudinal fractures, approximately parallel to the fold axis.**
2) **Transverse fractures, approximately perpendicular to the fold axis.**
3) **Conjugate shear fractures, generally occurring as paired fracture sets that intersect at characteristic angles and accommodate local shear deformation.**

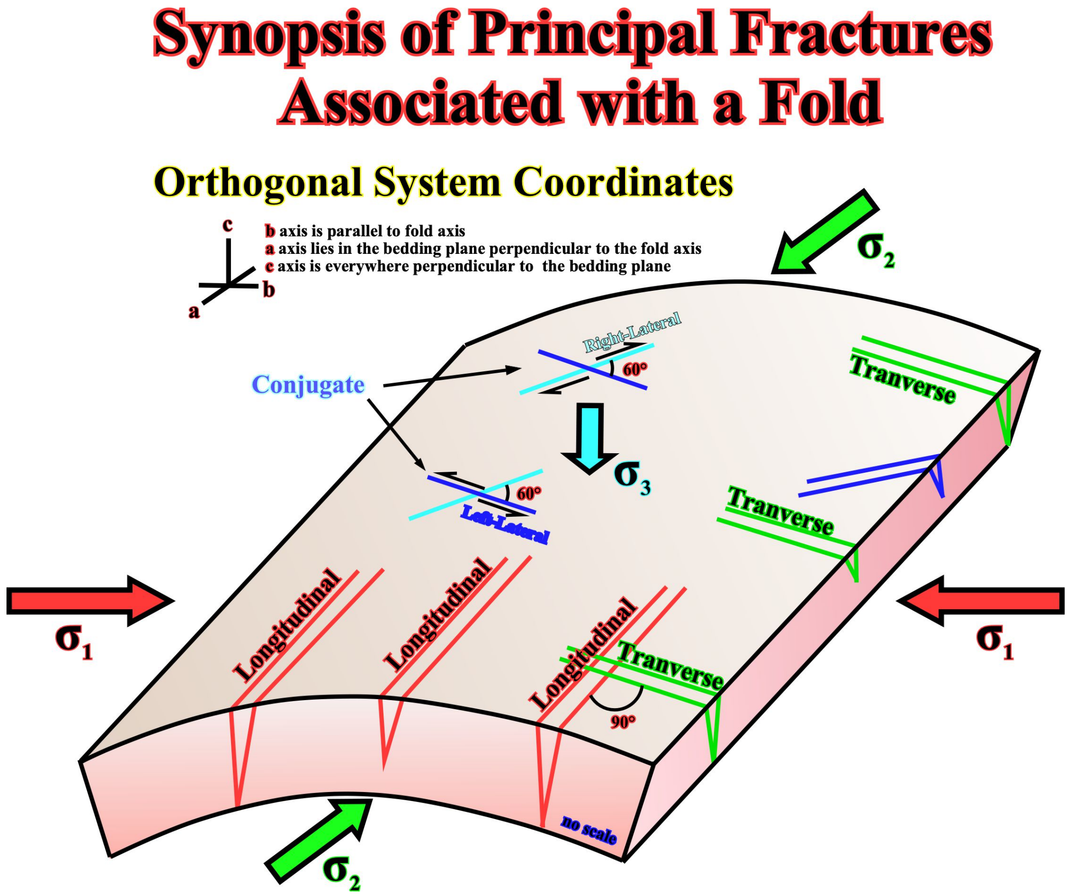


Figure 17- Synopsis of the Principal Fracture Sets Associated with Folding. The figure summarises the principal fracture orientations commonly associated with folded strata using a local orthogonal coordinate system in which the b-axis is parallel to the fold axis, the a-axis lies within the bedding plane and is perpendicular to the fold axis, and the c-axis is perpendicular to the bedding plane.

Under a compressional stress regime, the maximum effective principal stress (σ_1) is oriented approximately perpendicular to the fold axis, whereas the intermediate effective principal stress (σ_2) is commonly parallel to the fold axis. The minimum effective principal stress (σ_3) is oriented approximately normal to the folded bedding surfaces. Three principal fracture families are commonly developed:

1)Longitudinal fractures, approximately parallel to the fold axis and commonly associated with extensional strains generated during folding.

2) Transverse fractures, approximately perpendicular to the fold axis and commonly developed in response to fold-related extension and curvature.

3) Conjugate shear fractures, consisting of paired right-lateral and left-lateral fracture sets that intersect at characteristic angles, commonly around 60°, and accommodate local shear deformation.

The interaction and connectivity of these fracture families commonly generate complex fracture networks within folded carbonate reservoirs. Areas where several fracture sets intersect frequently exhibit enhanced fracture density and permeability and may therefore evolve into fracture corridors capable of controlling fluid flow, reservoir connectivity, and hydrocarbon production. This simplified diagram summarises the principal geometric relationships between fold-related fractures and the effective principal stresses and provides a conceptual framework for predicting fracture distribution within folded carbonate reservoirs.

