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The strainscope: an optical device for field measurement of homogeneous finite strain

J. SIMON,* M. S. JAPAS† and A. J. AMOS†

* Departamento de Física and † Departamento de Ciencias Geológicas, Universidad de Buenos Aires, Argentina

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Abstract—The strainscope is based on a simple optical system of coupled astigmatic lenses producing simultaneous 'shortening' and 'stretching' in orthogonal directions within the plane of the lenses. The technique is applicable to objects of known original shape, and can be used for determining original shape when finite strain is known. It is a handy tool, easy to manipulate, of very simple construction and can be used for educational purposes.

INTRODUCTION

DEFORMED objects found in rocks serve as excellent indicators of homogeneous finite strain. Several analytical and geometrical techniques have been applied to quantify strain parameters (Ramsay & Huber 1983) giving highly reliable results. Most of these techniques are performed in the laboratory, thus immediate checking and comparison of results in the field is precluded. A simple and inexpensive device is described here which can be readily used in the field for determining strain ratios from known original shapes. It consists of coupled astigmatic lenses that individually produce 'shortening' and 'stretching' in orthogonal directions within the plane of the lenses (Fig. 1a). The system allows very reliable estimates of strain values when the undeformed geometry of the strained objects is known. The technique differs from Gräf's (1958) thin metallic laminae of variable curvature as it uses astigmatic lenses of small size (Simon *et al.* 1985).

OPTICAL PRINCIPLES

The instrument uses the property of each astigmatic lens, $(-x/2; +x)$ in ophthalmic notation, to produce an affine transformation of the image. The $(-x/2)$ term produces shortening normal to the lens axis while the $(+x)$ term causes a stretching parallel to the axis of the lens due to an increase of the image in that direction (Fig. 1a). The lens characteristic is given by the (x) value (see Davey 1963), as (x) increases greater deformation occurs. When the cylindrical term $(-x/2)$ is half the spherical one $(+x)$, the image viewed through the lens will not show a substantial area change (as long as strain values are low). In this way a circle observed through the lens will be an ellipse of nearly equal area (Fig. 1a).

The eccentricity of the image can be controlled by coupling together several astigmatic lenses. For example, two lenses with their axes parallel to each other will give a more eccentric resultant ellipse. The degree of ellipticity varies with the number of lenses, the angle between lens axes, and the distance between the optical device and the original circle.

In the case of two lenses, the system allows the determination of a maximum value of strain, equivalent to the optical addition of the two lenses with their axes parallel, to a minimum value, equivalent to zero strain when two lenses have their axes normal to each other. All intermediate values depend on δ (half the angle between the lens axes) while the selection of dioptries of a binary system of lenses determines its range.

Adjusting mechanism

When n lenses do not give the necessary shortening and $n + 1$ lenses exceed the required eccentricity (Fig. 1b) it will be necessary to couple an adjusting device to the n lens system (Simon *et al.* 1985), either with:

(I) an astigmatic lens (Fig. 1bi). This lens must be rotated between 0 and 90° from the principal lens axis to an angular value in which the ellipse coincides with the one desired. When rotating the axial direction of the adjusting lens in relation to the fixed lenses, a rotation of the axis of the ellipse takes place with respect to that of the lenses (Fig. 1bi) that varies with the angle of rotation. Therefore it will be convenient to follow the next step;

(II) an adjusting device of two astigmatic lenses (Fig. 1bii). In this case the two lenses serve as an adjusting mechanism of the axial ratio of the desired ellipse. They must be rotated between 0 and 90°, symmetrically with relation to the axis of the main n lens system and in a reverse sense (Fig. 1bii). Applying this double rotation, the axis of the ellipse will always coincide with the axis of the lens system and the desired ellipticity will vary between the equivalent $n + 2$ lenses (auxiliary lenses parallel to the main n lenses) and $n - 2$ lenses (axis of the auxiliary lenses 90° with respect to the axial direction of the main lenses system). In this case the optical axis (OA) coincides with the axis of n lenses (AN in Fig. 1b).

