Applied structural geology (G410)

Lecture 1

Introduction in structural geology (part 1)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

Structural geology:

The structural geology is the science that deals with the secondary geological structures which resulting from deformation the rocks of the lithosphere by tectonic and non-tectonic forces. It is divided into: structural analysis and geotectonic.

The primary geological structures are formed during the sedimentary processes as a result of non-tectonic causes (stratification or bedding, cross bedding, mud cracks and ripple marks). While the secondary geological structures are formed after the sedimentary processes as a result of tectonic causes (folds, fractures, salt structures and igneous structures). The fractures are: joints, fissures, veins and faults) (Fig.1).

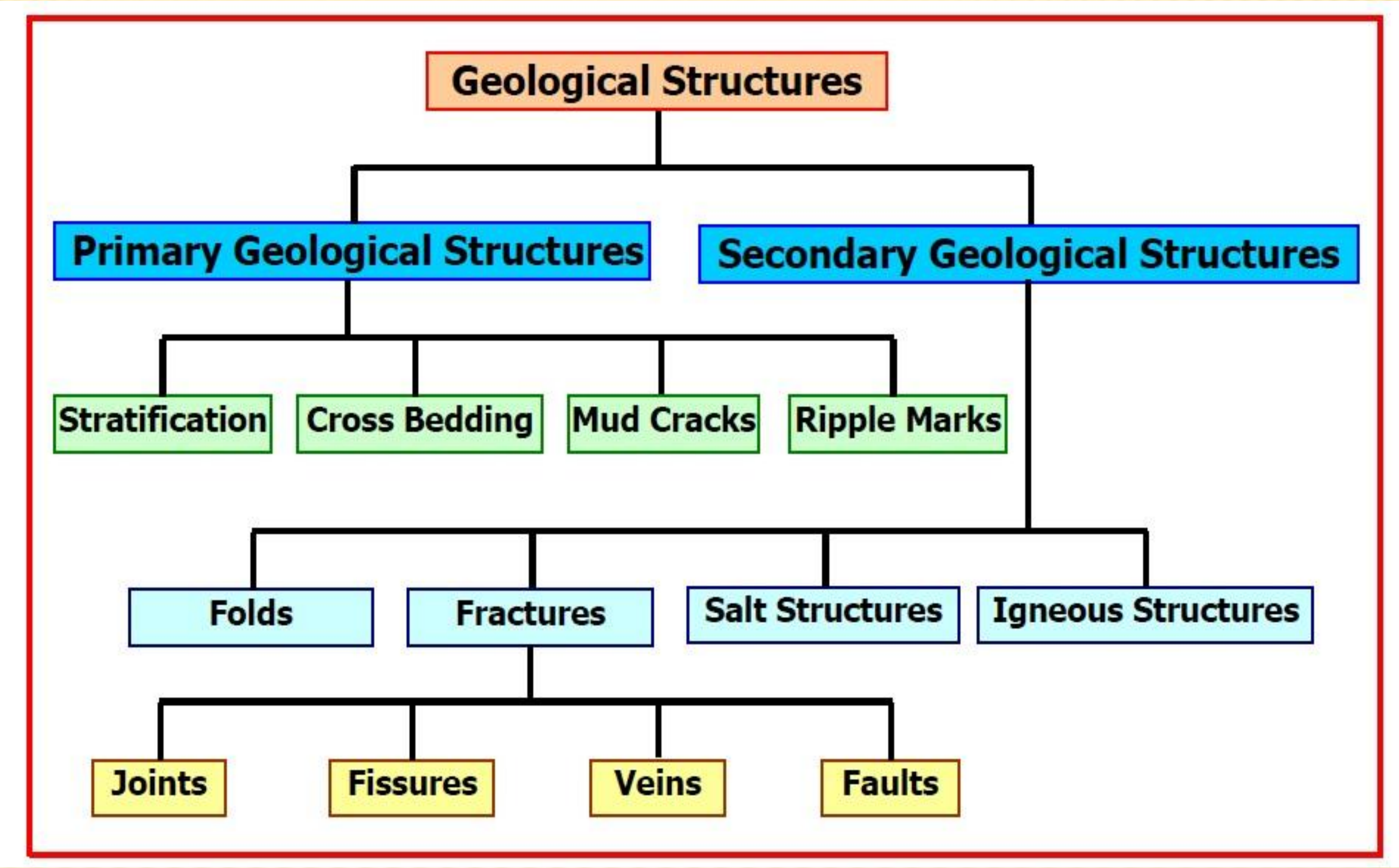

Fig.1: A flowchart showing the divisions of primary and secondary geological structures.

Structural geology data Tools:

The structural data sets can collected by:

1- Field data:

Fieldwork involves the use of simple tools such as a hammer, measuring device, topomaps, a hand lens and a compass, and the data collected are mainly structural orientations and samples for thin section studies. This type of data collection is still important, and is aided by the modern global positioning system (GPS) units and high-resolution aerial and satellite photos.

In many cases, the most important way of recording field data is by use of careful field sketches, aided by photographs, orientation measurements and other measurements that can be related to the sketch. Sketching also forces the field geologist to observe the features and details that may otherwise be overlooked. Field sketching is, largely, a matter of practice.

2- Remote sensing and geodesy:

Satellite images are now available at increasingly high resolutions and are a valuable tool for the mapping of map-scale structures. An increasing amount of such data is available on the WorldWideWeb, and may be combined with digital elevation data to create three-dimensional models.

Aerial photos may give more or other details with resolutions down to a few tens of centimeters in some cases. Both ductile structures, such as folds and foliations, and brittle faults and fractures are mappable from satellite images and aerial photos.

In the field of neotectonics, InSAR (Interferometric Synthetic Aperture Radar) is a useful remote sensing technique that uses radar satellite images. Beams of radar waves are constantly sent toward the Earth, and an image is generated based on the returned information.

GPS data in general are an important source of data that can be retrieved from GPS satellites to measure plate movements.

3- DEM, GIS and Google Earth:

Conventional paper maps are still useful for many field mapping purposes, but rugged laptops, tablets and handheld devices now allow for direct digitizing of structural features on digital maps and images and are becoming more and more important. **GIS** can combine field observations, various geologic maps, aerial photos, satellite images, gravity data, magnetic data, typically together with a digital elevation model, and perform a variety of mathematical and statistical calculations.

A digital elevation model (DEM) is a digital representation of the topography or shape of a surface, typically the surface of the Earth, but a DEM can be made for any geologic surface or interface that can be mapped in three dimensions.

The detailed data available from **Google Earth** and related sources of digital data have taken the mapping of faults, lithologic contacts, foliations and more to a new level, both in terms of efficiency and accuracy.

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Lecture 2

Introduction in structural geology (part 2)

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4- Seismic data:

In the mapping of subsurface structures, seismic data are invaluable and since the 1960s have revolutionized our understanding of fault and fold geometry. Some seismic data are collected for purely academic purposes, but the vast majority of seismic data acquisition is motivated by exploration for petroleum and gas.

Marine seismic reflection data (Fig.2) are collected by boat, where a sound source (air gun) generates sound waves that penetrate the crustal layers under the sea bottom. Microphones can also be put on the sea floor. This method is more cumbersome, but enables both seismic S- and P-waves to be recorded (S-waves do not travel through water). Seismic data can also be collected onshore, putting the sound source and microphones (geophones) on the ground.

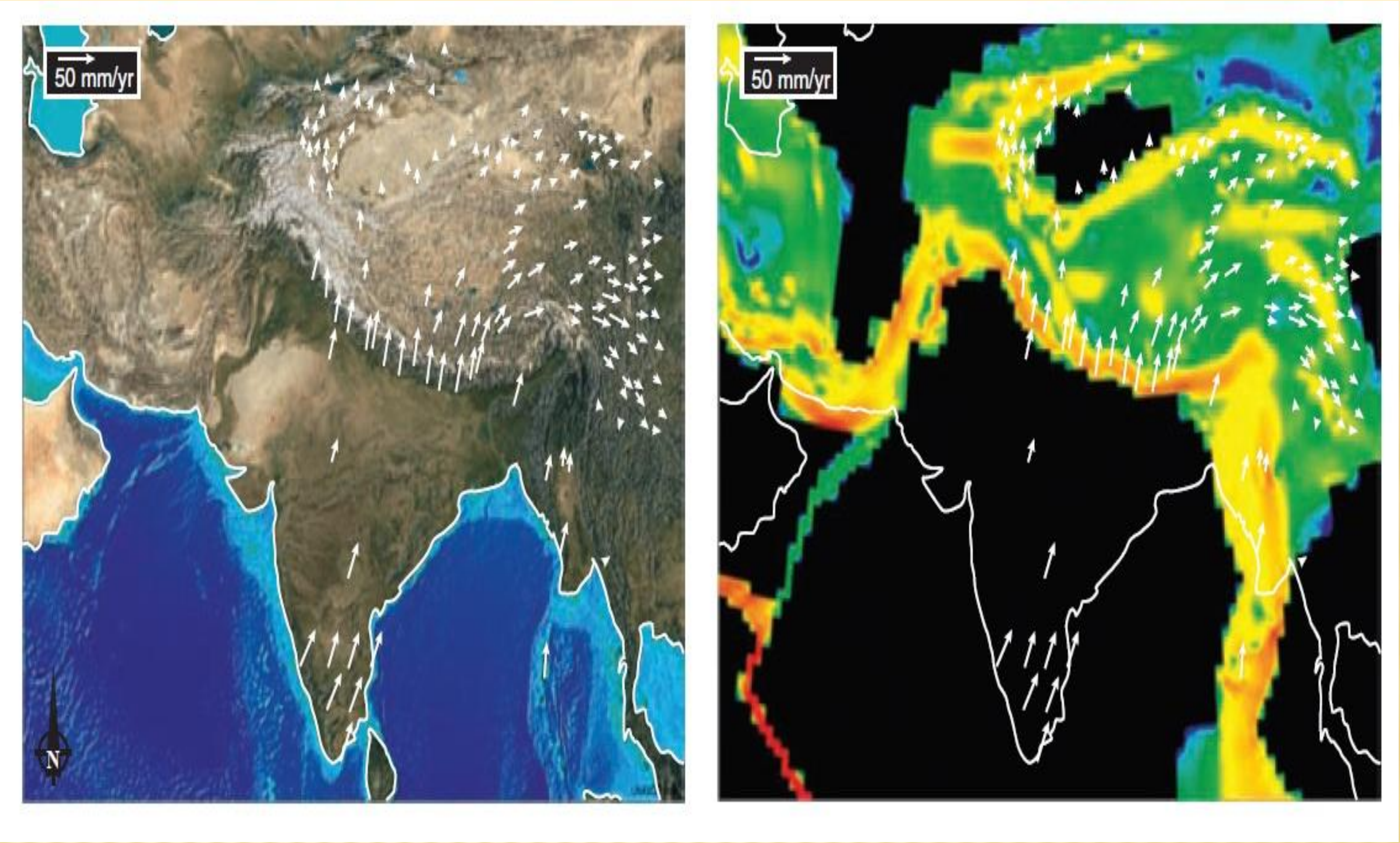

Fig.2: Use of GPS data from stationary GPS stations worldwide over time can be used to map relative plate motions and strain rates. (Left) White arrows (velocity vectors) indicating motions relative to Europe. The vectors clearly show how India is moving into Eurasia, causing deformation in the Himalaya–Tibetan Plateau region. (Right) Strain rate map based on GPS data. Calculated strain rates are generally less than 3 x 10-6 y-1 or 10-13 s-1. Warm colors indicate high strain rates. Similar use of GPS data can be applied to much smaller areas where differential movements occur, for example across fault zones. From the project The Global Strain Rate Map (http://jules.unavco.org).

The sound waves are reflected from layer boundaries where there is an increase in acoustic impedance, i.e. where there is an abrupt change in density and/or the velocity with which sound waves travel in the rock. A long line of microphones, onshore called geophones and offshore referred to as hydrophones, record the reflected sound signals and the time they appear at the surface. These data are collected in digital form and processed by computers to generate a seismic image of the underground (Fig.3).

5- Experimental data:

Physical modeling of folding and faulting have been performed since the earliest days of structural geology and since the middle part of the twentieth century such modeling has been carried out in a more systematic way. Buckle folding, shear folding, reverse, normal and strike-slip faulting, fault populations, fault reactivation, porphyroclast rotation and diapirism are only some of the processes and structures that have been modeled in the laboratory.

Experimental deformation of rocks and soils in a deformation rig under the influence of an applied pressure (stress) is used to explore how materials react to various stress fields and strain rates.

6- Numerical modeling:

Numerical modeling of geologic processes has become increasingly simple with the development of increasingly faster computers. Simple modeling can be performed using mathematical tools such as spreadsheets or Matlab™.

7- Other data sources:

There is a long list of other data sources that can be use in structural analysis. Gravimetric and magnetic data can be used to map large-scale faults and fault patterns in sedimentary basins, covered crust and subsea oceanic crust.

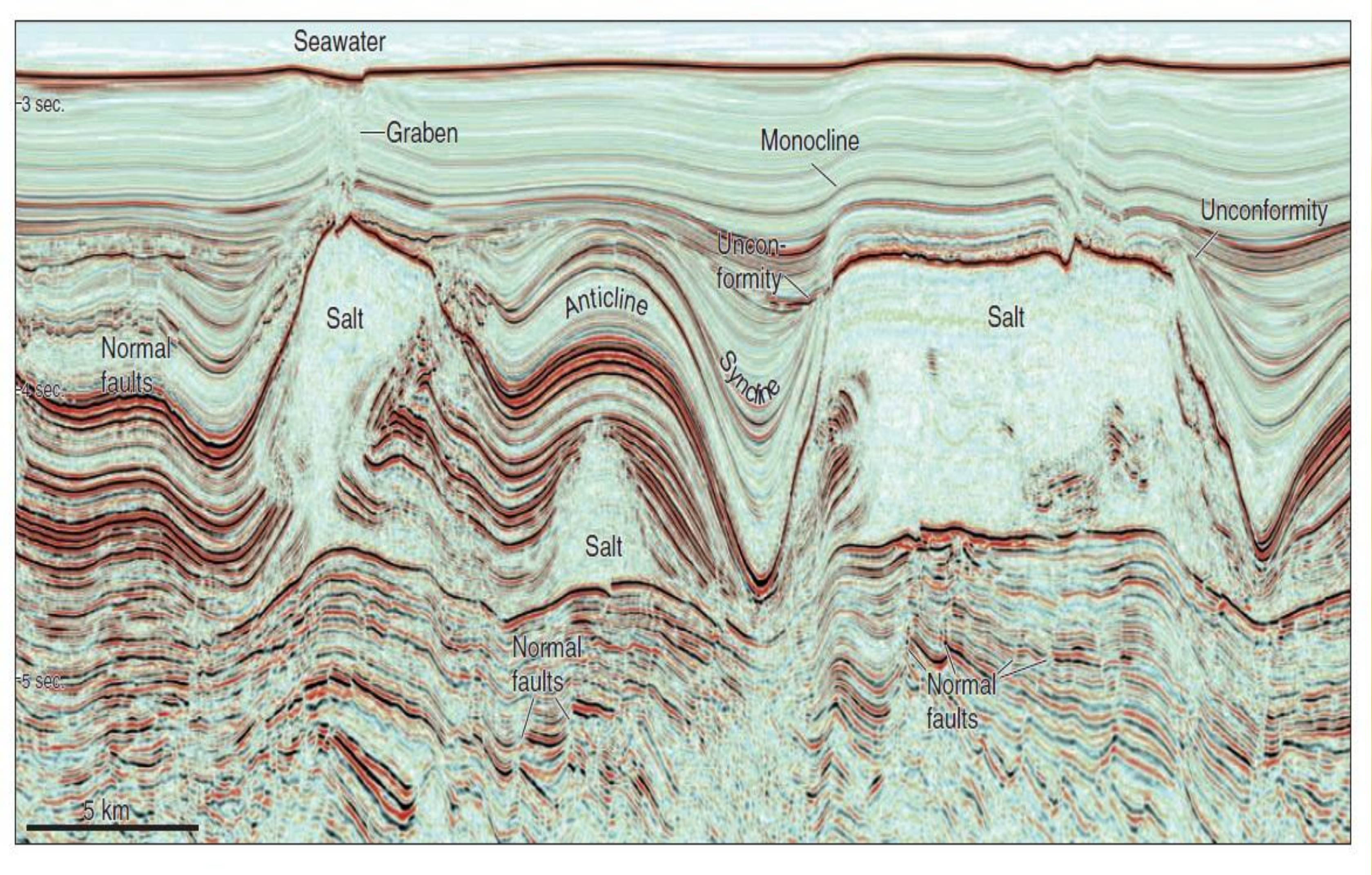

Fig.3: Seismic 2-D line from the Santos Basin offshore Brazil, illustrating how important structural aspects of the subsurface geology can be imaged by means of seismic exploration. **Note** that the vertical scale is in seconds.