The relative abundance of these fracture sets varies according to fold geometry, curvature, mechanical stratigraphy, deformation history, and the local orientation of the effective principal stresses. Therefore, different parts of the same fold may exhibit markedly different fracture patterns.

In naturally fractured carbonate reservoirs, the interaction and connectivity of these fracture sets commonly exert a major control on fracture-corridor development, reservoir permeability, and fluid-flow pathways.

5.5) Rock-Fractures & Classification of Reservoir-Rocks

All reservoir rocks are fractured to some degree and commonly by more than one geological process. However, not all fractures exert the same influence on reservoir behaviour.

In petroleum geology, the term fractured reservoir is generally used to describe a reservoir in which natural fractures contribute significantly to fluid flow, reservoir connectivity, and ultimately hydrocarbon production. For the many geoscientists, term 'fractured reservoir' is commonly applied to a relatively tight reservoir (matrix permeability < 0.1 mD) in which fractures provide a substantial proportion of effective.

In such reservoirs, the mapping, characterisation, and modelling of fracture systems are of paramount importance because fractures may strongly influence well productivity, pressure communication, drainage efficiency, and recoverable hydrocarbon volumes. In many carbonate reservoirs, matrix permeability may be low or highly heterogeneous, making fractures essential pathways for the migration and production of water, oil, and natural gas.

Because fractures may contribute differently to reservoir porosity and permeability, Ronald Nelson (2001) proposed a widely used classification of reservoirs based on the relative contributions of the rock matrix and the fracture system.

➡ **Type I Reservoirs**

In Type I reservoirs, fractures provide both the dominant porosity and the dominant permeability. The rock matrix contributes little to fluid storage or fluid flow. Reservoir Performance is therefore controlled almost by the fracture network. Such reservoirs commonly exhibit high initial production rates but may also display rapid decline curves. Examples include the Amal Field (Libya) and some Ellenburger reservoirs (Texas).

➡ **Type II Reservoirs**

In Type II reservoirs, the matrix provides most of the storage capacity (porosity), whereas fractures provide most of the flow capacity (permeability). Hydrocarbons are stored within the matrix and produced through the frac-

ture network. Examples include the Agha Jari Field (Iran) and the Rangely Field (Colorado).