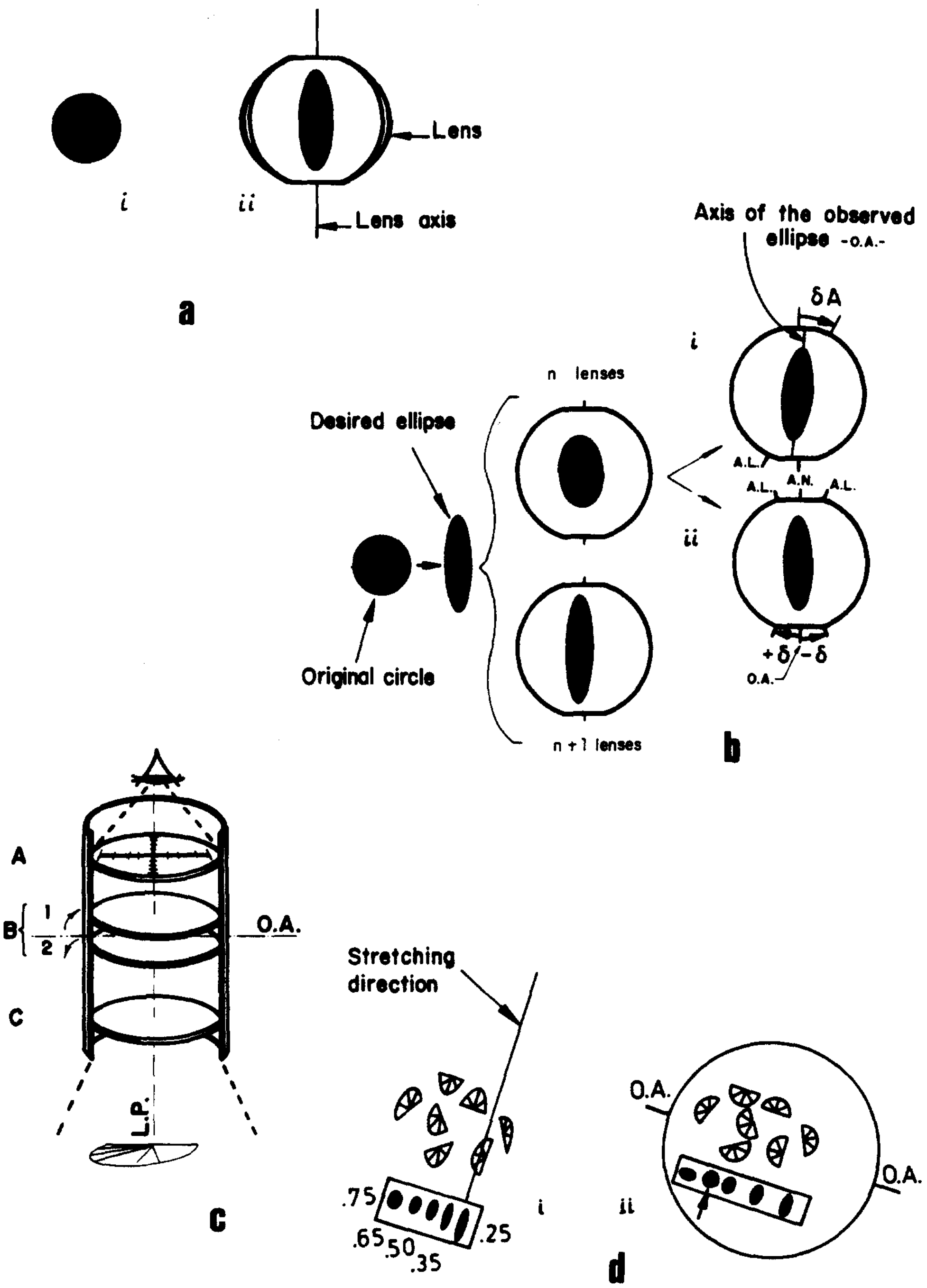

Fig. 1. (a) Image of a circle through an astigmatic lens. (b) Adjusting mechanism to obtain the desired ellipse: OA: optical axis; AL: adjusting lens axis; AN: axis of *n* lenses system; (i) procedure I, (ii) procedure II. (c) Simplified diagram of the proposed instrument: A: accessory upper plate; B: pair of astigmatic lenses; C: divergent basal lens; LP: light path. (d) Sketch showing the use of the plastic model. (i) Strained state with model on measured surface. (ii) Restored state. Strain ratio, 0.65.