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Lecture 3

Applications of structural geology (Importance in geology) (Part 1)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

A- Engineering geology:

It is very important to study of rock infrastructure, fractures, its type and direction and to do a complete structure geology test before constructing any huge structure like dams, huge buildings and tunnels. Where it is important to know:

1- Generally faults are accompanied by **earthquakes**. Earthquakes cause severe shaking of the ground. Such shaking may cause collapse of civil engineering structures (Fig.1).

2- The relation between the fault slope direction and the **tunnel** direction, width of the fault zone, type and thickness of the fill material and the hydrostatic pressures in both sides of the fault are some problems in the tunneling (Fig.2).

3- Faulted areas are **neither safe nor stable** for foundation works because of the various harmful effects produced by faults. This means that the fault ground is unstable as long as faulting remain active there.

4- Faults cause considerable **fracturing and shattering** of rocks along the fault zone. This means that are not compact or massive or strong. Such places are reduced to physically very weak grounds and hence unfit as foundation sites for withstanding heavy loads of structures like dams.

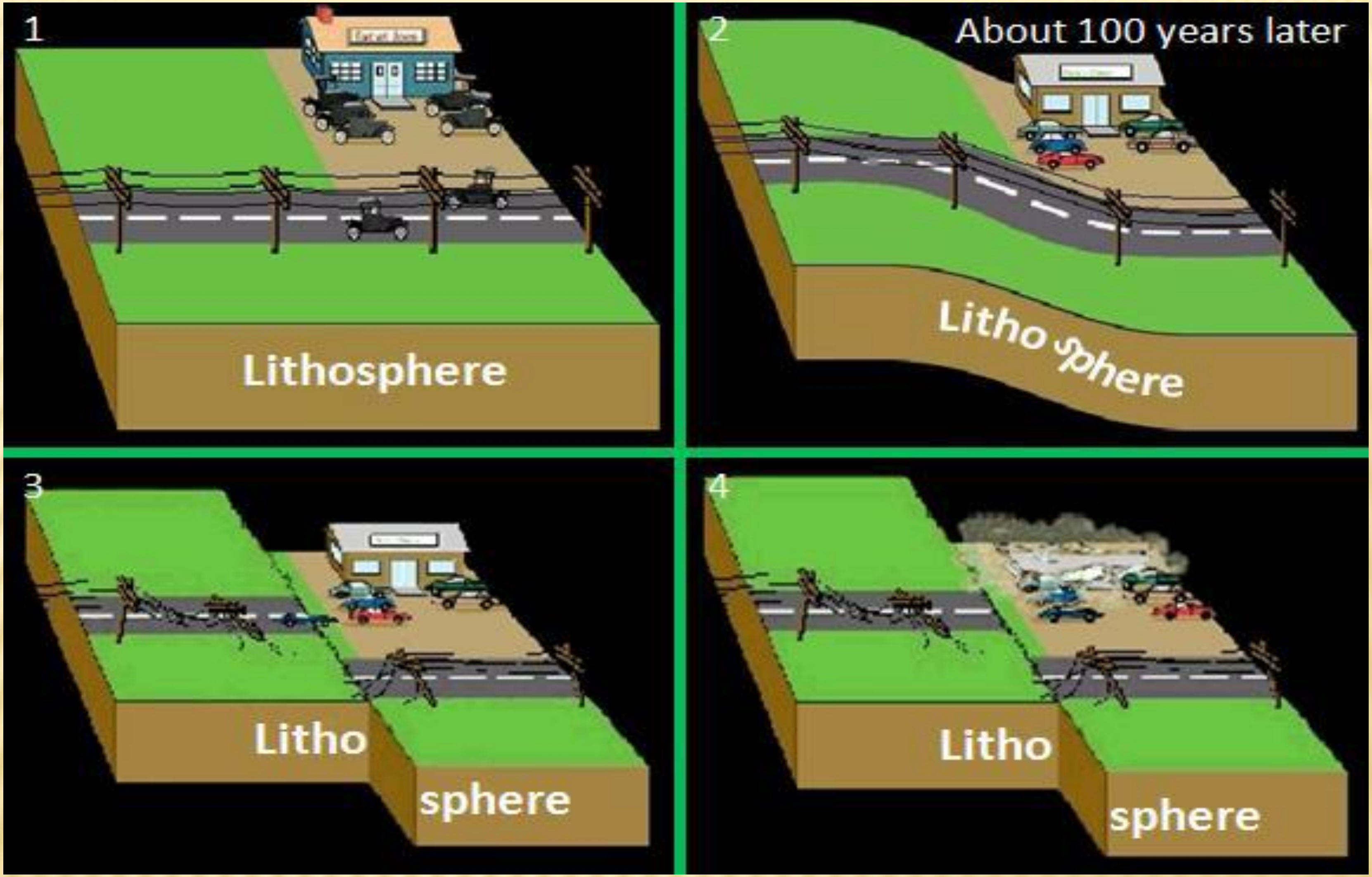

Fig.1: Earthquake activity.

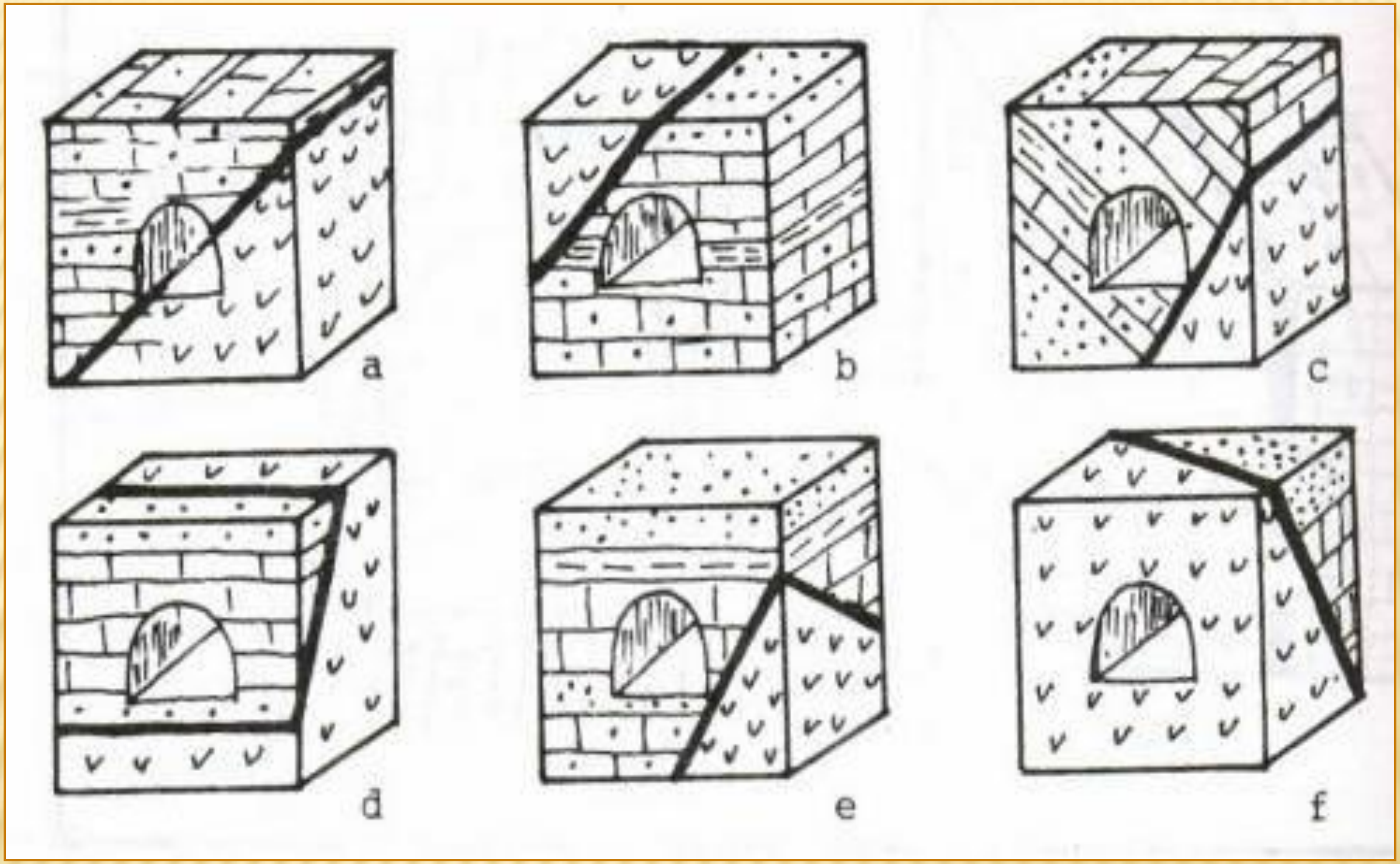

Fig.2: Relation between the fault zone and the tunnel.

5- The fault plane itself is a very prominent fracture plane in the fault zone and therefore may act as a severe **source** of **leakage of water**, such weathering further reduces the competence of the rock.

6- In some cases where the dip direction of the fault plane and the surface slope occur in the same direction, **land slides** may occur.

7- The **folds** are effected in **tunnel area** where different stresses and conditions may occur depending on the fold type. If tunnel located in anticline area, there will be decreased in pressure and the water flowing from it. While if tunnel located in syncline area, there will be an increase in pressure and the water flowing into it (Fig.3).

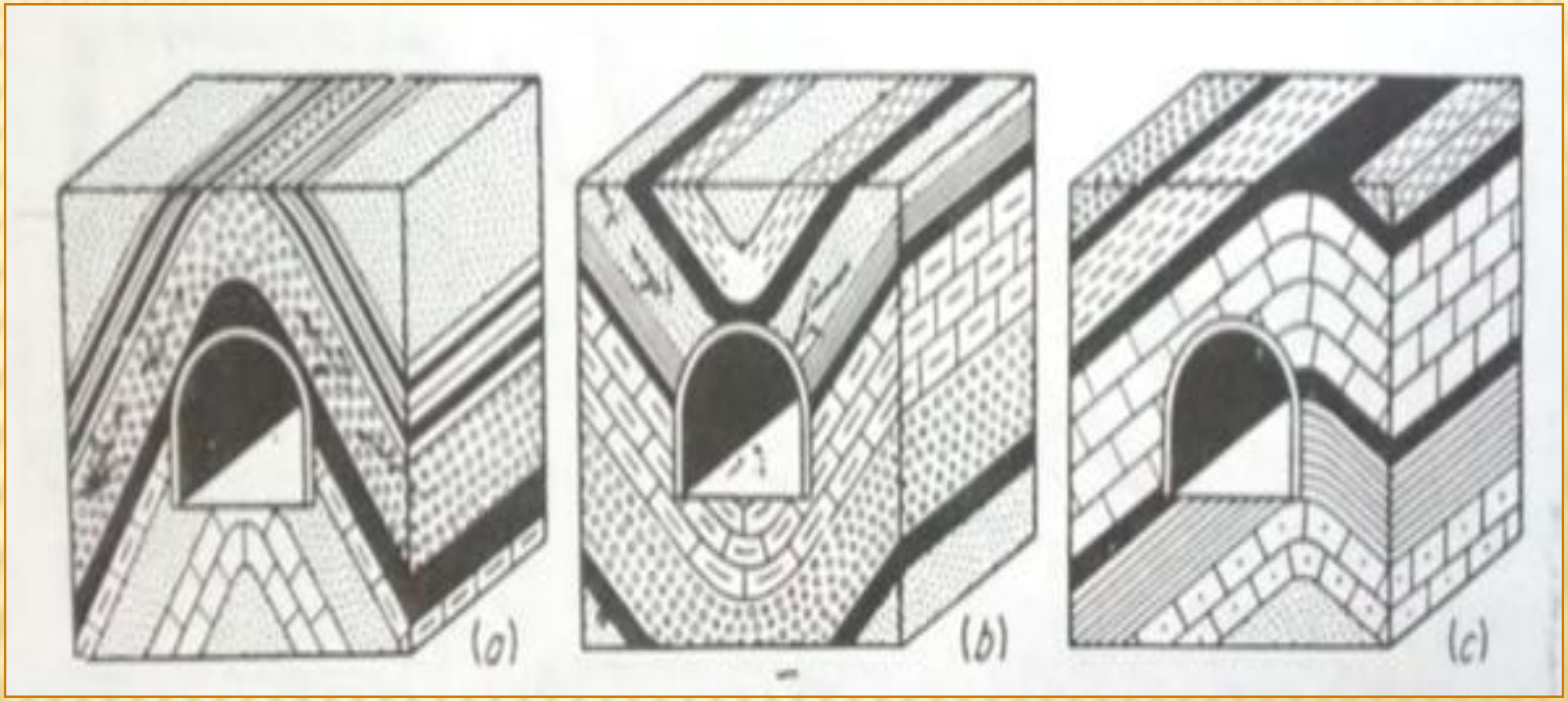

Fig.3: Tunnel located in anticline and syncline.

B- Ground water:

Water reservoirs are associated with the presence of geological structures such as fractures and folds as below:

1- The fractures, especially faults and joints influence the **movement** of surface water. The water can also follow the pattern of discontinuities such as cracks in rocks (Fig.4). It is worth to mention that the fault (and tectonics in general) can control drainages and rivers patterns. Where the faults control of the movement of the river and make it flow along it in a straight line such as the Euphrates river in the Mesopotamian area following the Abu Jir-Euphrates fault which is a longitudinal fault and belong to the Najd fault system. While, the tributaries of the Tigris and Euphrates rivers follow the faults that belong to Transverse fault system (Fig.5).

2- The lineaments such as faults, joints and dykes act as drainage channels of groundwater flow and also as **aquifers**. Moreover the folds (anticline and syncline) act as aquifer in the area (Fig.6).

3- When the faults forming horst and graben system they will form a **barrier** or semi-barrier to the ground water flow.

4- The **active tectonic** affects the characteristics of river channels, where Sometimes the river **tilts** in its watercourse because of subsurface structure as growing fold or salt intrusion (Fig.7). (More details in neotectonics chapter).

