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Relevant aspects to the recognition of extensional environments in the field

Aspectos relevantes para el reconocimiento de ambientes extensionales en campo

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Abstract

The understanding of each geological-structural aspect in the field is fundamental to be able to reconstruct the geological history of a region and to give a geological meaning to the data acquired in the outcrop. The description of a brittle extensional environment, which is dominated by normal fault systems, is based on: (i) image interpretation, which aims to find evidence suggestive of an extensional geological environment, such as the presence of scarp lines and fault scarps, horst, graben and/or half-graben, among others, that allow the identification of the footwall and hanging wall blocks; ii) definition of the sites of interest for testing; and iii) analysis of the outcrops, following a systematic procedure that consists of the observation and identification of the deformation markers, their three-dimensional schematic representation, and their subsequent interpretation, including the stereographic representation in the outcrop. This procedure implies the unification of the parameters of structural data acquisition in the field, mentioning the minimum fields necessary for the registration of the data in tables. Additionally, the integration of geological and structural observations of the outcrop allows to understand the nature of the geological units, the deformation related to the extensional environment and the regional tectonic context of the study area.

Keywords: Normal fault, deformation, stress, extensional environment.

Resumen

El entendimiento de cada aspecto geológico-estructural en campo es fundamental para poder reconstruir la historia geológica de una región y dar un sentido geológico a los datos adquiridos en afloramiento. La descripción de un ambiente extensional frágil, el cual está dominado por sistemas de fallas normales, se basa en: i) la interpretación de imágenes, que tiene como objetivo encon-

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trar evidencias que sugieran un ambiente geológico extensional, como lo son la presencia de líneas de escarpe y escarpes de falla, pilares tectónicos y grábenes y/o semigrábenes, entre otros, que permitan la identificación de los bloques yacente y colgante; ii) definición de los sitios de interés para comprobación; y iii) análisis de los afloramientos, siguiendo un procedimiento sistemático que consiste en la observación e identificación de los marcadores de deformación, su representación esquemática tridimensional, y su posterior interpretación, incluyendo la representación estereográfica en el afloramiento. Este procedimiento implica la unificación de los parámetros de adquisición de datos estructurales en campo, mencionando los campos mínimos necesarios para el registro de los datos en tablas. Adicionalmente, la integración de las observaciones geológicas y estructurales del afloramiento permite entender la naturaleza de las unidades geológicas, la deformación relacionada con el ambiente extensional y el contexto tectónico regional del área de estudio.

Palabras clave: Falla normal, deformación, esfuerzo, ambiente extensional.

1. Introduction

The observations of geological structures in the field allow the understanding of the geological processes that occur in the earth's crust, product of the dynamics of tectonic plates through geological time (Frisch et al., 2011; Moores and Twiss, 2000). The integration of sedimentological, petrological, stratigraphic and structural studies of a region allows establishing the geological environment, which is related to the tectonic regime (extensional, contractional and transcurrent) operating at a given time. One of these environments is extensional, which is associated with different geological processes (Frisch et al., 2011) such as intracontinental rift systems (Corti, 2009; Dickinson, 2002), mid-oceanic ridge systems (Batiza, 1996), basins (Yoon et al., 2014) and passive continental margins (Trumpy, 1980, cited in Frisch et al., 2011), among others.

At the structural level, the style of deformation in an extensional environment is dominated by normal fault systems that together form graben and semigraben structures (Fossen, 2010; Groshong, 1999; McClay, 1987; Moores and Twiss, 2000, Ragan, 2009). Each fault within the normal fault system records a spatial and temporal evolution with respect to the geological units it affects (Cowie et al., 1998; Cowie et al., 2000; Hus et al., 2005; Tanner and Brandes, 2020; Walsh et al., 2002). These faults can be classified according to their geometry, displacement magnitude, temporality and depth (Fossen, 2010; Twiss and Moors, 2007), thus obtaining the fault activity history.

The understanding of each geological-structural aspect in the field is fundamental to be able to reconstruct the geological history of a region and to give a geological sense to the data acquired in the outcrop. This review is aimed at non-specialists, or professionals from other disciplines who are dealing, or are faced, with the management of faults in extended zones. The paper proposes a methodology for the recognition of extensional environments that integrates pre-field photogeological interpretation, the establishment of a systematic process for data acquisition and structural analysis with a stereographic projection grid. Additionally, some basic concepts for the description and understanding of the structures and the mechanisms that generate them are included, in order to provide greater clarity. Next, the definition of several previous concepts is presented:

» **Deformation.** Geological structures observed in the field are deformations that represent the structural configuration of the Earth's crust. Deformation is the transformation of an initial geometry to a final geometry through distortion, rotation and translation (Figure 1a) (Ragan, 2009; van der Pluijm and Marshak, 2004). However, the latter two components are difficult to determine in practice, with distortion being the most commonly used in structural analysis, which involves a change of shape (Fossen, 2010; Ragan, 2009; Tanner and Brandes, 2020; van der Pluijm and Marshak, 2004). In addition, continuous medium mechanics, which analyses the physical behavior of matter (e.g. rock) at the meso- and macroscopic scale, without considering discontinuities at the microscopic level, is used to study the deformation of a rock body (Pollard and Fletcher, 2005; Ragan, 2009; Ramsay and Lisle, 2000).

The deformation can be homogeneous or heterogeneous (Fossen, 2010; Ragan, 2009; Tanner and Brandes, 2020; van der Pluijm and Marshak, 2004). The former happens when a body that is subjected to deformation the lines that were parallel in the pre-deformation state stay parallel, or when a circumference in the pre-deformation