The quality of the image obtained through the lenses deteriorates when more lenses are incorporated into the system, therefore a unique pair of astigmatic lenses of high dioptry (-1.5; $+3.0$) is used in the apparatus. These serve as the principal system of lenses and as the adjustment device (II). Systems of high dioptries allow measurement of more highly deformed objects, but the sensitivity of the instrument is reduced since large changes in ellipticity can be produced with small variations of δ. On the other hand lenses of low dioptries have an increased sensitivity but reduced restoration power for larger strains.

THE STRAINSCOPE

The apparatus presented here is a simple pocket instrument for precise and rapid strain field measurements (Figs. 1c and 2). The optical system consists of two astigmatic lenses of the same power (B in Fig. 1c) and a divergent lens (C in Fig. 1c). A plate with a scale (A in Fig. 1c) acts as an accessory. The astigmatic lenses recommended for viewing plane surfaces at a distance of about 80 cm have dioptries of (-1.5; $+3.0$). With this system, strain ratios of the order 0.30 can be measured depending on the distance between the strainscope and

Fig. 2. The strainscope.

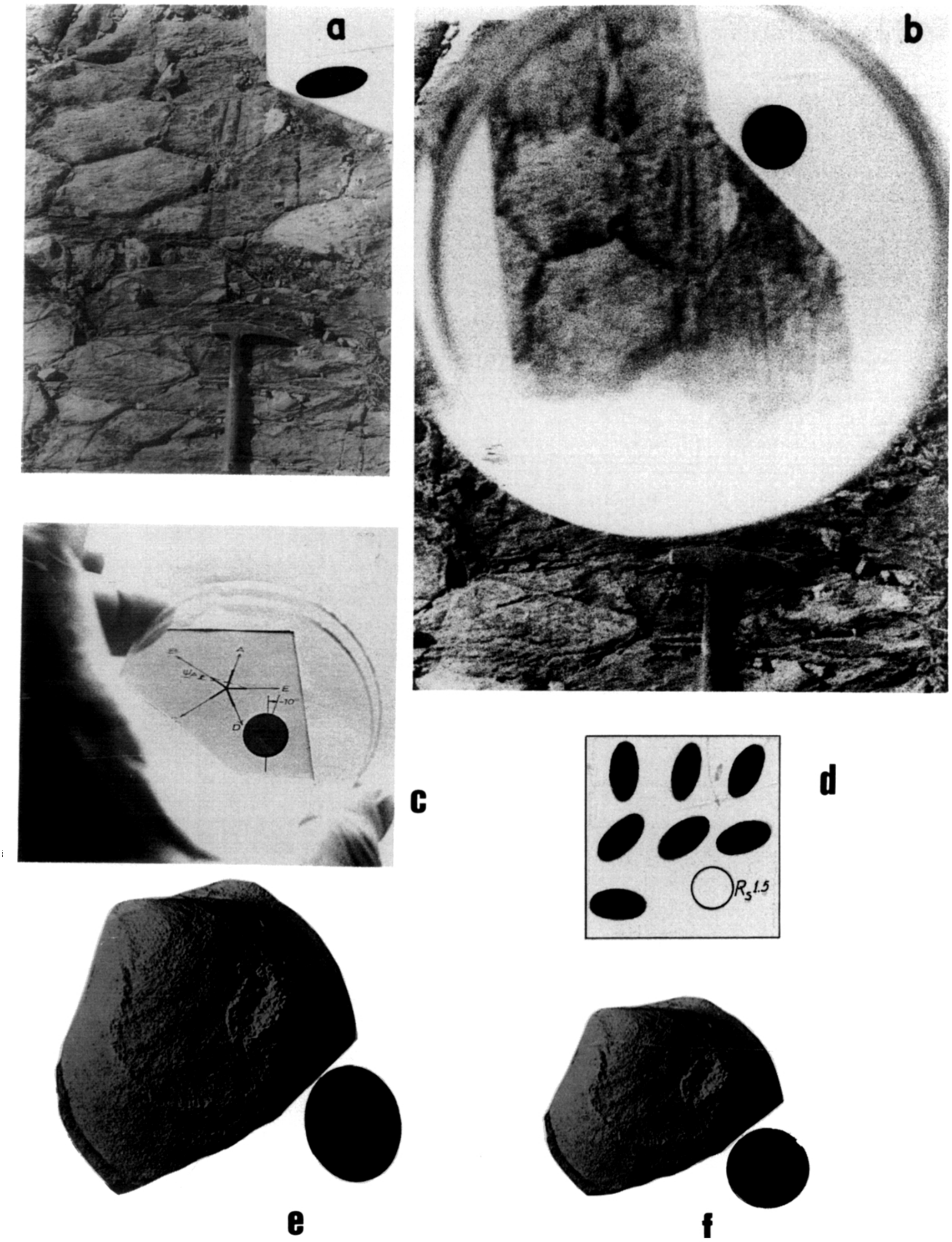

Fig. 3. Examples of application of the strainscope. Columnar jointing; (a) strained state, (b) restored. (c) Restoration of a fossil of pentagonal symmetry (for the strained state see Ramsay & Huber 1983, p. 135). (d) Restoration of initially elliptical strain markers (for the strained state see Ramsay & Huber 1983, p. 75). Restored *Eurydesma* (pelecypod); (e) deformed, (f) restored.

observation point (80 cm in this case) and on the distance between the strainscope and eye of the observer (~60 cm). To assess the strain ratio value with precision one is recommended to place the accessory plate with a graduated scale (A in Fig. 1c) or a plastic model of ellipses with variable eccentricities on top of the specimen surface, as will be explained later.

If the value necessary to restore the original shape of the object is smaller than that obtained with the two lenses 'in parallel' a symmetrical rotation should be performed—both lenses in opposite sense (see Fig. 1bii)—until the required value is obtained (see above).