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Lecture 4

Applications of structural geology (Importance in geology) (Part 2)

Instructer: Dr. Hanan Abdulqader Darweesh

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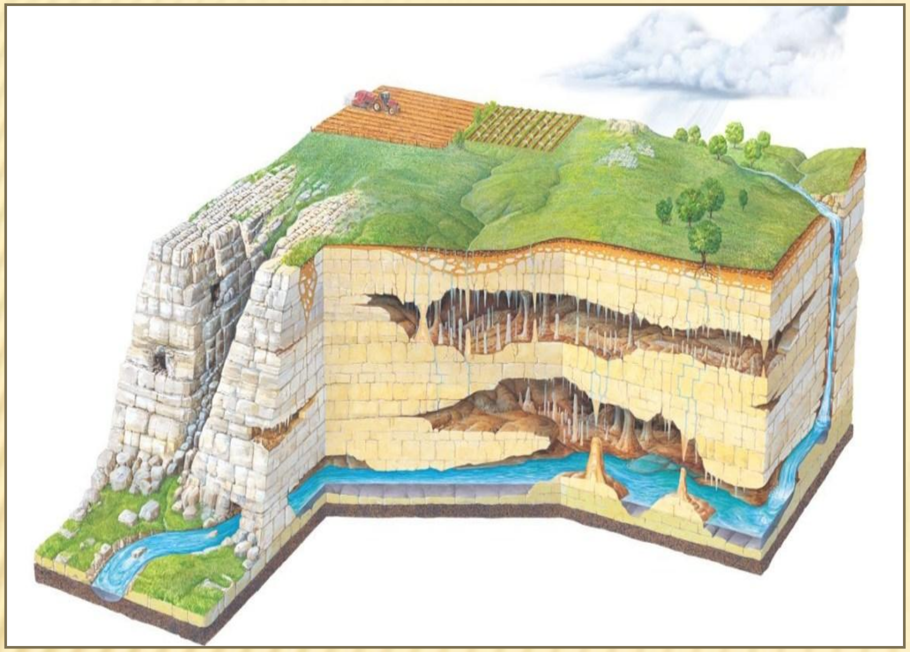

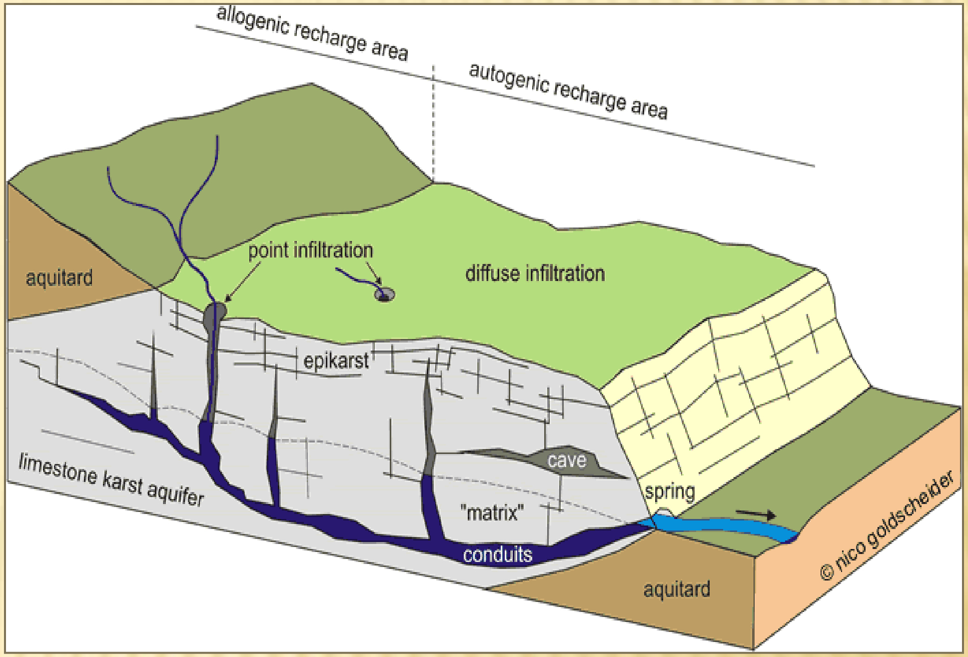

(A)

(B)

Fig.4: (A and B) Influence of fractures on the movement of water.

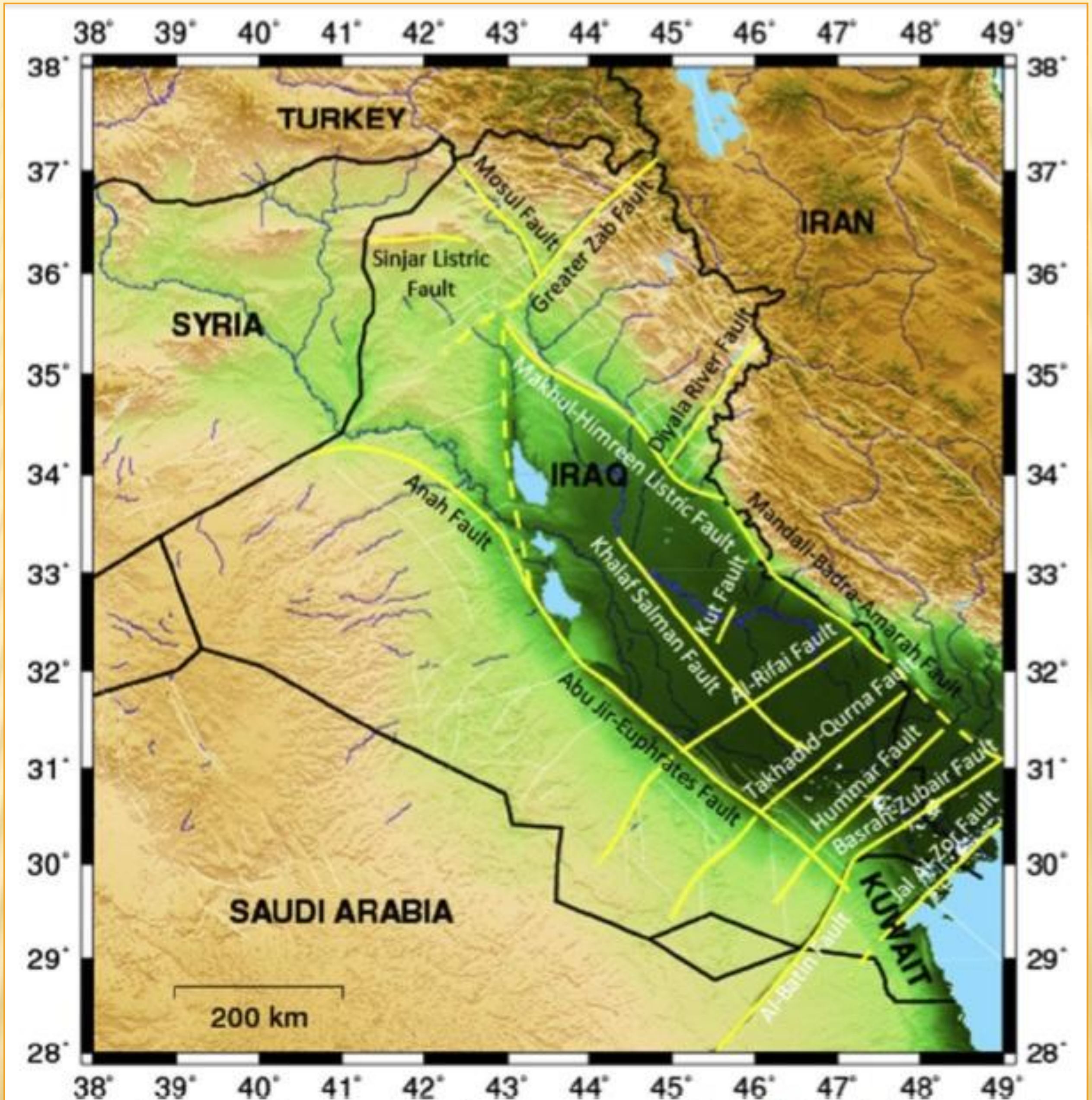

Fig.5: Map of Major Faults in the Mesopotamia plain (Abdulnaby, 2019).

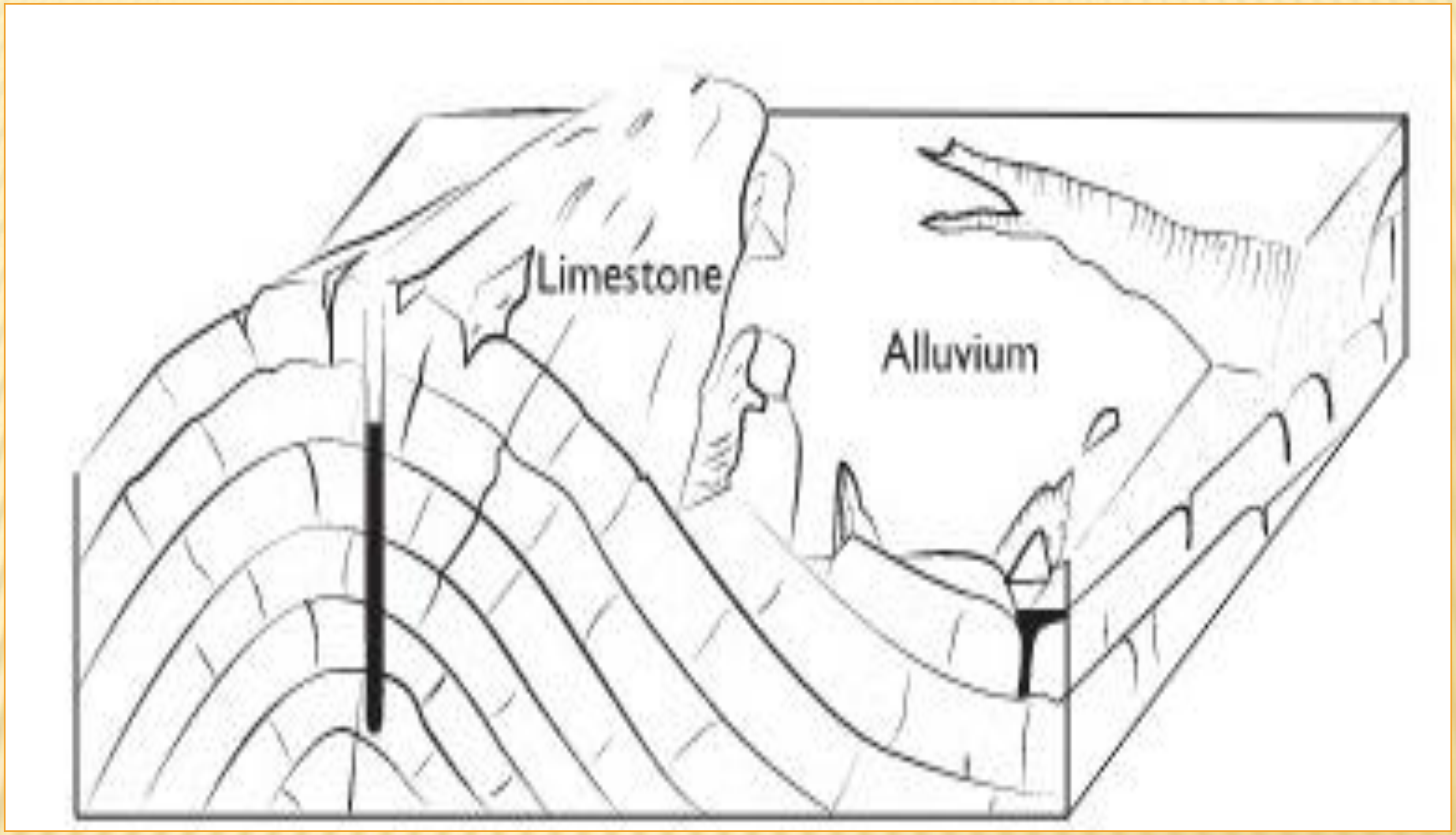

Fig.6: Occurrence of high-permeability zone in solution-enlarged fractures along the exposed crest of an anticline in carbonate rock.

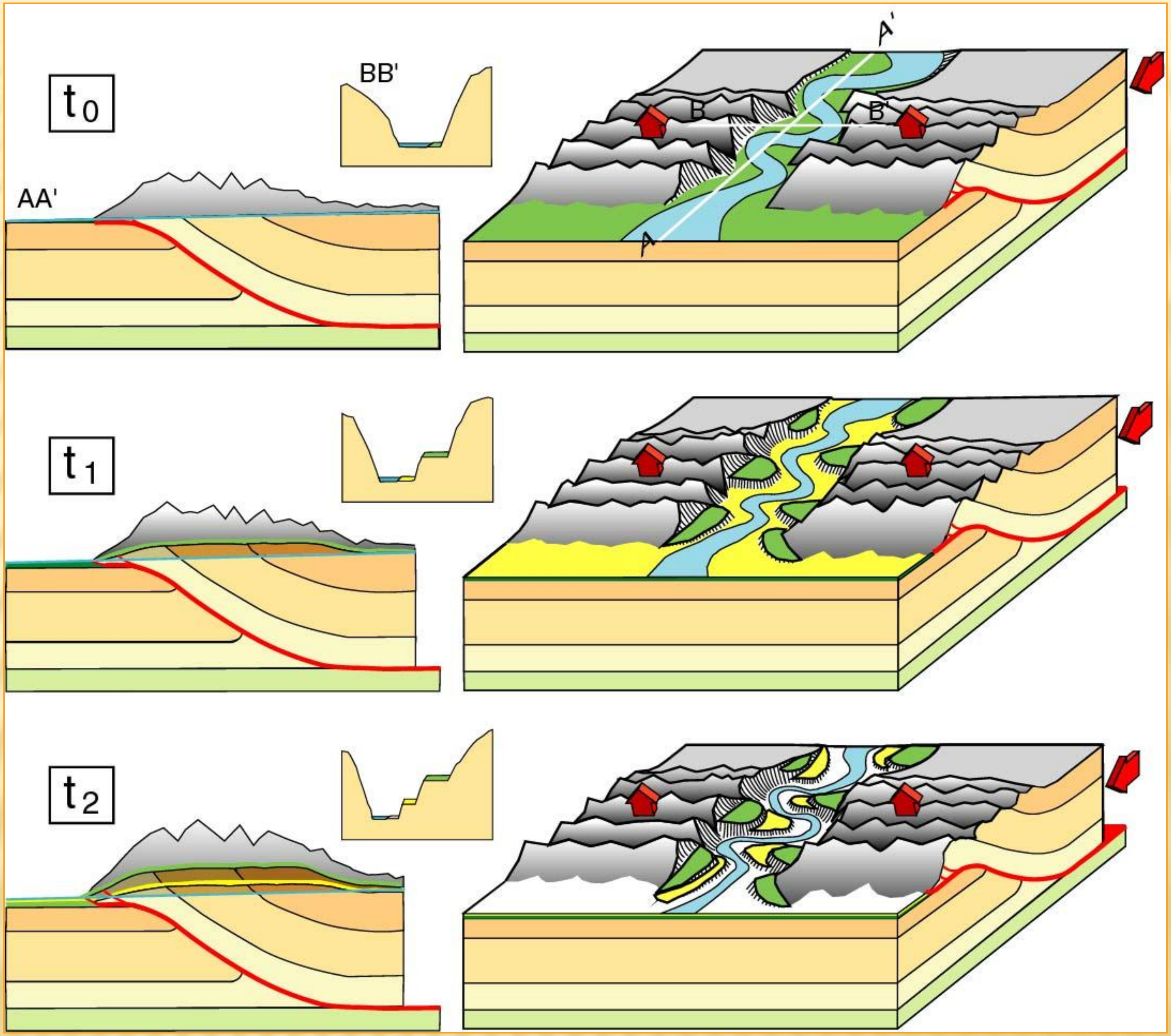

Fig.7: Effect of an active fold on meandering the river.

C - Economic Geology (Petrolum and mining):
The economic importance of ore or rock body such as coal or limestone can be known by determine the dimensions and status of the structure. The study of structural geology has a primary importance in economic geology, both petroleum geology and mining geology. That clear by:

1- Folds and faults rock strata commonly form **traps** for the accumulation and concentration of **fluids** such as petroleum and natural gas.

2-Veins of minerals containing various metals commonly occupy faults and fractures in structurally complex areas.

3- Fault, joint and fractures can act as a **passageway for groundwater** and **pathways for hydrothermal solution** to host valuable mineral deposits as gold, silver, copper, lead, zinc and other metals, which are commonly located in structurally complex areas.