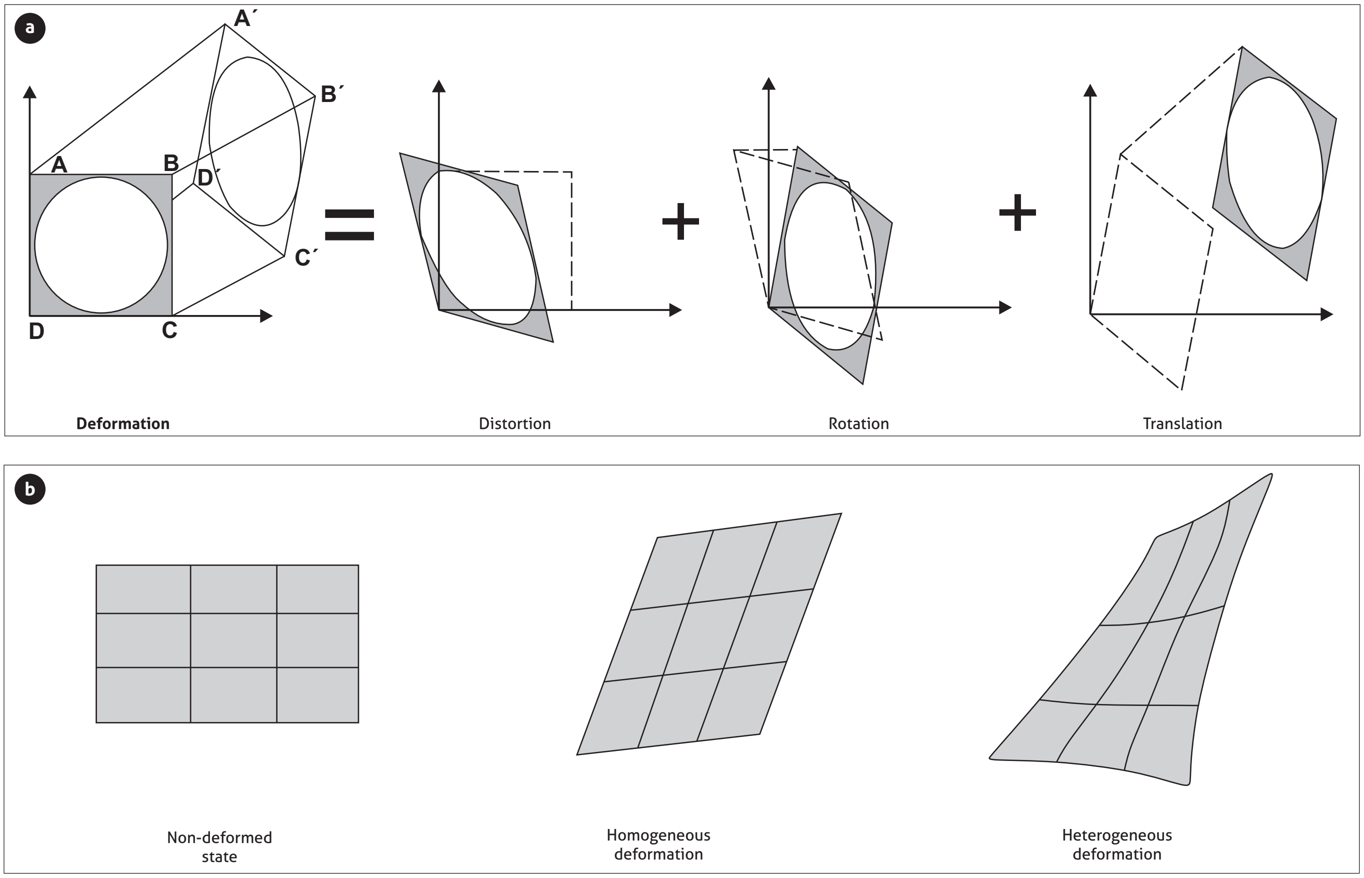

Figure 1. Deformation concepts
a) Deformation of a square as the result of three independent components: distortion, rotation and translation. b) Homogeneous and heterogeneous types of deformation. Source: modified from van der Pluijm and Marshak (2004).

state becomes an ellipse in the deformed state (Ragan, 2009; van der Pluijm and Marshak, 2004); if this does not occur, the result is heterogeneous deformation (Figure 1b). In the analysis of homogeneous deformation, material lines formed by a series of points on a body are taken as reference material lines that serve as deformation markers and are recognizable throughout the deformation process (van der Pluijm and Marshak, 2004).

For a two-dimensional body (e.g. a circle), when deformed homogeneously, there will be at least two material lines that do not rotate with respect to each other, thus forming the principal axes of the deformation ellipse (Figure 2a). Similarly, in three dimensions one has three material lines that remain perpendicular after deformation, which correspond to the principal axes of a deformation ellipsoid (Fossen, 2010; Ramsay and Huber, 1986; van der Pluijm and Marshak, 2004). Homogeneous deformation without volume change can be decomposed into pure shear and/or simple shear (Fossen, 2010; Ragan, 2009; Twiss and Moors, 2007; van der Pluijm and Marshak, 2004) (Figure 2b). Pure shear consists of coaxial or irrotational deformation where material lines parallel to the principal axes of deformation do not rotate and do not have no shear deformation, whereas simple shear consists of non-coaxial or rotational deformation where material lines rotate, passing through the principal axes of deformation; the only material lines that do not rotate are those parallel to the shear direction (Ragan, 2009; Twiss and Moors, 2007; van der Pluijm and Marshak, 2004).

» **Stress.** The structural analysis of a deformed rock body determines the possible stress field to which the body was subjected. The term stress is defined as the force (F) divided by the surface area (A) on which the force acts (Fossen, 2010; Means, 1976; Twiss and Moors, 2007). The mechanical behavior of a rock that is subjected to stress varies depending on its rheology and is conditioned by factors such as time, stress intensity, temperature and pressure (Means, 1976; Pollard and Fletcher, 2005; Ramsay and Huber, 1986).

» **Faults.** The generation of a fault in a homogeneous body responds to the Mohr-Coulomb fracture criterion ($|\tau| = C + \mu\sigma$ n), which postulates that a fault develops following the plane where the shear stress (τ) is equal to or greater than the body cohesion (C) plus the internal friction (μ) of the material multiplied by the normal stress (σn) (Means, 1976; Pollard and Fletcher, 2005). Generally speaking, a fault is a fracture over which relative motion occurs between two blocks that are separated by that fracture (Groshong, 1999; McClay, 1987; Ragan, 2009); that relative motion is called net slip and is represented geometrically by a vector connecting two originally adjacent points that are now on opposite sides of the fault (red dots in Figure 3) (Lisle and Walker, 2013; van der Pluijm and Marshak, 2004; Xu et al. 2009; Yamada and Sakaguchi, 1994). According to the components of the net slip vector, faults are classified according to whether the slip direction is parallel to the dip direction (normal fault or reverse fault) or to the strike direction (right lateral fault or left lateral fault), although it may happen that the slip is neither parallel to the dip direction nor to the strike direction (oblique faults, Figure 3) (Allmendinger, 2017; Groshong, 1999; van der Pluijm and Marshak, 2004).

The evolution of a normal fault begins with a nucleation point in the crust, followed by lateral growth (Burbank and Anderson, 2011; Gupta and Scholz, 2000; Peacock and Sanderson, 1991; Tanner and Brandes, 2020). There are two models of fault growth, the isolated propagation model (conventional model) and the constant-length coherent model (Cowie et al., 1998; Tanner and Brandes, 2020; Walsh et al., 2002). The conventional model states that faults nucleate randomly in space and their lateral growth occurs by systematic increases in both maximum displacement and fault length, or by the interaction of smaller faults fortuitously aligned to form a single transverse structure (Cowie et al., 1998). In turn, the coherent model proposes that in an early stage the fault lengths are constant and their kinematic components are inherited from an initial structure, and that, in the final stage, these faults interact to form a single continuous structure (Walsh et al., 2002).