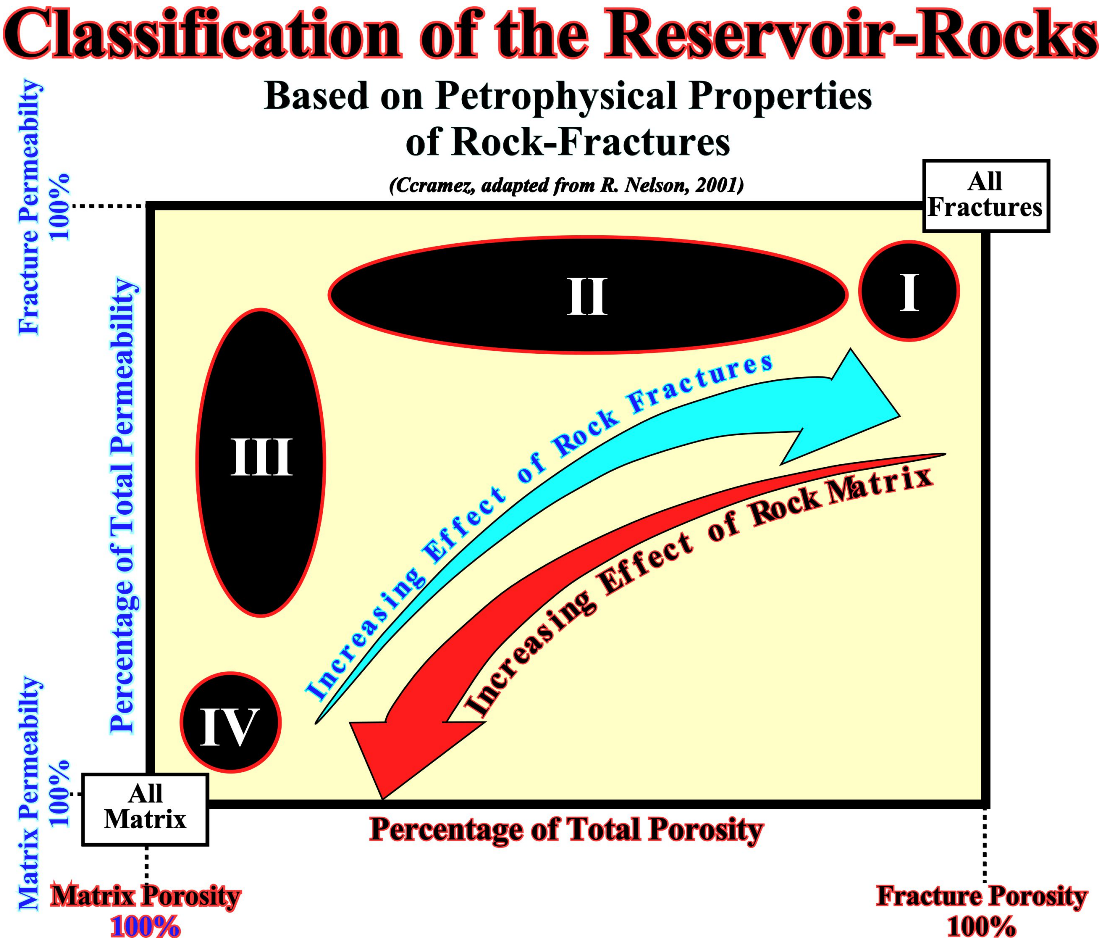


Figure 18- Classification of Reservoir Rocks Based on the Relative Contributions of Matrix and Fractures to Porosity and Permeability (after Nelson, 2001). The diagram classifies reservoirs according to the relative contributions of the rock matrix and natural fractures to total porosity and total permeability.

In Type I reservoirs, fractures provide both the dominant porosity and the dominant permeability. Reservoir performance is therefore controlled almost entirely by the fracture system.

In Type II reservoirs, the matrix provides most of the porosity (storage capacity), whereas fractures provide most of the permeability (flow capacity). Hydrocarbons are stored within the matrix and produced through the fracture network.

In Type III reservoirs, both matrix and fractures contribute significantly to permeability. Fractures enhance the performance of an already producible reservoir by improving connectivity and fluid flow.

In Type IV reservoirs, fractures behave predominantly as barriers or baffles to fluid flow, resulting in reservoir compartmentalisation and reduced connectivity. The figure demonstrates that the influence of fractures varies considerably from one reservoir to another. Consequently, the principal objective of fractured-reservoir studies is not simply to identify fractures, but to determine whether they act as conduits, barriers, or mixed-flow systems, and to quantify their contribution to reservoir porosity, permeability, connectivity, and ultimately hydrocarbon recovery.

➡ Type III Reservoirs

In Type III reservoirs, both matrix and fractures contribute to fluid flow. The reservoir would remain producible even without fractures, but the fracture network significantly enhances permeability, productivity, and reservoir connectivity. Examples include the Kirkuk Field (Iraq) and Cottonwood Creek (Wyoming).

➡ Type IV Reservoirs

In Type IV reservoirs, fractures act predominantly as barriers or baffles to fluid flow rather than conduits. Cementation, mineral precipitation, or sealing fractures may compartmentalise the reservoir and impede fluid flow. In such cases, fractures may reduce rather than enhance reservoir performance.

Subsurface fractures therefore represent both an opportunity and a challenge. Understanding their geometry, connectivity, aperture, permeability, and spatial distribution is essential for reservoir characterisation, well placement, production forecasting, and field development planning.

Consequently, fractured-reservoir studies commonly integrate information derived from regional tectonics, outcrop analogues, cores, borehole image logs, seismic interpretation, geomechanical analysis, well tests, production data, and reservoir simulation.

The Oligocene carbonate reservoirs of the Kurdamir/Topkhana (K/T) petroleum system are tentatively interpreted as belonging principally to Nelson's Type II and Type III fractured-reservoir categories. Hydrocarbons are believed to be stored largely within the carbonate matrix, whereas natural fractures and fracture corridors may provide a significant proportion of the effective permeability and reservoir connectivity.

However, localised zones associated with fault-related damage zones, fold-related fracture concentrations, or fracture corridors may exhibit behaviour approaching Type I reservoirs, where fluid flow is controlled predominantly by the fracture system. Conversely, cemented fractures, stylolites, and sealing fault zones may locally generate Type IV behaviour, resulting in reservoir compartmentalisation and reduced connectivity.

Consequently, the North Iraq petroleum systems is unlikely to behave as a single reservoir type. Rather, it is more plausibly interpreted as a heterogeneous fractured-carbonate system in which Type II, Type III, and locally Type I or Type IV behaviours may coexist within different parts of the reservoir.

K/T is unlikely to be a pure Type II or pure Type III reservoir; it is more likely a heterogeneous system where different Nelson reservoir types coexist spatially.

Part II of these *Notes on Natural Fractured Carbonate Reservoir-Rocks* examines the principal geological controls governing the distribution of natural fractures and their organisation into fracture corridors. Particular emphasis is placed on the influence of lithology, texture, porosity, pore-fluid pressure, bed thickness, structural position, and the geological factors that promote the development of connected fracture systems. This will be the subject of the next memorandum.