4- The structural styles have a close relationship with source rocks, hydrocarbon reservoirs, and the character and distribution of petroleum systems. Where many of the oil **traps** represent structural features (folds or faults) (Figs.8, 9 and 10).

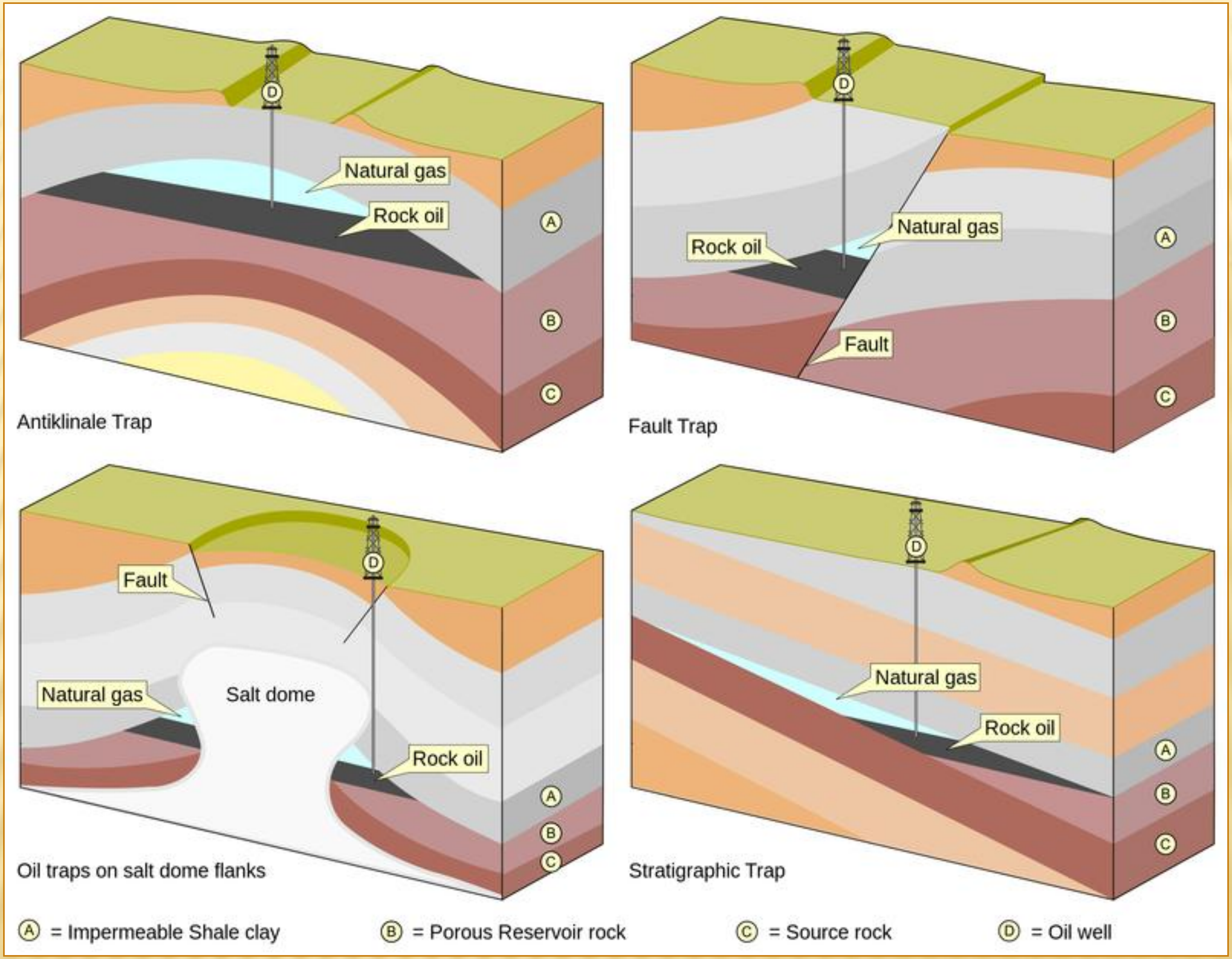

Fig.8: Hydrocarbon trap types.

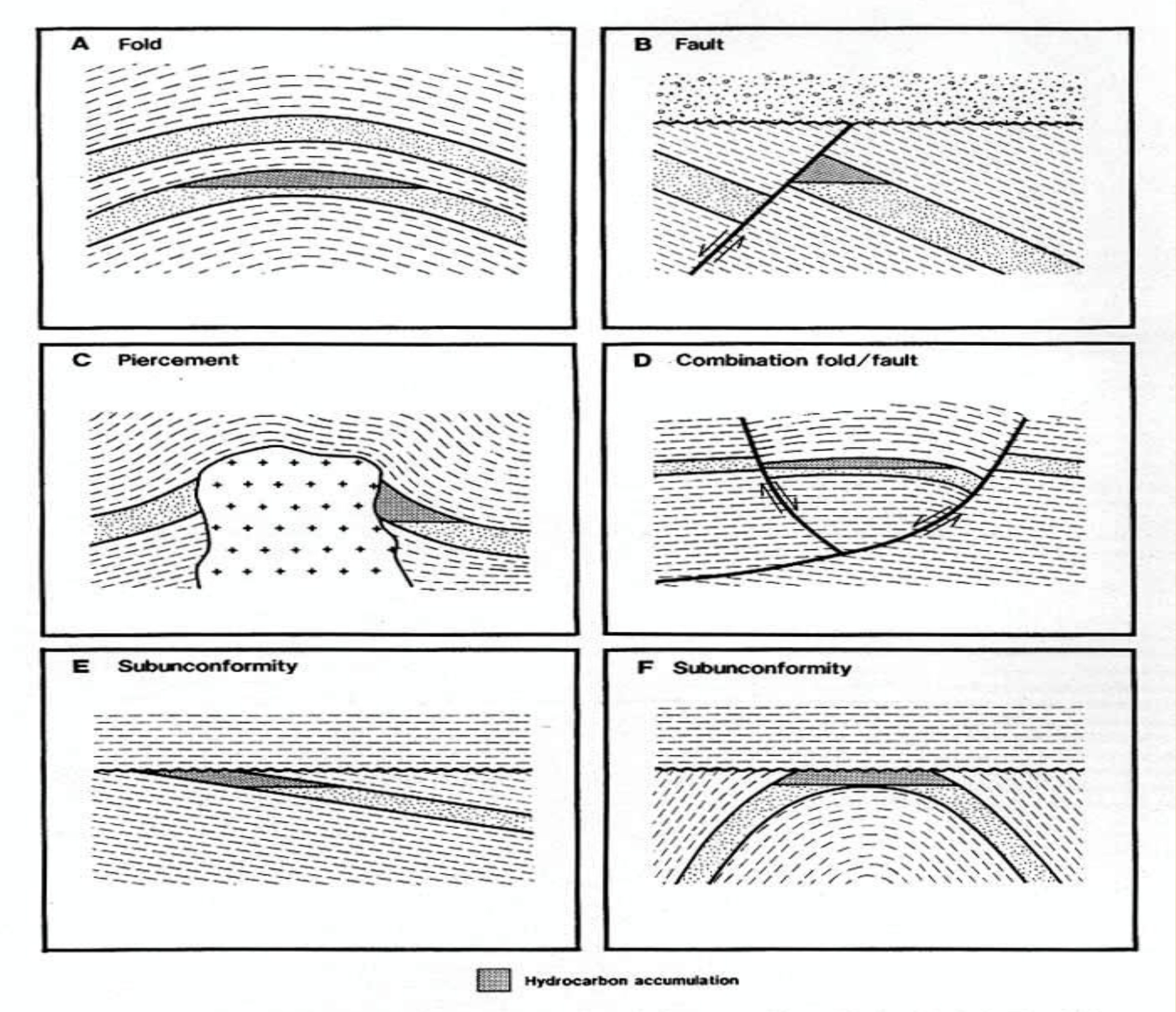

Fig.9: Structural traps.

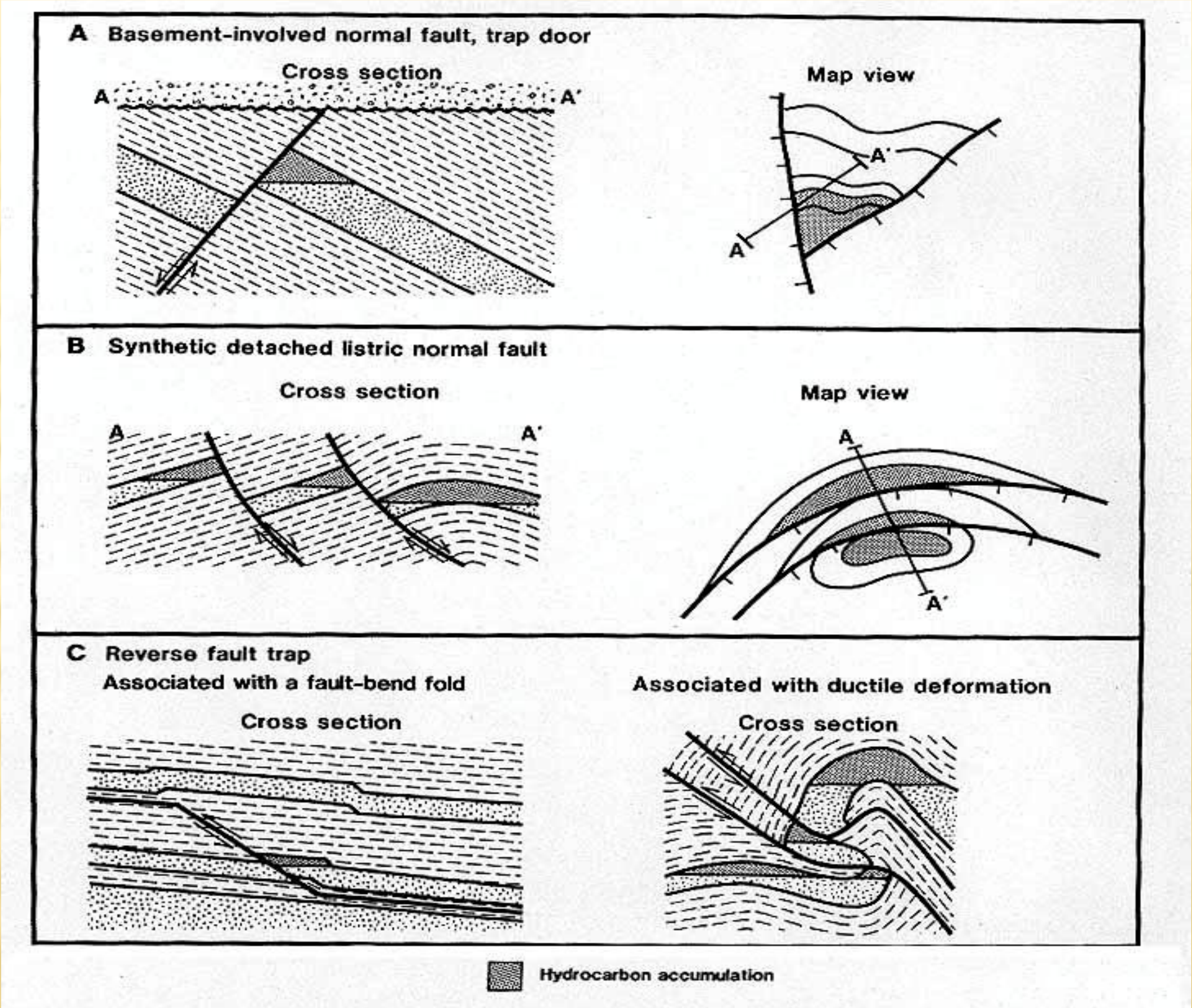

Fig.10: Faults traps.

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Lecture 5

Neotectonics (part 1)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

Neotectonics

The term **neotectonics** was described by Obruchev (1948) in the article as "recent tectonic movements occurred in the upper part of Tertiary (Neogene) and in the Quaternary, which played an essential role in the origin of the contemporary topography".

Some authors consider neotectonics to be basically synonymous with "active tectonics", while others date the start of the neotectonic period from the middle Miocene.

Neotectonics is the study of the motions and deformations of Earth's crust (geological and geomorphological processes) that are current or recent in geologic time (Pavlides, 1989).

In 1989 another definition was suggested: "**Neotectonics** is the study of young tectonic events which have occurred or are still occurring in a given region after its Orogeny or after its last significant tectonic set-up so, neotectonics can be considered as the activity of the earth. It is a continuation of the tectonic movements that accompanied the construction of the mountains and most of the structural heights that occurred since the oldest geological time to this day.

The term also refers to the motions/deformations themselves. Geologists refer to the corresponding time-frame as the neotectonic period, and to the preceding time as the palaeotectonic period.

Neotectonic is the study of the post-Miocene structures and structural history of the Earth’s crust (AGI, 2009).

According to Al-Sakini (1995), there are three factors responsible for the movement in the Mesopotamia plain. These are:

(1) the deep faults that extend from the basement to the surface in some cases, (2) the effects of alpine movements that are continuous to the present day and (3) the existence of thick salt beds.

Neotectonic is playing very important role in oil accumulations in Iraq, where they contribute in the growth of subsurface folds, which form an important oil traps in Iraq.

Neotectonic indications:

1-Topographic indications:

Which representing by the presence of a growing subsurface anticline in the region. For example growing of the Samarra subsurface anticline in the Mesopotamia Plain (Fig.1). The area is covered by Quaternary sediments (Sissakian, 2000), but the presence of the subsurface anticline is proven by geophysical studies (C.E.S.A., 1992 and Al-Kadhimi *et al.*, 1996), besides the morphology of the area that indicates clearly a double plunging anticline. Such Quaternary landform is a clear indication for a neotectonic activity (Markovic *et al.*, 1996).

Sissakian *et al.* (2017) studied the neotectonic activity of the Jabal Sanam vicinity and found that the rocks of the Dibdibba Formation (Pliocene–Pleistocene) which belong to the two circular rims surrounding Jabal Sanam are folded and show clear dip towards the outer circumference.

This is a clear indication of neotectonic activity in a mostly flat terrain. Furthermore the faults that are present in the area are active faults. Considering that the faults are younger in geological age than the exposed rocks, thus it would be regarded as neotectonic activity (Fig.2).

Fig.1: Google Earth image for the Samarra subsurface anticline.

Fig.2: Earth image of Jabal Sanam structure (Sissakian *et al.*, 2017).

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Lecture 6

Neotectonics (part 2)

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2-Abandoned River Channels:

The Tigris River has abandoned channels in different places within the Mesopotamia Plain. The main one is between Al-Ghar'raf River and the current river channel (Fig.3) (Sissakian, 2000).

This abandoned channel is either the old course of the Tigris River or that of Al-Ghar'raf River. The authors believe that the growing of the subsurface anticlines in the area was the main factor for abandoning of the river its original channel. Many authors (Al-Sakini, 1993; Mello *et al.*, 1999; Bhattacharya *et al.*, 2005 and Philip and Virdi, 2007) recorded such cases.

The Euphrates River has also abandoned its channel, between Samawa and Nasiriyah cities; it is south of the current river course (Sissakian, 2000). The authors believe that the main reason for abandoning of the channel is the activity of the Abu Jir Fault Zone. The activity of this fault is proved by Fouad (2007).