The distribution of displacements on a fault ranges from zero at fault terminations to a maximum value at some point along the fault trace (Stewart, 2001). Muraoka and Kamata (1983) determined two patterns of normal fault profiles from displacement distribution plots (length [L] *vs.* displacement [D]), thus obtaining C-type faults, cone-shaped

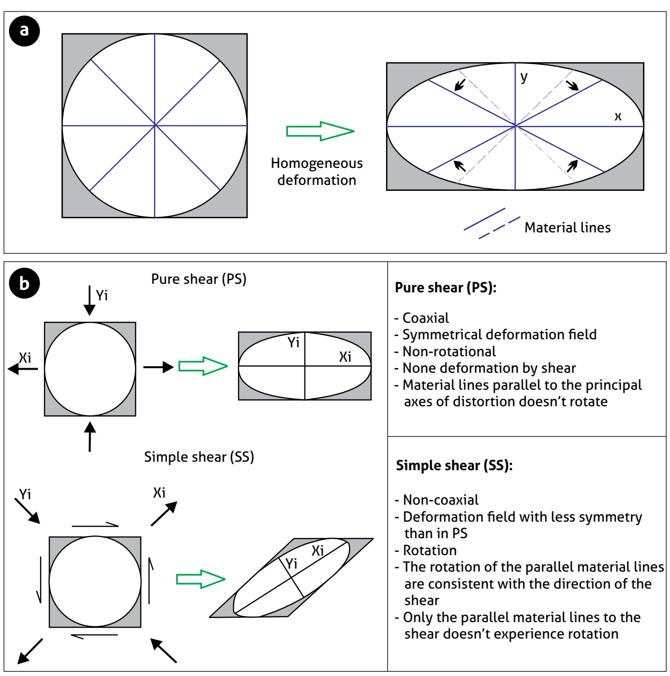

Figure 2. Homogeneous Deformation Concepts
a) Homogeneous deformation of a circle; b) Types of deformation by pure shear and simple shear. Source: modified from van der Pluijm and Marshak (2004).

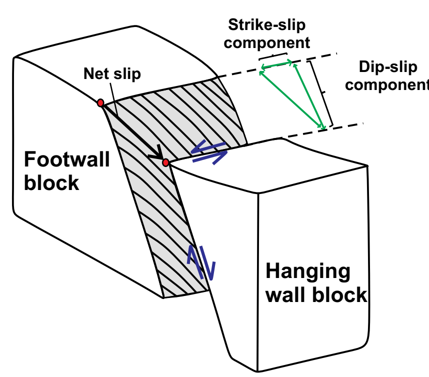

Figure 3. Schematic of a normal fault illustrating the net slip vector and its components in strike and dip
Source: modified from van der Pluijm and Marshak (2004).

and symmetric with smooth change in displacement, and M-type faults, table-shaped, with a profile that has a broad central part with little variation in displacement and steep slopes toward the ends of the structure. The distribution and displacement profiles show three types of faults, based on their evolution and growth: isolated faults, echelon fault array, with soft links forming relay ramps with other faults, and fault arrays with strong links (Xu et al., 2014).

In nature there are deformation zones that are generated at different depths, giving rise to brittle, brittle-ductile, and ductile shear zones (Fossen, 2010; Fossen and Cavalcante, 2017; Forero-Ortega et al., 2021; Mitra and Marshak, 1988; Sibson, 1977; Sibson, 1980). Brittle structures are generated in shallow structural levels, where the rock loses cohesion, generating the rupture of the rock; however, structures generated by ductile shear can be found originated in deeper structural levels, where the movement occurs without loss of cohesion (Jiang and White, 1995; Sibson, 1977; Sibson, 1980; Twiss and Moores, 2007). Those structural levels of deformation from brittle to ductile level present intrinsic characteristics depending on the temperature and pressure at which the deformation occurred (Forero-Ortega et al., 2021; Fossen and Cavalcante, 2017; Hatcher, 1995; Sibson, 1980).

2. Recognition of extensional environments in the field

The fieldwork is supported by the bibliographic review of the geological and geodynamic context of the area of interest, and of the sites planned from the interpretation of images. To recognize an extensional environment in the field, all observations of the outcrop that lead to a hypothesis about the nature of the geological units and the deformation being observed must be integrated. The observations will be focused on recognizing the formation environment of the rocks, the geometry of the structures and the temporal and spatial relationships of the stratigraphic units.

2.1. Image interpretation

Image interpretation aims to find evidence that suggests a particular geological environment, in this case, extensional. A normal fault corresponds to a fault in which the hanging wall block slides downward with respect to the footwall block, on a fault plane, driven by gravity (Anderson, 1951; van der Pluijm and Marshak, 2004). The normal faults that are generated in such an environment develop in the topography different geometries (Faulds and Varga, 1998) and types of structures (Figure 4), such as: fault scarps, grabens, half-graben, horst, and ba-