If the value necessary to restore the original form is larger than that produced by the two lenses 'in parallel', a third astigmatic lens with identical characteristics (−1.5; +3.0) should be added in order to increase the restoring power of the system. This lens should be mounted in the same way as the other ones (between A and B or B and C, see Fig. 1c) with the axis parallel to the optical axis of the apparatus. In practice the maximum strain restorable using lenses (−1.5; +3.0) should be adequate for many situations. A pair of lenses (−2.0; +4.0) will increase the restoration power (strain ratio 0.20), but boundaries undergoing visual elongation will start to blur.

The observation field can be enlarged with a 'basal' divergent lens placed between the object and the system (C in Fig. 1c). Higher dioptries for divergent lenses in general produces distortion of the image, so that a divergent lens (−2.0) can be more appropriate.

Due to the optical system, the distance between the astigmatic-divergent lenses and the distance from divergent lens to object govern the restoration power. For example, with a distance of 80 cm from the system to the object and 60 cm between the system and the observer, an approximate area of 16 × 16 cm can be measured; when the distance is increased to 160 cm the area increases to 63 × 63 cm for a 20 cm distance between the system and the observer.

Also the restoration power can be modified by changing the relative position of the lenses. The maximum restoring power is reached when lenses are equidistant from object and observer.

The upper plate (A in Fig. 1c) does not introduce additional distortion and it functions as a support for a pair of graduated orthogonal scales one of them being parallel to the optical axis of the apparatus and therefore parallel to one of the principal strain axes. Instead of the accesssory upper plate a drawing of model ellipses of various known ellipticities can be placed on the surface to be measured (see Procedure).

Additionally the strainscope framework can carry an angular graduated scale on its border such that 0° coincides with the normal to the optical axis of the apparatus and the elongation can be measured with reference to some known lineation on the exposure surface.

The apparatus can be inexpensively built and easily handled in the field. Standard 60 mm diameter commercial ophthalmic lenses can be used. Specially designed lenses can enlarge the range of application of the technique but may become heavy, large and fragile. For large observation surfaces special larger diameter lenses can be used in the laboratory, compiling tables showing strain ratios for different values of δ and 'lens-object' and 'lens-observer' distances. On the other hand the instrument is very handy as a teaching aid.