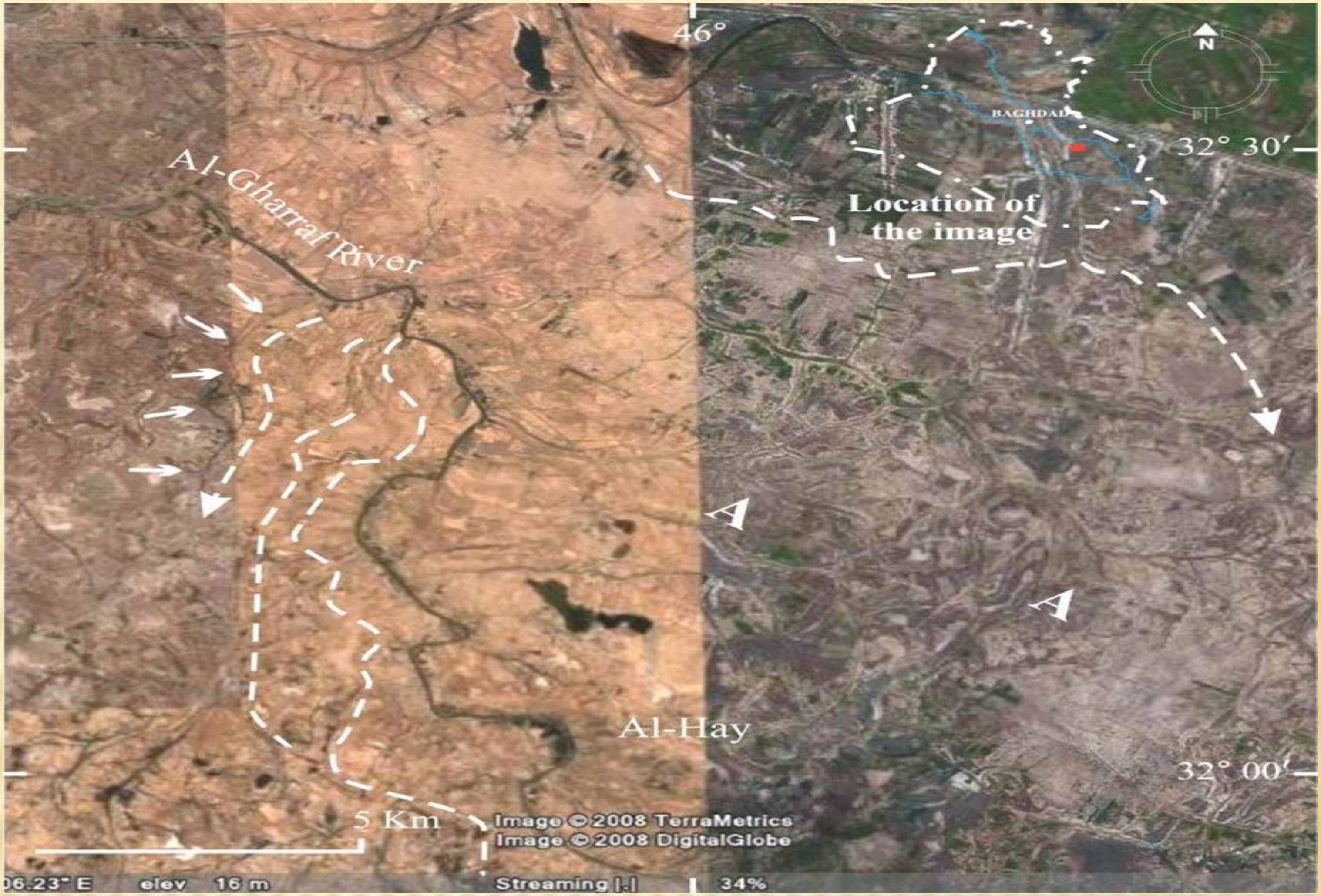

Fig.3: Google Earth image showing the old trends of Al-Ghar'raf River,due to growing of subsurface Ahdab and Abu Amood anticlines (Ahdab is few kilometers NW off the image area, Abu Amood is marked by AA).

Note: The dashed lines represent the ancient courses of the rivers; the small arrows indicate the exact location of the river course.

3-Shifting of River Channels:

The Tigris River has continuously shifted its course and is still shifting (Al-Sakini, 1993). Interpretation of the Google earth image confirms the shifting of the river course between Samarra town and southeast of Baghdad, that was previously running in the middle part of a huge alluvial fan (Jassim, 1981), which is called Al-Fatha Alluvial Fan (Sissakian, 2000), whereas the nowadays course is exactly along the eastern limits of the fan. The traces of the old channel are still clear in small parts, although the major part is vanished by urban and agricultural activities. The eastwards shifting of the channel is attributed, by the authors to the growing of Balad subsurface anticline.

The Tigris River has also shifted its course south of Nu'maniyah town to south of Kut city, most probably due to growing of the subsurface Azizziyah anticline (Fig.4).

Al-Ghar'raf River also has shifted its course in two areas (Fig.3); the reason is the growing of subsurface Ahdab and Abu Amood anticlines (Al-Sakini, 1993). Such activities are attributed to neotectonic movements by many authors (Mello *et al.*, 1999; Philip and Virdi, 2007, and Woldai and Dorjsuren, 2008).

Fig.4: Google Earth image showing traces of the old Tigris River course, SE of Baghdad (Azizziyah anticline is a few kilometers off the image, towards south).
Note: The dashed line represents the ancient courses of the river.

In the Zubair sub-zone there are many evidences of neotectonic activities. Studying the DEM Satellite images of the Rumaila oilfield to look for evidence of the Morphotectonics associated with the anticline resulted in observing change in the direction of the Euphrates River. The river shifted from its normal course to take a U-shape. The area of this curvature is located in above West Qurna culmination (Fig.5).

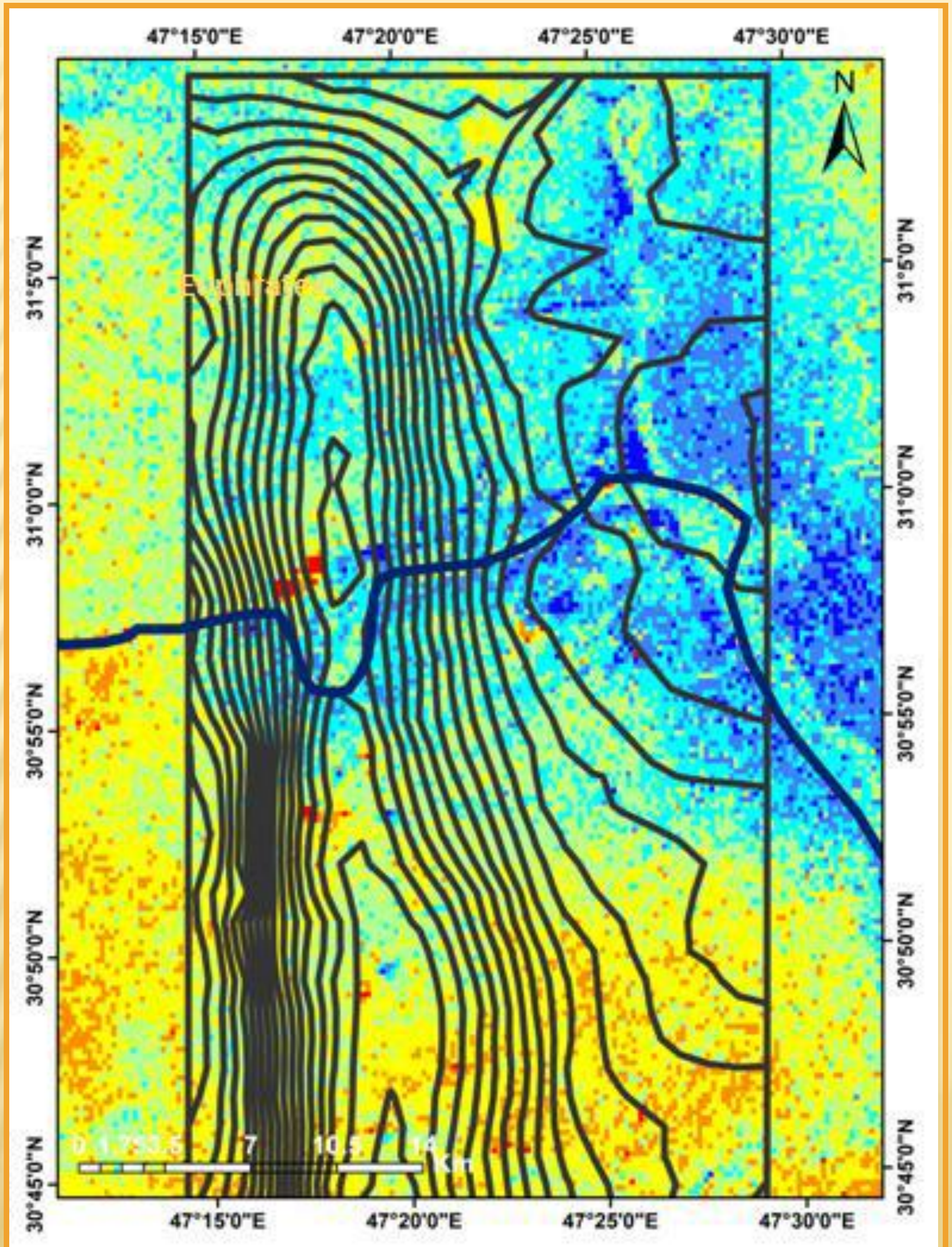

Fig.5: DEM Satellite image of the curvature of the Euphrates River in North Rumaila anticline (Personal Communication).

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Lecture 7

Neotectonics (part 3)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

4-Alluvial Fan Activities:

Alluvial fans are developed, mainly due to the drop in the energy of the stream that caries the sediments, due to drop in the gradient of the stream. On the other hand, the active fan indicates continuous subsiding of the distal part of the fan, whereas inactive fan indicates uprising of the distal part of the fan.

However, the climatic changes should not be ignored (Cohen *et al.*, 2002). It is worth to mention that the activity of the fan is also attributed to neotectonic movements (Cohen *et al.*, 2002, and Jones and Arzani, 2005).

Along the eastern margin of the Mesopotamia Plain, a well developed system of alluvial fans is developed (Figs.6 and 7). They all are of Pleistocene age (Sissakian, 2000). Some of them are still active (Fig.6) indicating continuous subsidence of the Mesopotamia Plain, as it is shown in the Neotectonic Map of Iraq (Sissakian and Deikran, 1998), and interpretation of satellite images. The inactive nature of other alluvial fans (Fig.7) may be attributed to growing of Buzurgan and Halfaya subsurface anticlines, as the authors believe.

Fig.6: Google Earth image showing complex alluvial fans system, near Badra, developed due to continuous subsiding of the Mesopotamia Plain.

Fig.7: Google Earth image showing a big inactive alluvial fan, between Kumait and Amara, the fan is inactive most probably due to uplifting of Buzurgan (B) and Halfaya (H) subsurface anticlines.

5-Structural noses:

The presence of incomplete closed-end structural noses to be completed and closed from an oil field. These structures appear as a seismic subsurface reflector. For example: Ratawi, Luhais and East Baghdad oil fields subsurface Structures.

6-River islands:

When river islands present in the area mean that there is neotectonic. Such as in Al-sayba structure in Shatt al-Arab river, where many islands appear at the intersection of the northern end of the structure with Shatt al-Arab River such as Um Al-Rusas island.

7-River terraces:

The presence of river terraces in the region is an indicating of neotectonic.

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Lecture 8

Stress & Strain (part 1)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

Stress & Strain

Stress is strictly defined as force per unit area that used to describe all forces that deform rocks.

Stress, σ, is defined as the intensity of force at a point:

$\sigma = dF / dA$

If the state of stress is the same everywhere in a body,

$\sigma = F / A$

The SI unit of stress is **pascal** (Pa) = N/m^2

The stress state at a point has three orthogonal normal tractions. These three normal tractions are called **the principal stresses** and are designated as σ_1, σ_2, and σ_3 where:

$\boldsymbol{\sigma_1 \geq \sigma_2 \geq \sigma_3 \neq 0}$

Stress Ellipsoid:

The state of stress at a point can be expressed graphically as an ellipsoid where the axes of the ellipsoid correspond to the principle stresses (Fig.1).

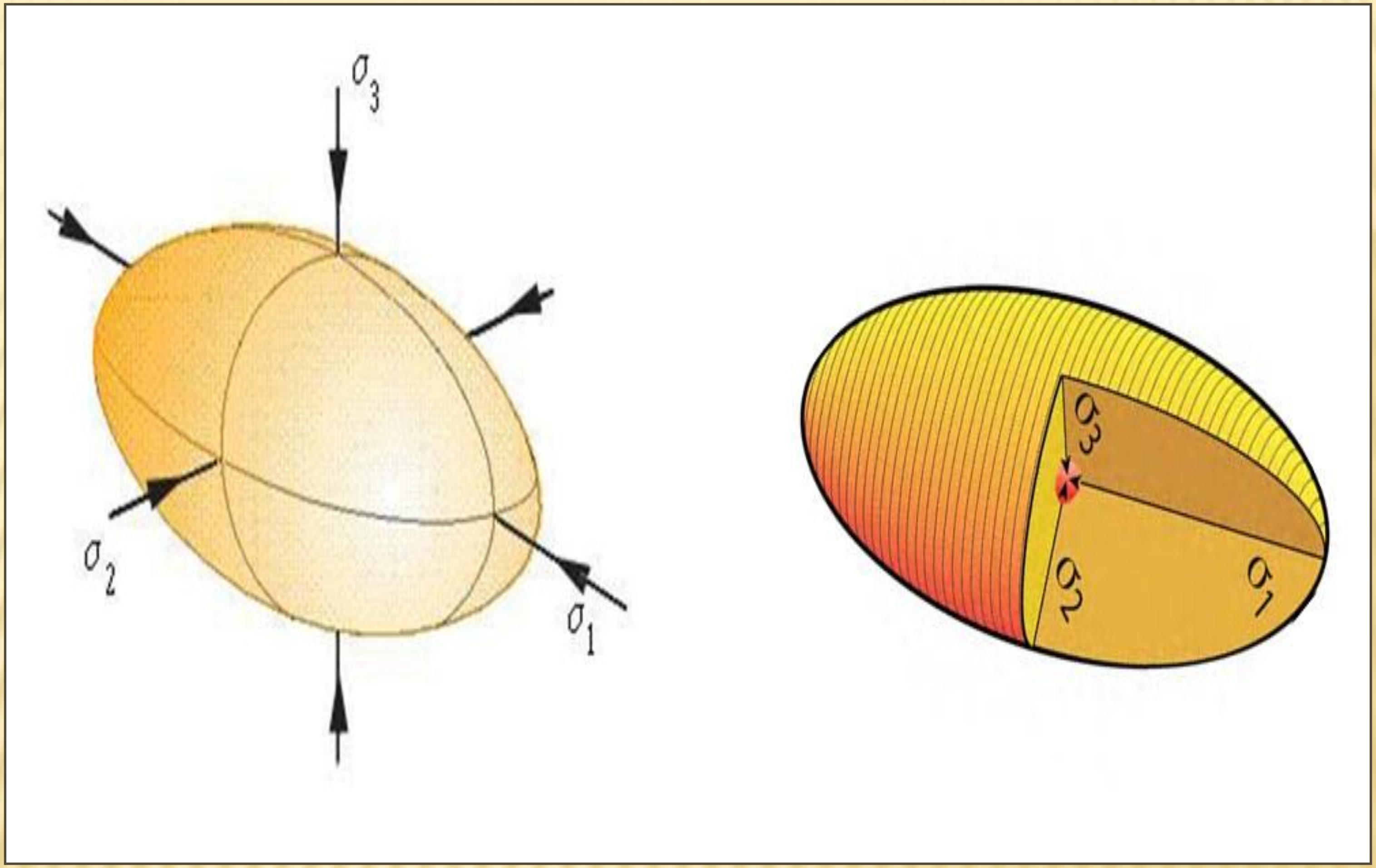

Fig.1: Stress Ellipsoid.

How do we recognize deformation or strain in a rock?

Strained means that something primary or preexisting has been geometrically modified, be it cross stratification, pebble shape, a primary magmatic texture or a preexisting deformation structure. Hence strain can be defined as a change in length or shape, and recognizing strain and deformation structures actually requires solid knowledge of undeformed rocks and their primary structures.

Hence, being able to recognize tectonic deformation depends on our knowledge of primary structures.