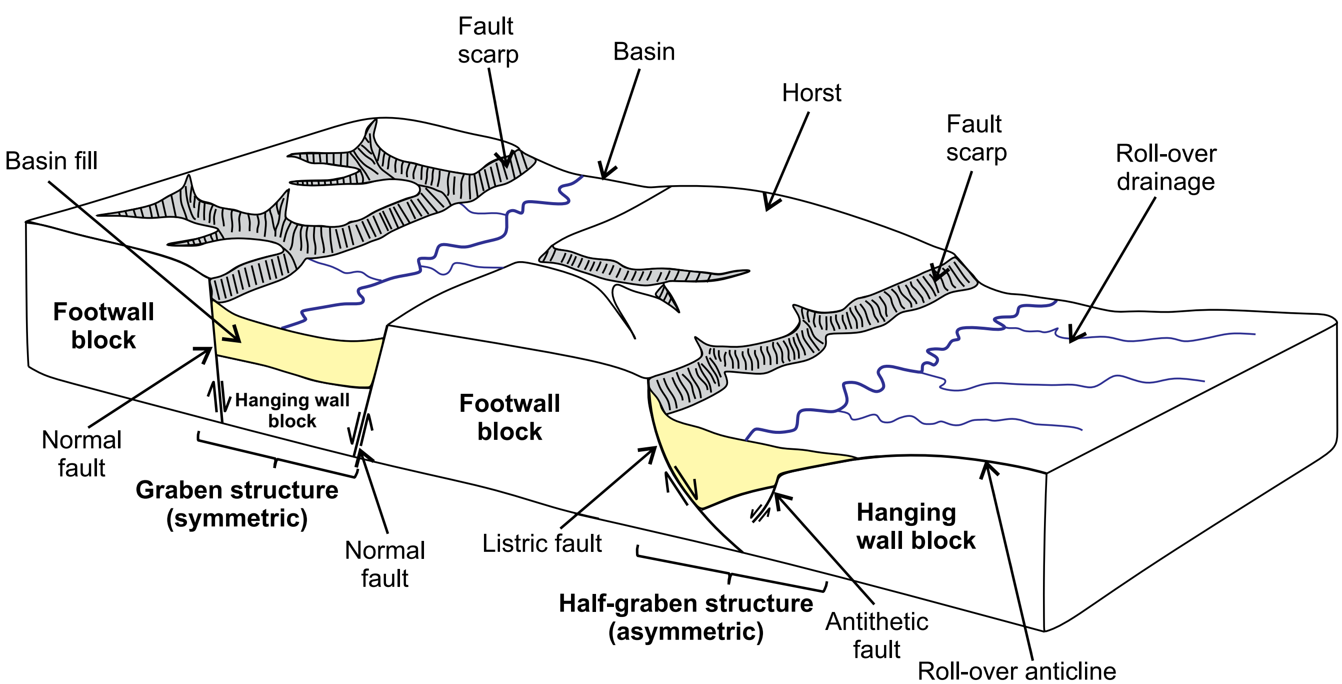

Figure 4. Block diagram showing some of the tectonic structures generated in extended zones
Source: modified from Huggett (2007).

sins, among others (Bull, 2008; Burbank and Anderson, 2011; Huggett, 2007; McCalpin, 2009; Peacock et al., 2000). Synthetic and antithetic normal faults can occur, which correspond to secondary faults that define their orientation and kinematics with respect to the main or master fault. A synthetic fault is parallel to the main fault and has the same shear direction, while an antithetic fault is a fault conjugate to the main fault, with an opposite shear direction (Twiss and Moors, 2007). A listric normal fault corresponds to a rotational fault that presents a curved surface, where the dip decreases with increasing depth (Fossen, 2010; Hartcher, 1995; Twiss and Moors, 2007), and a rotational fault with a domino arrangement occurs when rotation is simultaneous between faults and layers (Axen, 1988; Stewart and Argent, 2000; Xu et al., 2004). Other characteristic features are the development of roll-over anticlines and horst. A roll-over anticline develops on a hanging wall block of a rotational listric normal fault (Fossen, 2010; Groshong, 1999; Twiss and Moors, 2007). A horst corresponds to an uplifted tectonic block resulting from a normal fault (Fossen, 2010; Groshong, 1999; Hartcher, 1995; Huggett, 2007; Twiss and Moors, 2007).

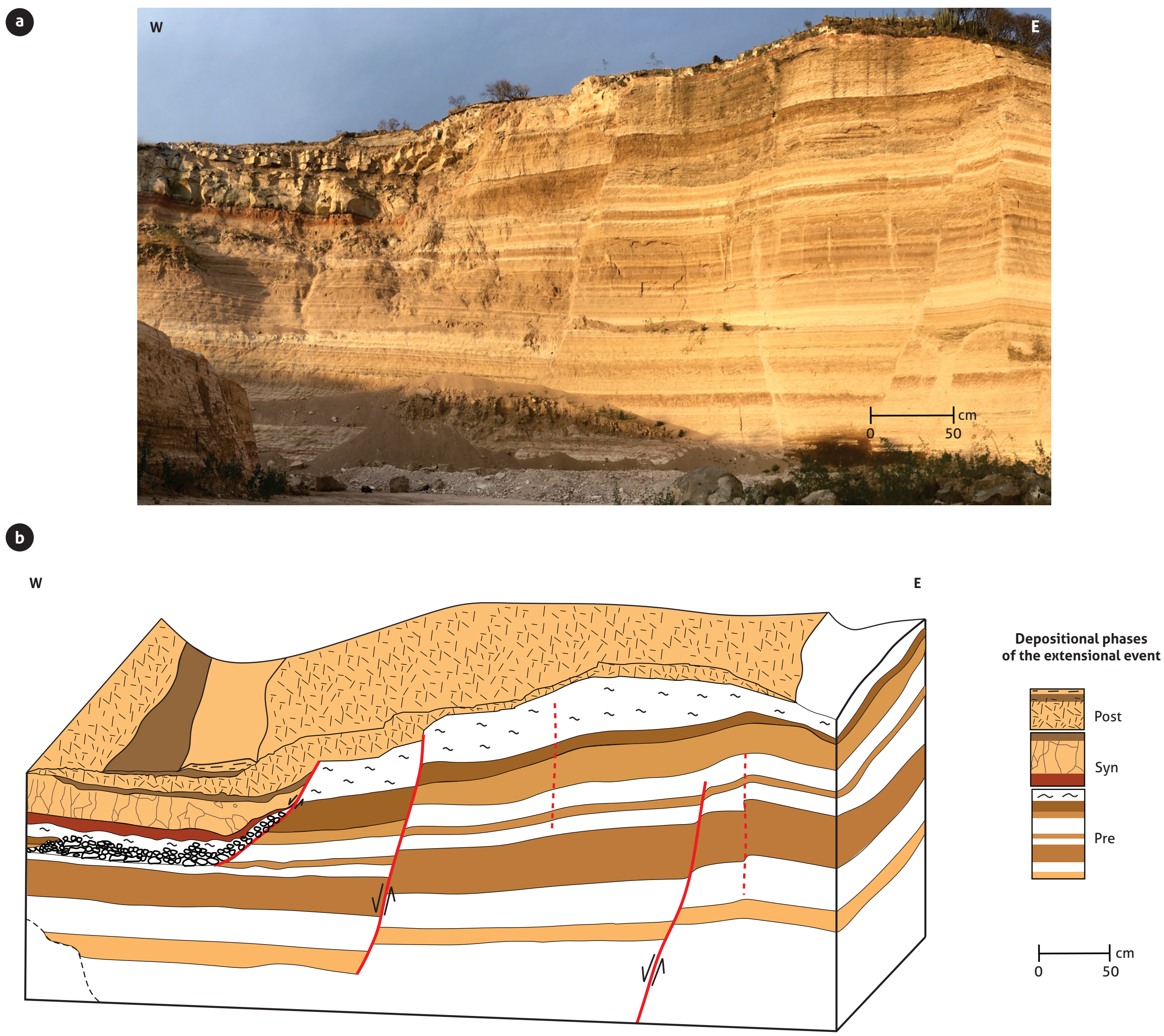

Figure 5. Three-dimensional schematic of an outcrop with evidence of faulting associated with an extensional environment
a) Outcrop of volcanic rocks affected by normal faults evidencing an extensional environment; b) Block diagram representing outcrop observations (geological structures and fault shear relationships). For the definition of the temporal evolution of the structure, the depositional phases are established in relation to the extensional event. Photograph taken in Querétaro, Mexico.