STRAINSCOPE DETERMINATIONS OF HOMOGENEOUS FINITE STRAIN

Theoretical principles

The principle is based on the concept of strain reciprocity (see Ramsay 1967). The technique consists of restoring the original shapes of geological objects of known geometry using the system of lenses described above. Once the strained object has been 'unstrained' with the strainscope a circle is placed in the plane of the object. The shape observed through the lenses is the reciprocal strain ellipse, whose axial ratio is equivalent to that of the finite strain ellipse. The axial ratio of the finite strain ellipse can be obtained together with its orientation, which is normal to that of the reciprocal strain ellipse in case of the pure shear component. The accessory scales of the strainscope serve to measure the major and minor axes of the reciprocal strain ellipse.

Procedure

The following steps are suggested:

(1) check that strain experienced by the deformed objects does not exceed the maximum range of the apparatus (lenses placed 'in parallel'). If greater, an auxiliary astigmatic lens should be introduced;

(2) turn the adjustment mechanism until the objects are restored to their original form. It is convenient to find approximately the elongation direction of the objects and orient the optical axis of the apparatus normal to it;

(3) draw a circle in the plane of the deformed objects from which the axial ratio of the reciprocal strain ellipse can be measured.

Otherwise a plastic model with different ellipses of varying ellipticity (e.g. a series of 0.05 interval between them) can be placed on the specimen surface. For a given restoration only one of these ellipses will be transformed into a circle; therefore the axial relationship of this particular ellipse on the model will indicate the strain ratio sought. The orientation and finite strain will automatically be defined (Fig. 1d). This procedure eliminates the accessory upper plate.

Examples

A few examples will illustrate the use of strainscope:

(1) regular to subregular structures such as mudcracks, columnar jointing, (Fig. 3a), coralline structures such as *Favosites* (Table 1), etc.;

(2) fossils of known original shape, such as pentago-

nal symmetry: *Pentacrinus* (see Table 1 and Fig. 3c); brachiopods and ammonites (with constant spiral angle);

(3) objects of equal initial ellipticity but different orientations: pebbles of identical initial shapes; elliptical tubes initially normal to stratification (Fig. 3d).

Comparative tests have been carried out with alternative graphical methods and the results obtained prove to be equivalent. For example in Table 1 some comparative measurements using other methods are shown.

Table 1

Sample	Method/ratio	Strainscope ratio
Favosites	Ramsay & Huber (p. 135): 0.51	0.51
Pentacrinus	Ramsay & Huber (p. 135): 0.58	0.59
Brachiopods	Ramsay & Huber (p. 143): 0.28	0.29
Ammonoids	Shear box: 0.58	0.60
Elliptical objects	Shear box: 0.40	0.39

Japas *et al.* (1985) have shown the appplication of this method to columnar jointing arriving at values similar to those obtained with other graphical methods (Sellés Martínez 1986) (Fig. 3a).

Advantages and disadvantages

The advantages are:

(1) easy and fast to manipulate. Visually rapid and rather precise estimation of the finite strain ratio based on the restoration of objects of known original shape or constant shape;

(2) it can rapidly be applied to determine zones of different strain ratio within an apparent homogeneous area (Japas *et al.* 1985);

(3) given a zone of superposed strain (one of them known in orientation and magnitude) it is possible to find rapidly the other component.

No major disadvantages are known except for optical problems involved, as mentioned above. It is rather heavy (about 500 g), depending on construction materials (bronze in our prototype) and it has a limited range. Size and objects may be a constraint.

Other uses

Using the strainscope one can restore rapidly in the field objects of unknown original form; Japas & Amos (1986) have shown its use in systematic paleontology. On some deformed objects belonging to the same original form the strain ratio is not a prerequisite for the determination of its original shape as both parameters (original shape and strain ratio) can be determined simultaneously with the strainscope. The lenses of the strainscope have to be adjusted to a position in which all strained objects are restored to their original shape which is assumed to be the same for all individuals.

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