The resulting deformation structure also depends on the initial material and its texture and structure.

Types of differential forces in rock:

There are many types of differential forces in rock (Fig.2) as below:

a- Tension (pulled apart, elongates).

b - Compression (pushed together, shortens).

c- Shear (tearing, causes splaying, e.g. deck of cards).

d- Torsion (e.g. clothes squeezing).

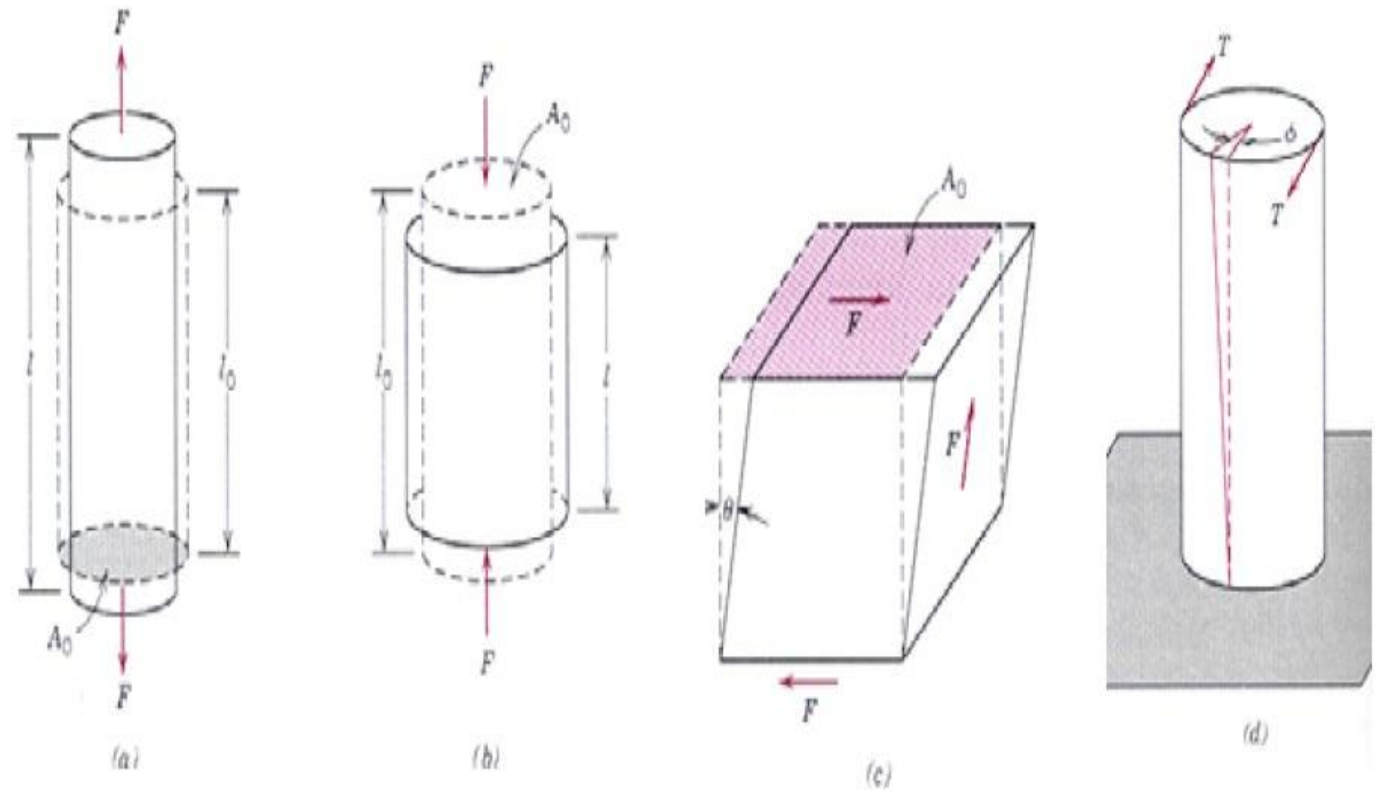

Fig.2: Types of differential forces in rocks.

Strain (Deformation):

The strain is a change in shape or the internal configuration of a body and it is the resultant deformation, **or** it is the change in shape or volume arising from stress, so the strain is a result of stress.

Rheology is the study of the relationships between stress imposed on a body and resulting strains or strain rates.

Types of strain:

Four types of strain (Fig.3):

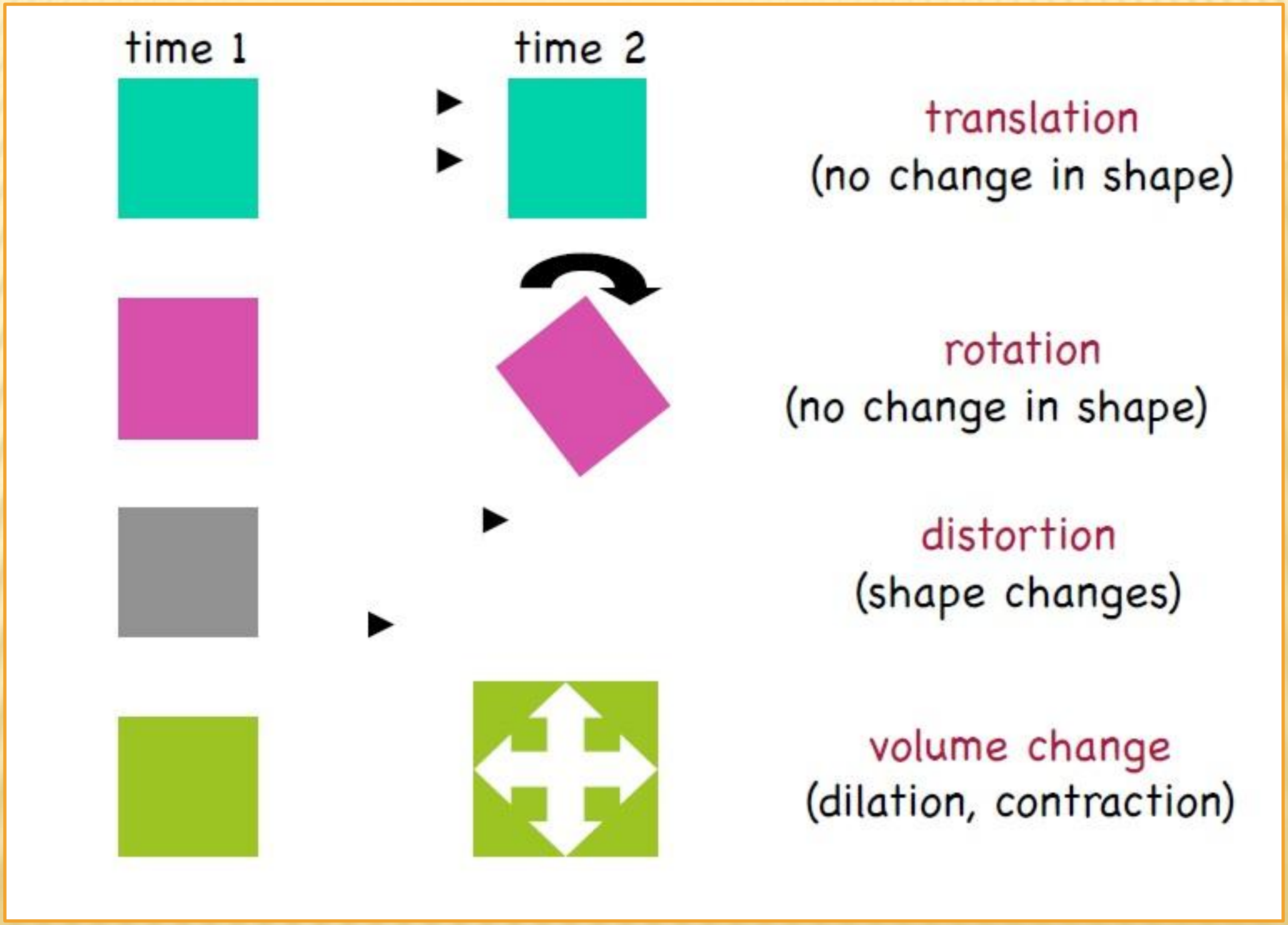

Fig.3: Types of strain.

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Lecture 9

Stress & Strain (part 2)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

Factors that affect deformation of rock:

1- Lithostatic pressure: is the weight of overlying rock.

2- Heat: causes atomic bonds to weaken.
- temperatures low at shallow depths (brittle).
-temperatures high at great depths (ductile).

3- Time: allows stress to be applied slowly or quickly.

4- Composition: controls rock response to stress.
- minerals, weaknesses in rock, fluids in pores, etc.

How rocks respond to stress?

Rock DeformationTypes:

Rock deformation refers to changes in the shape, volume, or orientation of a rock due to changes in temperature and pressure over time. Rocks behave as elastic, brittle, or ductile bodies (Fig.4).

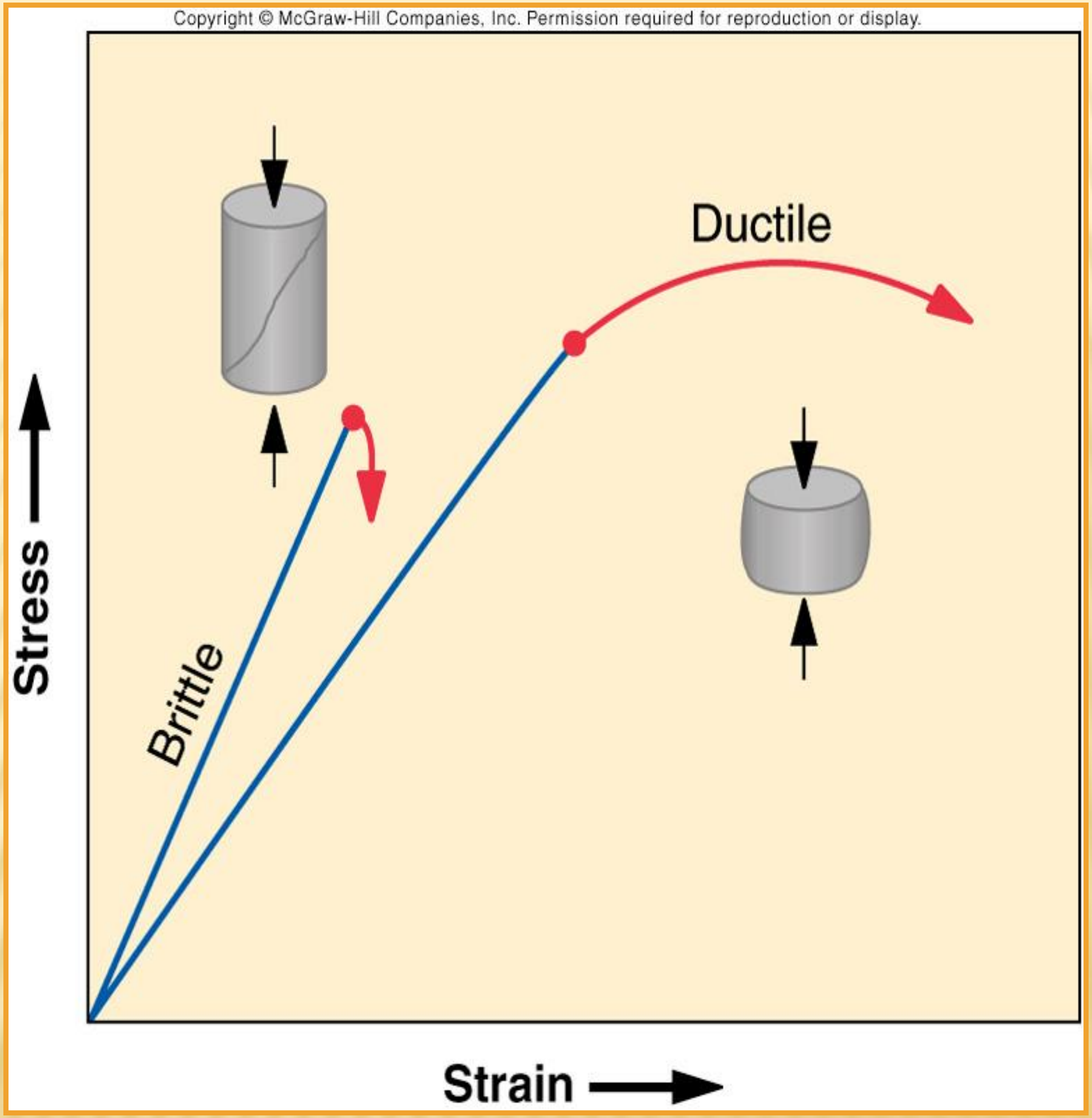

Fig.4: Rocks respond to strain.

1-Elastic deformation:

The rock will return to original shape and form after the stress is removed (Fig.5).

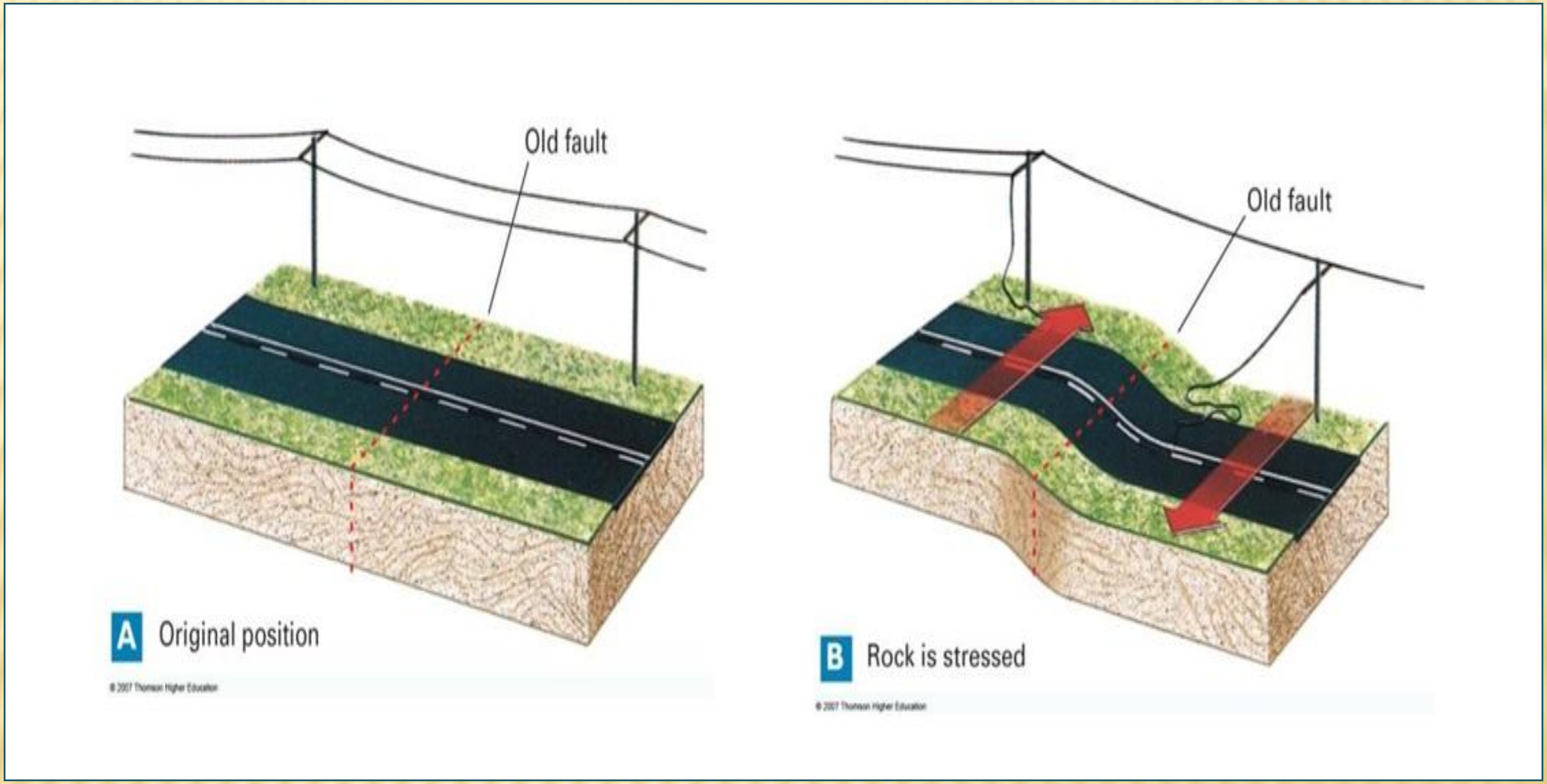

Fig.5: Elastic deformation.