Scarps are features in the landscape characterized by steep slopes in the topography (Huggett, 2007). There are two types: fault scarps, which correspond to a linear break in slope that is generated as a result of fault movement, and fault line scarps, which correspond to a new form of relief resulting from erosion of the fault scarp (Twiss and Moors, 2007). Grabens are symmetrical extensional structures, which are bounded by two conjugate, non-rotational master faults (Twiss and Moors, 2007). Their morphological feature is evidenced by two horst, which represent the footwall blocks of the conjugate faults, which limit the hanging wall block, generating a basin where sediments accumulate. The half-graben correspond to asymmetric extensional structures, which are formed by a listric and rotational master fault (Twiss and Moors, 2007).

2.2. Field data acquisition

To study each site or outcrop in the field, it is proposed to apply the following systematic procedure for the acquisition of geological and structural data.

1. Observe the structural arrangement of the outcrop where deformation markers such as faults, folds or fractures are identified. In an extensional environment, normal faults predominate that are dip-slip type, where the hanging wall block has descended with respect to the footwall block, generating a displacement. These structures are characterized by stratigraphic truncation in their vertical section, putting younger rocks in contact with older rocks.
2. Make a three-dimensional schematic of the outcrop where the observed deformation markers are identified (Figure 5). The three-dimensional schematic in Figure 5 illustrates the different rock shear relationships and depositional phases with respect to the extensional deformational event (pre-extension, syn-extension and post-extension).
3. Describe the rock type being observed (Table 1) and establish the possible formation, emplacement and/or depositional environment of outcropping stratigraphic units (Hollocher, 2014; Jerram and Petford, 2011; Stow, 2005).
4. Description of the geological structures of the outcrop. To understand the spatial and temporal distribution of geological structures, it must be established whether those observed in the field correspond to primary or secondary structures (Hatcher, 1995; McClay, 1987; Mitra and Marshak, 1988). Primary structures form simultaneously with rock formation (e.g. stratification, sedimentary structures, lamination, dykes, melts or lava flows) and secondary structures are generated after lithification (e.g. folds, faults, foliation) (Hatcher, 1995; McClay, 1987; Mitra and Marshak, 1988).
5. Measurement of the geological structures of the outcrop. Geological structures observed at the mesoscopic scale will be measured first, then located in the three-dimensional scheme of the outcrop and written down in the structural data table (table 2). Subsequently, the detailed outcrop structures will always be measured, classifying their shear and temporal relationship between each one, from most to least old.

Table 2 presents the structural data recording scheme for measurements of geological structures or rock fabric elements (López-Isaza et al., 2021). Structural data can be recorded in different ways, according to the different types of notation that exist (azimuthal or quadrant direction, right hand rule or dip line direction), but it is recommended to the reader to adopt only one type of notation for the measurement and its

Table 1. Important aspects for the description of sedimentary, igneous or metamorphic rocks in the field

Type of rock	Description
Sedimentary rocks	Texture, mineralogical composition (%), granulometry, matrix, cementitious, shape and roundness, degree of lithification and classification. Thickness and shape of strata, layer recognition, alternation of lithologies, sedimentation rhythm, sequence polarity, fossiliferous content. Identification of primary and secondary structures.
Igneous rocks	Color index, degree of weathering, texture, mineralogical composition (%), habit and crystal size. Rock classification. Identification of primary and secondary structures.
Metamorphic rocks	Color index, structure (foliated or non-foliated), texture, mineralogical composition (%), index minerals, mineral size and classification. Identification of secondary structures.

Table 2. Data register scheme for geological structures or fabric elements

Plane		Lineation	
Structural data	Planar type[1]	Structural data	Lineation type
	Planar fabric elements (S)		
Dip → Dip Direction (*Dip →Dir*)[2]	S_0		Linear fabric elements (L)
	$S_1 – S_n$	Plunge → Azimuth Plunge[2]	Mineral line
Quadrants	$S_{n+1} – S_{n+n}$		Hinge line of folds
	Axial axis plane	Pitch or Rake and Pitching direction	Crenulation
Right Hand Rule	Veins		Intersection line
Strike Azimuth	Contacts		
	Joints (J)		

[1] Designation of the type of plan, i.e. S_n.- Foliation.
[2] Notation taken from McClay (1987). Source: modified from López-Isaza et al. (2021).

respective recording. In addition, different nomenclatures are indicated in the table, corresponding to: L for lineations, S for planar surfaces, and the subscripts that accompany this ($S_{0,}$ S_1 – $S_{n,}$ S_{n+1} – $S_{n+n)}$), which indicate the relative chronology of each structure - for a deeper understanding of the types of linear and planar structures the reader is suggested to review McClay (1987), Twiss and Moors (2007) and López-Isaza et al. (2021).

The recognition and description of a normal fault in an outcrop starts with the identification of structural discontinuities, lithological discontinuities and deformation zones that have associated fault rocks, either breccias, cataclasites, or mylonites, among others (Forero-Ortega et al., 2021). Then, the kinematics of the fault is established (Figure 6), with the help of stratigraphic markers, riedel structures or kinematic indicators (Doblas, 1998; Doblas et al., 1997; Petit, 1987; Sugden, 1987). When the kinematics of the fault have been determined, the structures will be measured in a systematic way (table 3), starting from one end of the deformed zone. In addition to this, it will be of great importance to establish the main plane of the structure (Y), in order to define the orientation of the fault trace on the geological map.

2.3. Structural analysis with stereographic network

The careful analysis of the structural data of faults will be one of the key tools to understand and reconstruct the deformation history observed in the field, for which it is necessary to perform a kinematic analysis (Marrett and Allmendinger, 1990) and, later, a dynamic analysis (Angelier, 1984; Angelier, 1990; Simpson, 1997). The kinematic analysis is based on the geometric analysis of the structures, where the orientation of the main axes of shortening and elongation is determined (Figure 7a). For this analysis, the orientation and inclination of the fault plane, the pole of the fault plane, the direction and inclination of the slickenline and the sense slip must be plotted in