2- Brittle Deformation: Rocks behave like a brittle solid and fracture.

-Rock under compression (break).

-Near surface conditions.

-Relatively low pressures and temperatures.

- The result is faulting (Fig.6).

Fig.6: Brittle Deformation (faults).

3-Ductile deformation: solid state flow of rocks that results in permanent deformation without fracture.

-Rock (flows) at yield point (No continuous break).

-Conditions at depth.

-Relatively high pressures and temperatures.

-The result is folding (Fig.7).

Fig.7: Ductile Deformation (folding).

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Lecture 10

Cratons (Basement complexes)   (part 1)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

Cratons (Basement complexes):

Continents are more than simply land areas above sea level. They have a composition similar to granite and that **continental crust** is thicker and less dense than **oceanic crust**, which is made up of basalt and gabbro.

Cratons or **Basement complexes** are the ancient igneous and metamorphic rocks (usually pre-Cambrian age) that are not exposed to folding Although they suffered of huge deformation processes .The craton represent the continent's ancient nucleus and it is divided into two areas (Fig.1):

1-Stable platforms:

The area near the mountain ranges, which is usually covered with thin horizontal layers of sedimentary rocks .A platforms are a buried ancient rock, merely extensions of the shields, that underlie much of each continent.

2-Shields:

It is an area far from the mountain range that is exposed to the surface and exposed to erosion process .A shield consisting of a vast area or areas of exposed ancient (Precambrian) rocks is found on all continents.

The Deformation:

Earth is a dynamic planet. Tectonic forces deformed rock to produce our planet's spectacular mountain belts. When rocks are subjected to forces (stresses) greater than their own strength, they begin to deform usually by folding and faulting (Fig.2).

Some of the geologic structures associated with crustal deformation include folds, faults and joints or fractures (Fig.3).

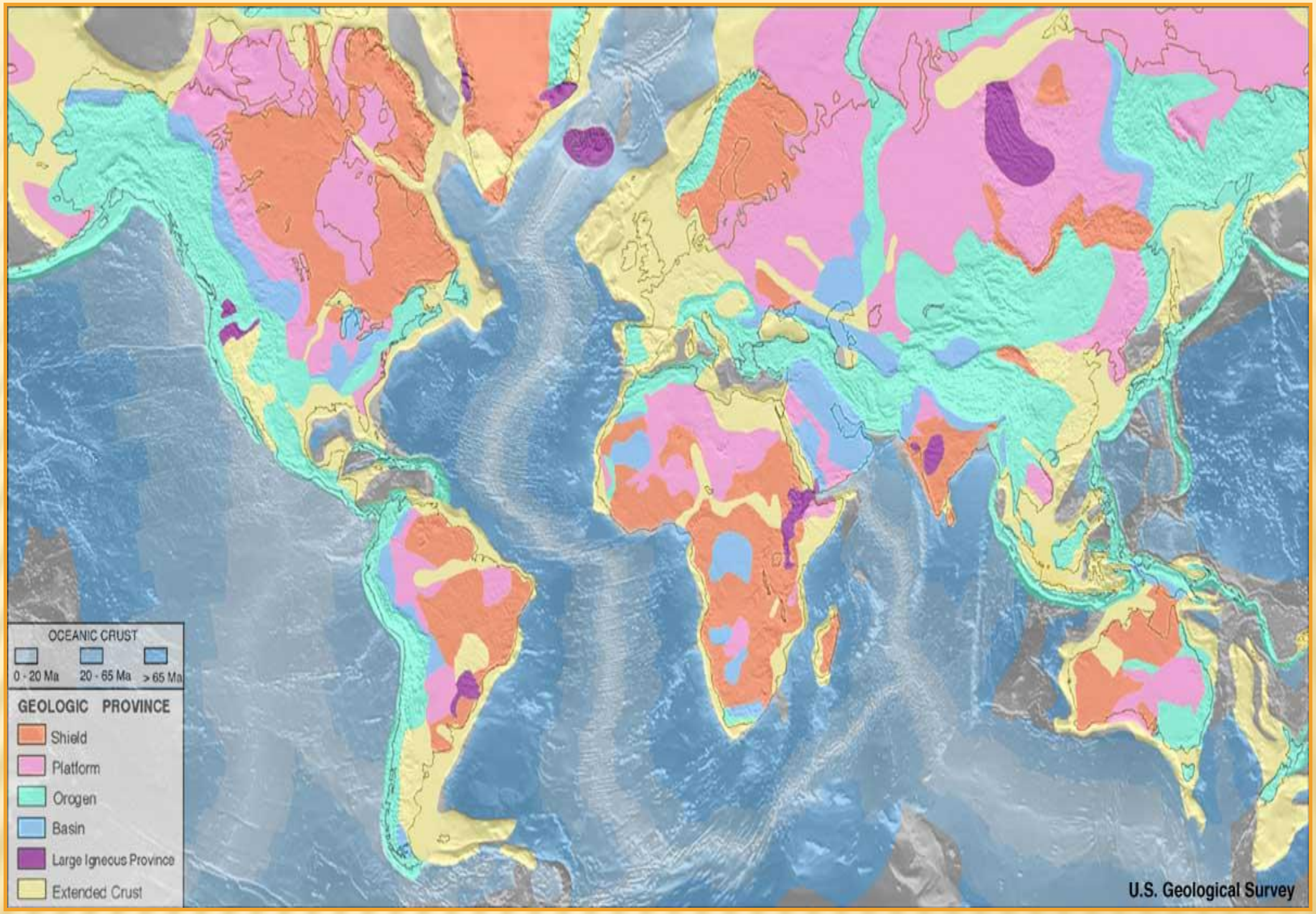

Fig.1: Geologic Provinces of the world (USGS).

Shield Oceanic crust:
Platform 0–20 Ma
Orogen 20–65 Ma
Basin >65 Ma
Large igneous province
Extended crust

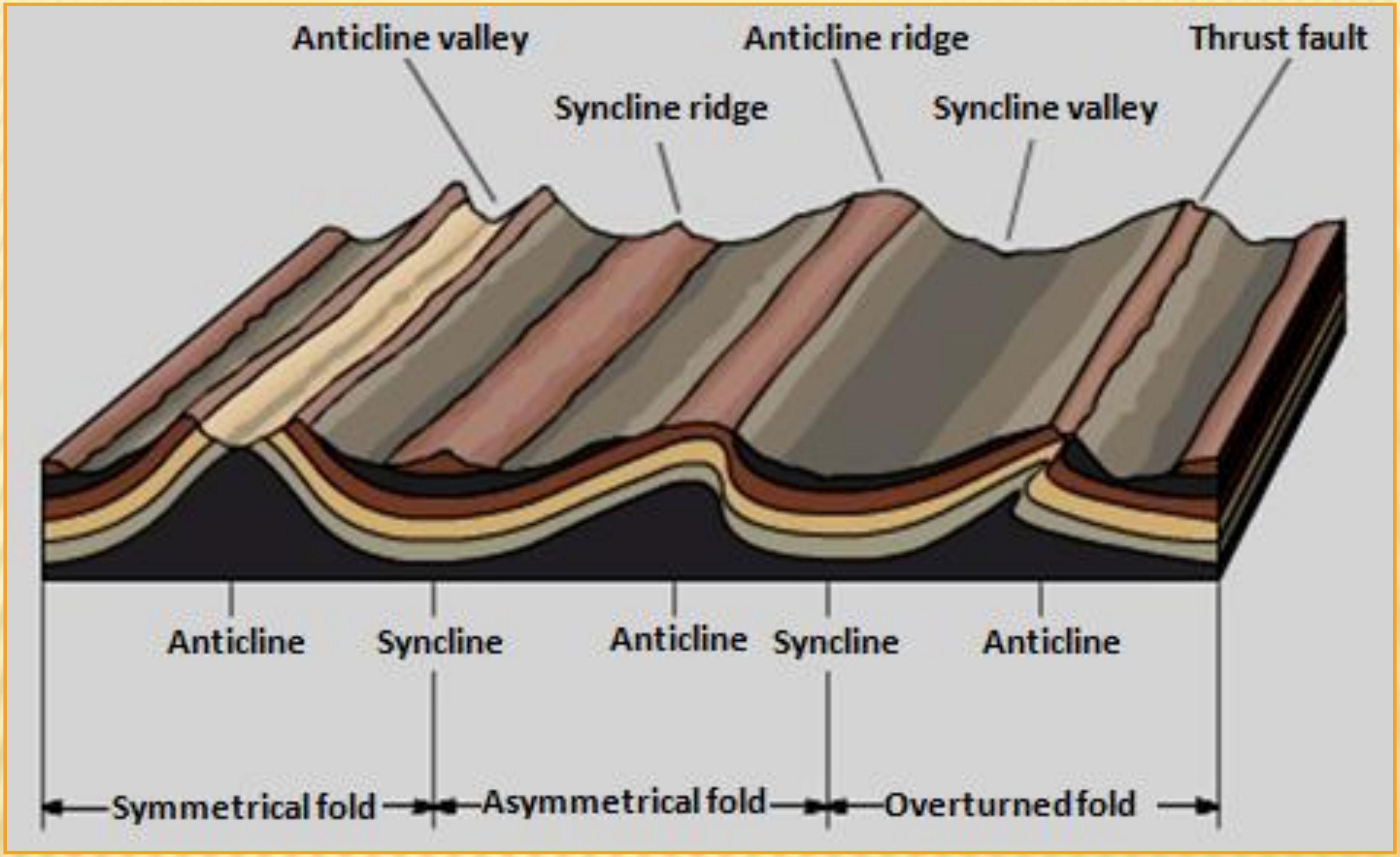

Fig.2: When rocks are subjected to forces (stresses) greater than their own strength, they begin to deform usually by folding and faulting.

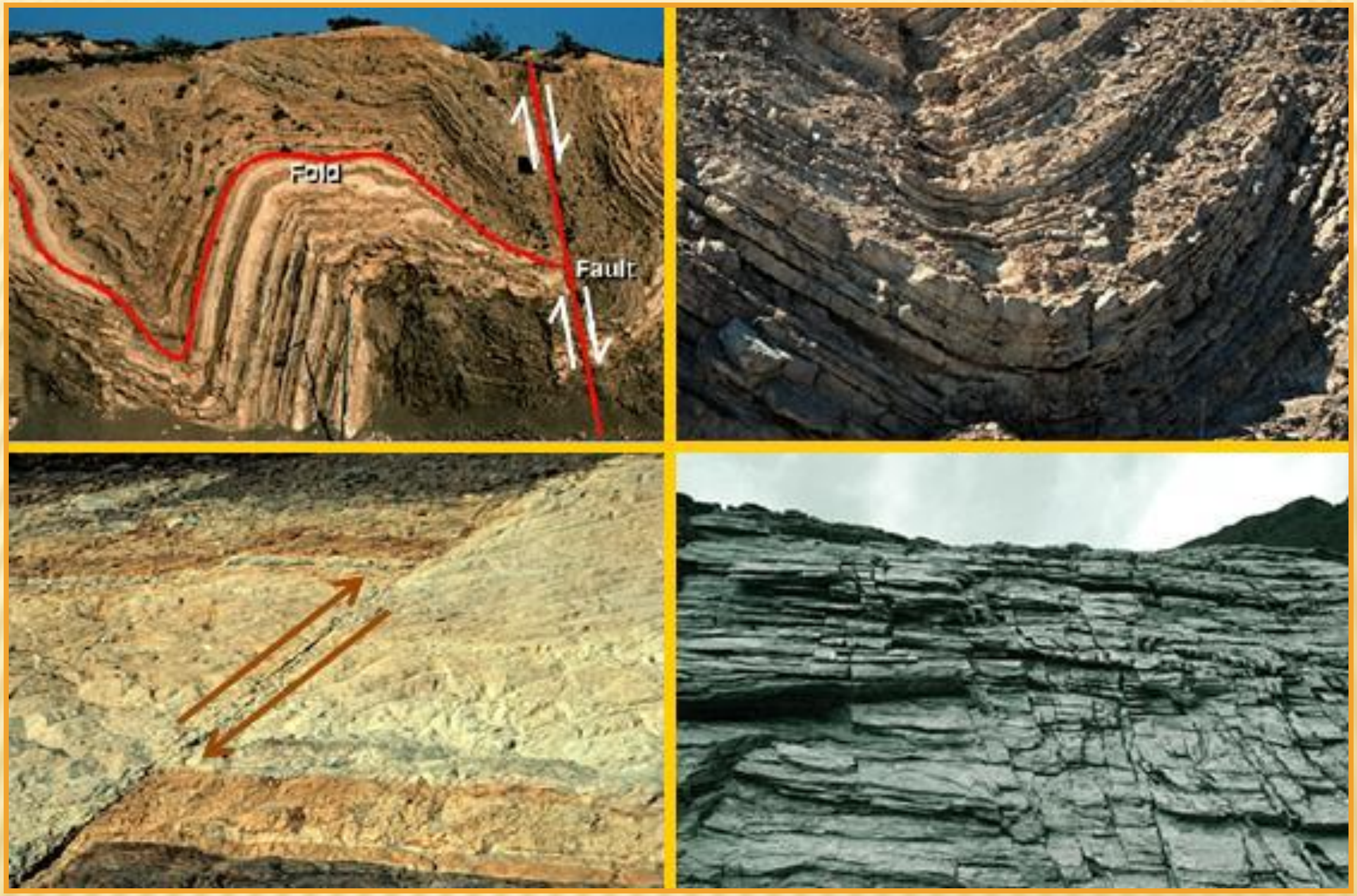

Fig.3: Some of the geologic structures associated with crustal deformation include folds, fault.

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Lecture 11

Cratons (Basement complexes)   (part 2)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

Orogeny (Mountain building):

An orogeny is referring to mountain genesis or mountain building. Orogeny is an event that leads to both structural deformation and compositional differentiation of the Earth's lithosphere (crust and uppermost mantle) at convergent plate margins.

An orogen or orogenic belt develops when a continental plate crumples and is pushed upwards to form one or more mountain ranges; this involves a series of geological processes collectively called **orogenesis**.

Orogenic belts are formed as a result of the plate movements specifically the convergent movements. In general, there are two main types of orogens of convergent plate margins:

The first one is Subduction Zone responsible for the formation of mountain ranges. That zone is a result between oceanic-continental plates or oceanic-oceanic plates to result in either continental arc magmatism or the accretion of island arc terranes to continental margins.

The second is the collision zone between two continental plates to form the mountains.

There are many earth movements happened in the Phanerozoic Eon such as Caledonian and Hercynian Orogeny at Paleozoic, Nevadan and Laramide Orogeny at Mesozoic and Alpine Orogeny at Cenozoic.
Alpine Orogeny formed Alpine and Himalaya Mountains and Many of the mountain ranges that exist today are due to the activity of this movement. For example Zagros and Torose mountains are the result of the collision of the Arabian plate with the Iranian and Turkish plates at the end of the Tertiary.

Continental collisions:

Mountains are often spectacular features that rise several hundred meters or more above their surroundings. Mountain ranges also developed when two continental plates are convergent (Fig.4) to form the folded mountains.

These mountains are broad and linear mountain ranges found along Collision zone. The rocks of this region are characterized by severe exposure to horizontal pressures that cause the twisting of rock layers and break them. Because of the difficulty of subduction one of the two layers below the other because they have the same density, the horizontal forces are very large, and therefore the mountain ranges formed very complex and high altitude, which is the most prominent are: Alpine Mountains Belt, Himalaya Mountains, Zagros Mountains and Torose Mountains.

However, most major mountain belts show evidence of enormous compressional forces that have folded, faulted and generally deformed large sections of the earth's crust. Most of these major mountain belts were formed during the collision of two or more buoyant crustal blocks.

Zagros Belt:

Zagros Fold-Thrust Belt (ZFTB) is widely accepted as an example of continental collision between the Arabian and Iranian plates. The belt is a result of the Alpine orogeny which is continuously active till our day and caused the compression phase of the Arabian plate. As a result of that the Outer Platform is unstable and has different indications on neotectonics.

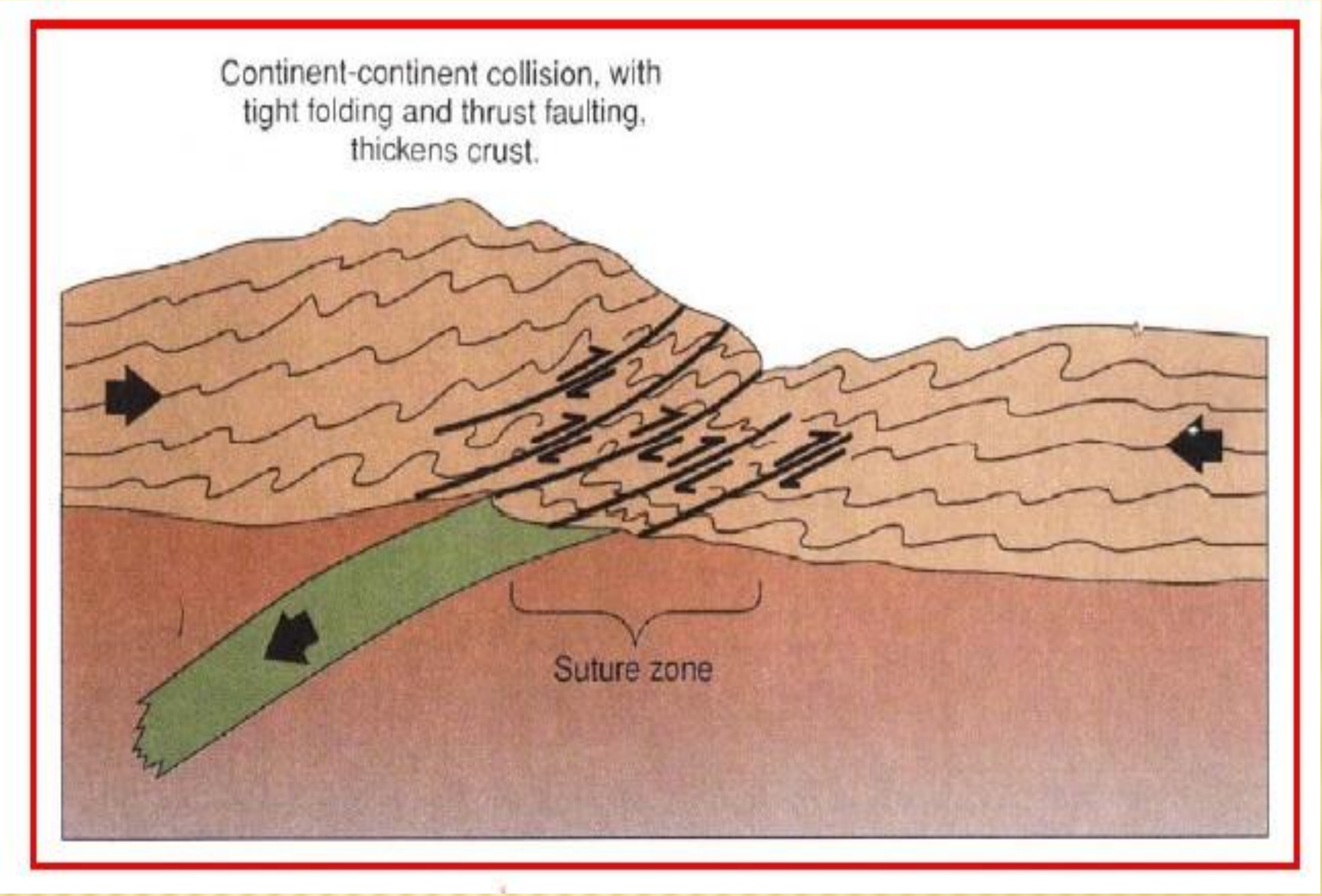

Fig.4: Folded mountains in convergent continental plates and forming the suture zone (Montgomery, 1997).

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Lecture 12

Cratons (Basement complexes)   (part 3)

Instructer: Dr. Hanan Abdulqader Darweesh

2019-2020

The dominant structures in the Zagros fold-thrust belt are folds and thrusts with northwestern-southeastern trend. This structure has main tendency toward southwestern. Based on morphology view, this belt is divided to High Zagros and Folded Zagros. The average height of this belt is near to 1200 meters. According to structural classification, the Zagros fold-thrust belt from northeastern to southeastern is divided to High Zagros Thrust Belt, Simply Folded Belt, Zagros Foredeep and Coastal Plane (Alavi, 2007).

The Zagros fold-thrust belt develops principally consequent of folding and thrusting of the Cenozoic foreland sequence. This sedimentary sequence deformed has been underlaid during Paleozoic-Mesozoic and mainly belongs to deposits of the Arabian plate and margin. In the Zagros, the northward motion of Arabian plate related to the Eurasia plate has caused the active deformation. The Zagros belt is divided into several geological zones that are different based on their sedimentary history, stratigraphy facies and structural style (Falcon, 1974) (Motiei, 1993).

The Zagros belt is one part of the Outer Arabian plate within Iraq, according to Fouad (2010a and 2010b) where the other part is the Mesopotamia Foredeep (Fig.5).

At the regional scale, the Zagros Fold-Thrust Belt consists of relatively straight and continuous series of high mountains that runs from southeast of the Arabian to the eastern part of Anatolia at the northwest. The Zagros Fold-Thrust Belt trends NW and represents the most deformed part in Iraq. It consists of the Suture or Thrust, Imbricate, High Folded, and Low Folded Zones according to (Numan, 1997, Jassim and Goff, 2016, and Fouad, 2010a and 2010b) (Fig.6).

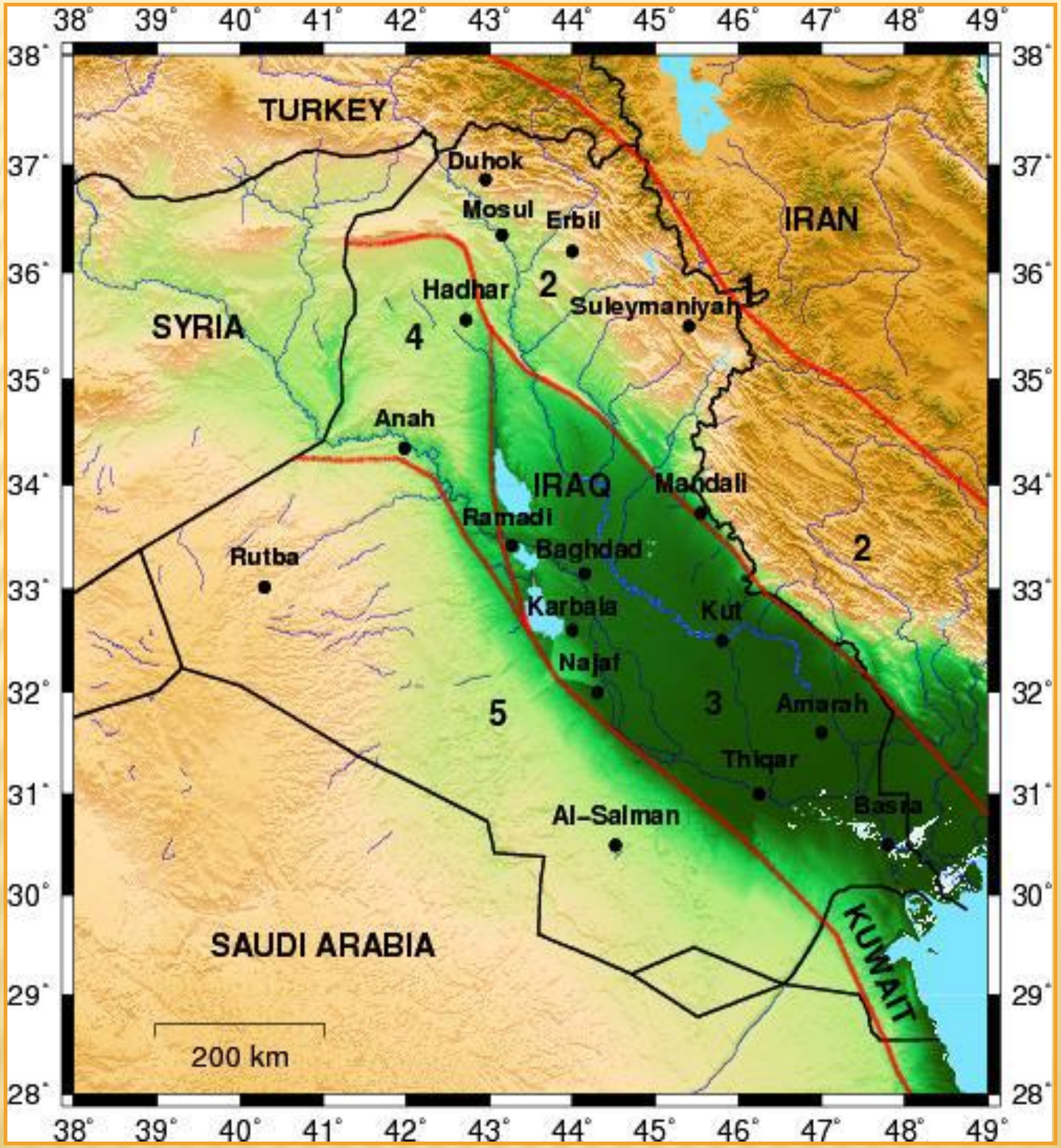


Fig.5: The tectonic divisions of Iraq after Fouad (2010a and 2010b).

1 Sanandaj-Sirjan Zone.

2 Zgros Fold-Thrust Belt.

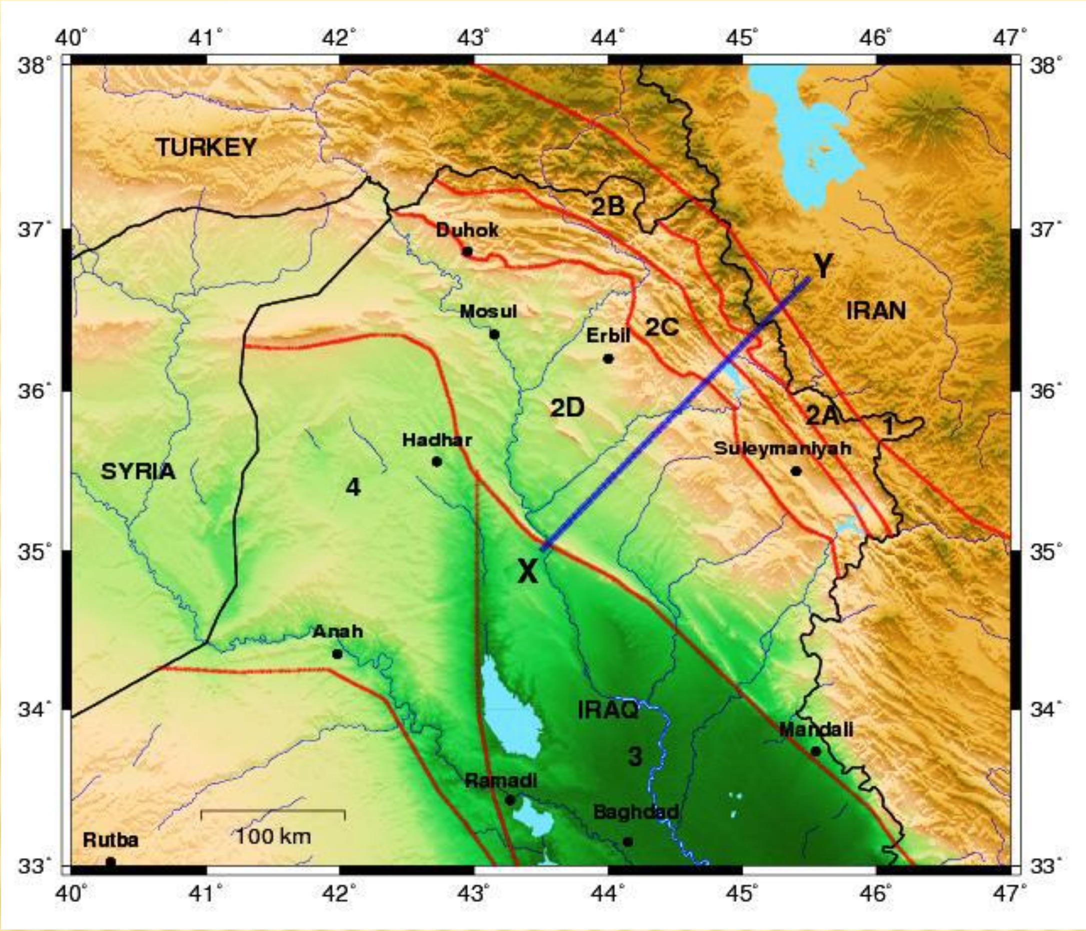
3 Mesopotamia Plain.

4 Al-Jazira Plain.

3 and 4 Mesopotamia Foredeep.

2, 3, and 4 Outer Platform.

5 Inner Platform.



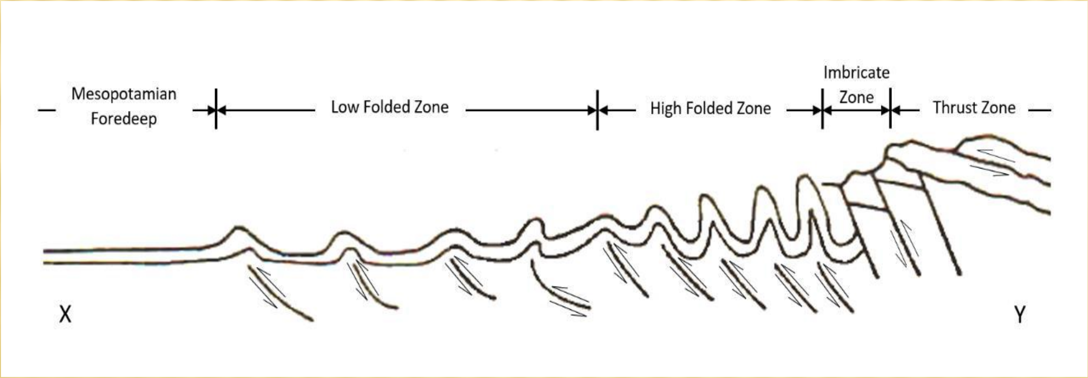


Fig.6: (a) Tectonic divisions of the Zagros Fold-Thrust Belt (After Numan, 1997, Jassim and Goff, 2006, and Fouad, 2010a and 2010b). 1 Sanandaj-Sirjan Zone. 2A Suture or Thrust Zone. 2B Imbricate Zone. 2C High Folded Zone. 2D Low Folded Zone. 3 Mesopotamia Plain, 4 Al-Jazira Plain.

(b) Cross section through the Zagros Fold-Thrust Belt with the direction of Northeast-Southwest shows the Thrust, Imbricate, High Folded, and Low Folded Zones (After Numan and Al-Azzawi, 1993).