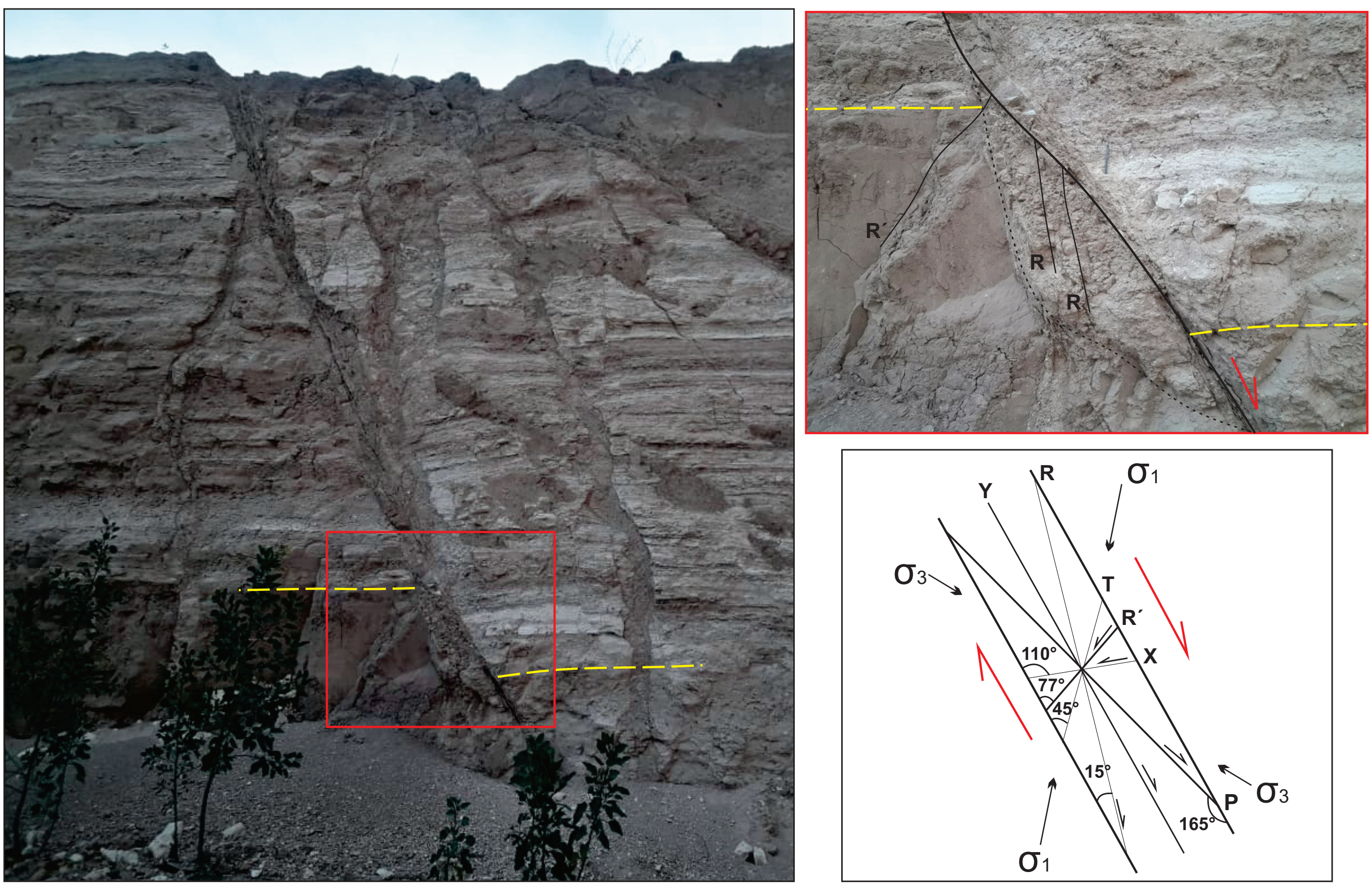

Figure 6. Outcrop of volcanic rocks affected by normal faulting
The red box is a zoom of the fault core where it is determined by stratigraphic markers (yellow lines), riedel structures (R and R') and kinematic indicators, that the kinematics of fault is normal. Photograph taken in Querétaro, Mexico.

the stereographic projection grid –for the projection of planes and lines in the stereographic network, the reader is suggested to review Ramsay and Huber (1983) and López-Isaza et al. (2021)–. The orientation of the main axes of elongation and shortening are found in the plane of motion, which contains the slip vector (slickenline) and the vector normal to the fault plane (pole), and forms 45° angles with each of the vectors (Figure 7a) (Marrett and Allmendinger, 1990).

In the dynamic analysis, the orientation of the principal stresses σ1, σ2 and σ3 is obtained, which would be adjusted to the deformation of the faults observed in the outcrop. Anderson (1951) proposed for conjugate and two-dimensional faults that: the orientation of the maximum principal stress axis (σ1) is determined by the vector bisecting the acute angle between the two conjugate faults, the orientation of the intermediate principal stress axis (σ2) is the intersection of the two fault planes and the orientation of the minimum principal stress axis (σ3) corresponds to the vector bisecting the obtuse angle between two conjugate faults (Figure 7b). In the case of normal faults, the principal orientation of the shortening axis is vertical and corresponds to the orientation of the maximum principal stress axis (σ1), and the orientation of the elongation axis corresponds to the orientation of the minimum principal stress axis (σ3).

3. Conclusions

The recognition of any geological environment in the field is based on image interpretation, direct observation of the outcrop, establishment of the rock-forming environment, and careful and systematic recording of the structural data revealed

Table 3. Data register scheme for geological faults measured in the field

Plane (fault)	Line (slickenline)	Block	Planar type	Kinematics	Certainty	Remarks
Direction and inclination	Direction and inclination	Footwall Block (BF) Hanging wall block (BH)	Plane or fault Shear type Riedel (R, R', P, T, X) Main plane (Y)	Right lateral (RL) Left lateral (LL) Normal (N) Thrust (T) Oblique (O)	Low (kinematic: supposed) Medium (kinematic: possible or probable) High (kinematic: true)	Kinematic indicators

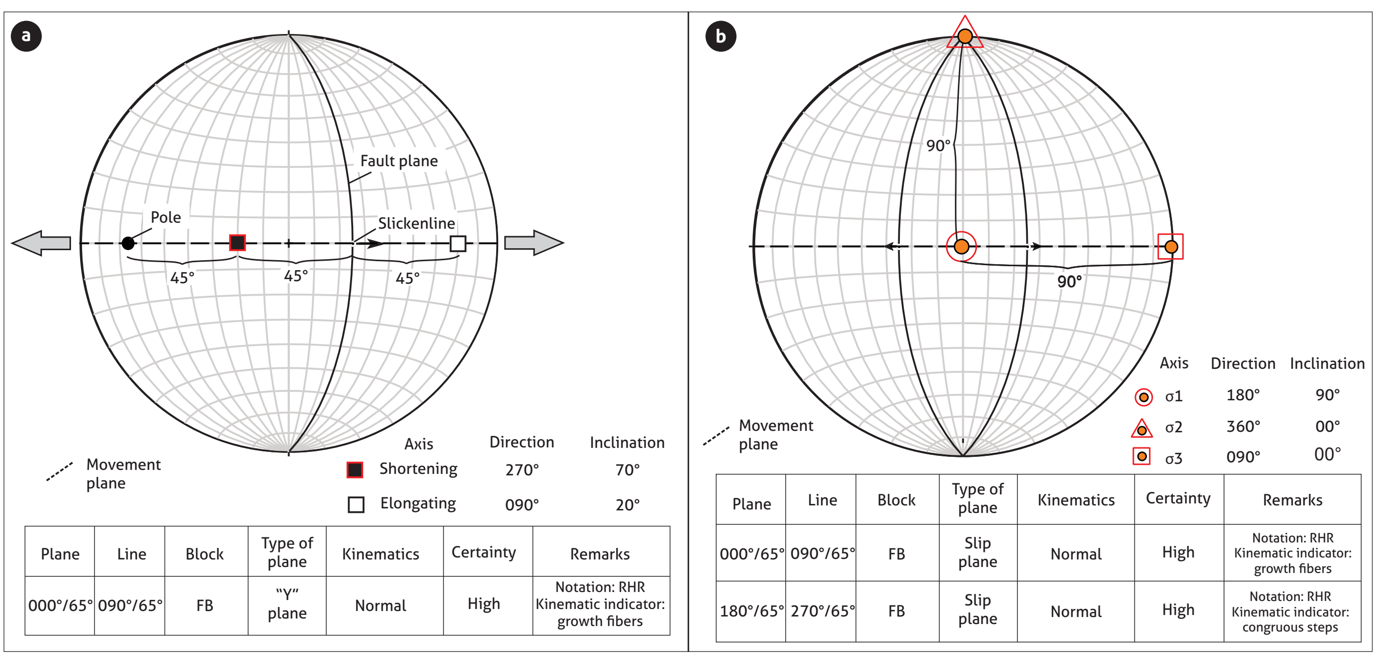

Figure 7. Structural analysis with stereographic network
a) Kinematic analysis of a fault, where the principal orientations of the shortening and elongation axes are determined. The gray arrows indicate the main elongation direction; b) Dynamic analysis for two conjugate faults, where the orientation of the principal stresses is defined. The data were plotted on the Schmidt stereographic projection grid, lower hemisphere. BF: footwall block, RHR: right hand rule.

by each outcrop. The determination of a regional-scale extensional environment associated with a given geological process (intracontinental rift systems, mid-oceanic ridge systems, basins, passive continental margins, etc.) requires bringing together all the geological evidence (morphological features associated with normal faulting, stratigraphic relationships, structural style and unconformities) collected in different outcrops, which implies the understanding of the spatial and temporal distribution of geological units and the hierarchization of deformation structures present in the study area. In addition, the integration of different tools from other branches of geology, such as geochronology, geochemistry and geophysics, is necessary. The results obtained with each tool should be consistent with the stratigraphic and structural relationships observed in the field.

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References

Allmendinger, R.W. (2017). *Modern Structural Practice. A structural geology laboratory manual for the 21st Century*. V.1.7.0. http://www.geo.cornell.edu/geology/faculty/RWA/structure-lab-manual/

Anderson, E. M. (1951). *The dynamics of faulting and dike formation with application to Britain*. Oliver and Boyd.

Angelier, J. (1984). Tectonic analysis of fault slip data sets. *Journal of Geophysical Research: Solid Earth*, *89*(B7), 5835-5848. https://doi.org/10.1029/JB089iB07p05835

Angelier, J. (1990). Inversion of field data in fault tectonics to obtain the regional stress-III. A new rapid direct inversion method by analytical means. *Geophysical Journal International*, *103*(2), 363-373. https://doi.org/10.1111/j.1365-246X.1990.tb01777.x

Axen, G. (1988). The geometry of planar domino-style normal faults above a dipping basal detachment. *Journal of Structural Geology*, *10*(4), 405-411. https://doi.org/10.1016/0191-8141(88)90018-1

Batiza, R. (1996). Magmatic segmentation of mid-ocean ridges: a review. In C. J. MacLeod, P. A. Tyler, & C. L. Walker (eds.), *Tectonic, Magmatic, Hydrothermal and Biological Segmentation of Mid-Ocean Ridges* (pp. 103-130). Special Publications 118. Geological Society.

Bull, W. B. (2008). *Tectonic geomorphology of mountains: a new approach to paleoseismology*. John Wiley & Sons.

Burbank, D. W., & Anderson, R. S. (2011). *Tectonic geomorphology*. John Wiley & Sons.

Corti, G. (2009). Continental rift evolution: from rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. *Earth-Science Reviews*, *96*(1-2), 1-53. https://doi.org/10.1016/j.earscirev.2009.06.005

Cowie, P. A. (1998). A healing-reloading feedback control on the growth rate of seismogenic faults. *Journal of Structural Geology*, *20*(8), 1075-1087. https://doi.org/10.1016/S0191-8141(98)00034-0

Cowie, P. A., Gupta, S., & Dawers, N. H. (2000). Implications of fault array evolution for synrift depocentre development: insights from a numerical fault growth model. *Basin Research*, *12*(3-4), 241-261. https://doi.org/10.1111/j.1365-2117.2000.00126.x

Dickinson, W. R. (2002). The Basin and Range Province as a composite extensional domain. *International Geology Review*, *44*(1), 1-38. https://doi.org/10.2747/0020-6814.44.1.1

Doblas, M. (1998). Slickenside kinematic indicators. *Tectonophysics*, *295*(1-2), 187-197. https://doi.org/10.1016/S0040-1951(98)00120-6

Doblas, M., Mahecha, V., Hoyos, M., & López-Ruiz, J. (1997). Slickenside and fault surface kinematic indicators on active normal faults of the Alpine Betic cordilleras, Granada, southern Spain. *Journal of Structural Geology*, *19*(2), 159-170. https://doi.org/10.1016/S0191-8141(96)00086-7

Faulds, J. E., & Varga, R. J. (1998). The role of accommodation zones and transfer zones in the regional segmentation of extended terranes. *Geological Society of America, Special Papers*, *323*, 1-45. https://doi.org/10.1130/SPE323

Forero-Ortega, A. J., López-Isaza, J. A., López Herrera, N. R., Cuéllar-Cárdenas, M. A., Cetina Tarazona, L. M., & Aguirre Hoyos, L. M. (2021). Geological-structural mapping and geochronology of shear zones: A methodological proposal. *Boletín Geológico*, *48*(1), 81-122. https://doi.org/10.32685/0120-1425/bol.geol.48.1.2021.524

Fossen, H. (2010). *Structural geology*. Cambridge University Press.

Fossen, H., & Cavalcante, G. C. G. (2017). Shear zones - A review. *Earth-Science Reviews, 171*, 434-455. https://doi.org/10.1016/j.earscirev.2017.05.002

Frisch, W., Meschede, M., & Blakey, R. (2011). *Plate Tectonics: Continental drift and mountain building*. Springer.

Groshong Jr, R. H. (1999). *3D structural geology: a practical guide to surface and subsurface map interpretation*. Springer.

Gupta, A., & Scholz, C. H. (2000). A model of normal fault interaction based on observations and theory. *Journal of Structural Geology*, 22, 865-879. https://doi.org/10.1016/S0191-8141(00)00011-0

Hatcher Jr. R. D. (1995). *Structural geology*. *Principle, concepts and problems*. Prentice Hall.

Hollocher, K. (2014). *A pictorial guide to metamorphic rocks in the field*. CRC Press.

Huggett, R. (2007). *Fundamentals of geomorphology*. Routledge.

Hus, R., Acocella, V., Funiciello, R., & De Batist, M. (2005). Sandbox models of relay ramp structure and evolution. *Journal of Structural Geology*, *27*(3), 459-473. https://doi.org/10.1016/j.jsg.2004.09.004

Jerram, D., & Petford, N. (2011). *The field description of igneous rocks*. John Wiley & Sons.

Jiang, D., & White, J. C. (1995). Kinematic of rock flow and the interpretation of geological structures, with particular reference to shear zones. *Journal of Structural Geology*, *17*(9), 1249-1265. https://doi.org/10.1016/0191-8141(95)00026-A

Lisle, R. J., & Walker, R. J. (2013). The estimation of fault slip from map data: The separation-pitch diagram. *Tectonophysics*, *583*, 158-163. https://doi.org/10.1016/j.tecto.2012.10.034

López Isaza, J. A., Cuéllar Cárdenas, M. A., Cetina Tarazona, L. M., Forero Ortega, A. J., Suárez Arias, A. M., Muñoz Rodríguez, O. F., Aguirre Hoyos, L. M., & Gutiérrez López, M. J. (2021). Graphical representation of structural data in the field: A methodological proposal for its application in deformed areas. *Boletín Geológico*, *48*(1), 123-139. https://doi.org/10.32685/0120-1425/bol.geol.48.1.2021.504

Marrett, R., & Allmendinger, R. W. (1990). Kinematic analysis of fault-slip data. *Journal of Structural Geology, 12*(8), 973-986. https://doi.org/10.1016/0191-8141(90)90093-E

McCalpin, J. P. (2009). *Paleoseismology*. Academic Press.

McClay, K. R. (1987). *The mapping of geological structures*. John Wiley & Sons.

Means, W. D. (1976). *Stress and Strain. Basic concepts of continuum mechanics for geologists*. Springer-Verlag.

Mitra, G., & Marshak, S. (1988). *Basic methods of structural geology*. Prentice Hall.

Moores, E., & Twiss, R. (2000). *Tectonics*. W. H. Freeman and Company.

Muraoka, H., & Kamata, H. (1983). Displacement distribution along minor fault traces. *Journal of Structural Geology*, *5*(5), 483-495. https://doi.org/10.1016/0191-8141(83)90054-8

Peacock, D. C., Knipe, R. J., & Sanderson, D. J. (2000). Glossary of normal faults. *Journal of Structural Geology*, *22*(3), 291-305. https://doi.org/10.1016/S0191-8141(00)80102-9

Peacock, D. C. P., & Sanderson, D. J. (1991). Displacements, segment linkage and relay ramps in normal fault zones. *Journal of Structural Geology*, *13*(6), 721-733. https://doi.org/10.1016/0191-8141(91)90054-M

Petit, J. P. (1987). Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of Structural Geology*, *9*(5-6), 597-608. https://doi.org/10.1016/0191-8141(87)90145-3

Pollard, D., & Fletcher, R. C. (2005). *Fundamentals of structural geology*. Cambridge University Press.

Ragan, D. M. (2009). *Structural geology. An introduction to geometrical techniques*. Cambridge University Press.

Ramsay, J. G., & Huber M. I. (1983). *The techniques of modern structural geology. Volume 1: Strain Analysis*. Academic Press.

Ramsay, J. G., & Huber M. I. (1986). *The techniques of modern structural geology. Volume 2: Folds and Fractures*. Academic Press.

Ramsay, J. G., & Lisle, R. J. (2000). *The techniques of modern structural geology. Volume 3: Applications of continuum mechanics in structural geology*. Academic Press.

Sibson, R. H. (1977). Fault rocks and fault mechanisms. *Journal of the Geological Society*, 133, 191-213.

Sibson, R. H. (1980). Transient discontinuities in ductile shear zones. *Journal of Structural Geology*, *2*(1-2), 165-171.

Simpson, R. W. (1997). Quantifying Anderson's fault types. *Journal of Geophysical Research: Solid Earth*, *102*(B8), 17909-17919.

Stewart, S. A. (2001). Displacement distributions on extensional faults: Implications for fault stretch, linkage, and seal. *AAPG Bulletin*, *85*(4), 587-599. https://doi.org/10.1306/8626C951-173B-11D7-8645000102C1865D

Stewart, S. A., & Argent, J. D. (2000). Relationship between polarity between extensional fault arrays and presence of detachments. *Journal of Structural Geology*, *22*(6), 693-711. https://doi.org/10.1016/S0191-8141(00)00004-3

Stow, D. A. (2005). *Sedimentary Rocks in the Field: A color guide*. Gulf Professional Publishing.

Sugden, T. (1987). Kinematic indicators: structures that record the sense of movement in mountain chains. *Geology Today*, *3*(3-4), 93-99. https://doi.org/10.1111/j.1365-2451.1987.tb00496.x

Tanner, D., & Brandes, C. (2020). *Understanding Faults: Detecting, Dating, and Modeling*. Elsevier. https://doi.org/10.1016/C2017-0-03320-7

Twiss, R. J., & Moores, E. M. (2007). *Structural geology*. W. H. Freeman and Company.

Van der Pluijm, B. A., & Marshak, S. (2004). *Earth Structure. An introduction to structural geology and Tectonics*. W. W. Norton & Company.

Walsh, J. J., Nicol, A., & Childs, C. (2002). An alternative model for the growth of faults. *Journal of Structural Geology*, *24*(11), 1669-1675. https://doi.org/10.1016/S0191-8141(01)00165-1

Xu, S., Nieto-Samaniego, A. F., & Alaniz-Álvarez, S. A. (2004). Tilting mechanism in domino faults of the Sierra de San Miguelito, Central Mexico. *Geologica Acta*, 3, 189-201. https://doi.org/10.1344/105.000001426

Xu, S., Nieto-Samaniego, A. F., & Alaniz-Álvarez, S. A. (2009). Quantification of true displacement using apparent displacement along an arbitrary line on a fault plane. *Tectonophysics*, *467*(1-4), 107-118. https://doi.org/10.1016/j.tecto.2008.12.004

Xu, S. S., Nieto-Samaniego, A. F., & Alaniz-Álvarez, S. A. (2014). Estimation of average to maximum displacement ratio by using fault displacement-distance profiles. *Tectonophysics*, *636*, 190-200. https://doi.org/10.1016/j.tecto.2014.08.023

Yamada E., & Sakaguchi, K. (1994). Fault-slip calculation from separations. *Journal of Structural Geology*, *17*(7), 1065-1070. https://doi.org/10.1016/0191-8141(95)00003-V

Yoon, S. H., Sohn, Y. K., & Chough, S. K. (2014). Tectonic, sedimentary, and volcanic evolution of a back-arc basin in the East Sea (Sea of Japan). *Marine Geology*, *352*, 70-88. https://doi.org/10.1016/j.margeo.2014.03.004