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# An experimental approach to wide-necked pinch-and-swell structures

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**Abstract**—In the granite gneiss of Purulia District of West Bengal, India, foliation-parallel or -subparallel quartz veins show exceptionally wide-necked pinch-and-swell structures. Tensile experiments with tubes of polyethylene, a viscoelastic plastic polymer, have been carried out at a constant load (just exceeding the yield stress, $0.68 \times 10^8$ dynes $cm^{-2}$) in order to study such structures. The development of pinch-and-swell in the experimental models involves widening of neck zones by propagation of the neck fronts in the extension direction. Both the theoretical and experimental results enumerate a linear relationship between neck zone widening and bulk elongation when neck fronts propagate at a constant neck thickness (defined as a stable neck). The study predicts that propagation of neck zones in a stable state gives rise to the wide-necked pinch-and-swell structures. On the other hand, necks undergoing continuous thinning all along its course of development (defined as an unstable neck) may produce a pinch-and-swell structure with narrow torn neck zones. In the progressive deformation of experimental models a swell is reduced in size due to propagation of its adjacent two necks and subsequently the swell dies out when the two necks coalesce with each other.

## INTRODUCTION

IN ROCKS of contrasting competencies boudinage structures develop in the brittle layers by extension fracturing (Lohest 1909, Corin 1932, Wegmann 1932). Such fracturing is triggered by the tensile stresses exerted by the viscous flow of the surrounding incompetent materials (Ramberg 1955). Boudinage structures may also develop by shear fracturing of the competent layers (Cloos 1947, Rast 1956, Uemura 1965). Such boudins separated by fractures oblique to the layering are generally rotated and offset with or without getting separated from each other (Mandal & Khan 1991).

When the stiffer units are ductile and the layer separation is incomplete, showing a narrowing or 'necking', the structure is often termed pinch-and-swell (Ramberg 1955, Park 1983, Ramsay & Huber 1983). According to Smith's (1977) theoretical analysis the neck-localization is controlled by the non-Newtonian behaviour of the mechanically contrasting materials, such that necking at a definite wavelength will grow with a maximum velocity producing a pinch-and-swell structure with a dominant wavelength. The growth rate of such structures depends upon the material properties, e.g. viscosity contrasts (Neurath & Smith 1982). This analysis can explain a periodic geometry observed in some of the natural pinch-and-swell structures. However, pre-existing geometrical irregularities, e.g. layer-thickness inhomogeneity, may play an important role in localization of necks (Tvergarrd *et al.* 1981).

In cross-sections natural pinch-and-swell structures may have various geometrical shapes. They are often associated with subsequent fractures along the necklines (Fig. 1a). In some of the pinch-and-swell structures, the swells are lensoidal and connected by narrow hair-like necks (Fig. 1b). Tabular swells with sharp narrow necks (Fig. 1c) are also common in natural pinch-and-swell structures (Ramsay 1967, fig. 3-41). Pinch-and-swell structures are sometimes observed to have an exceptionally wide extent of neck zones in deformed rocks such as marbles and gneisses. This type of pinch-and-swell structure is of particular interest in the present study. The length of necks in these structures is generally much larger than the swell's width and thickness (Fig. 1d).

In the deformations of metals and some organic materials, e.g. polystyrene, polymethylmethacrylate, etc., plastic zones are localized inhomogeneously at the yield stresses (Bowden & Raha 1970, Suh & Turner 1975, Anand & Spitzig 1982). These are the localities of high strain with respect to their surroundings and are

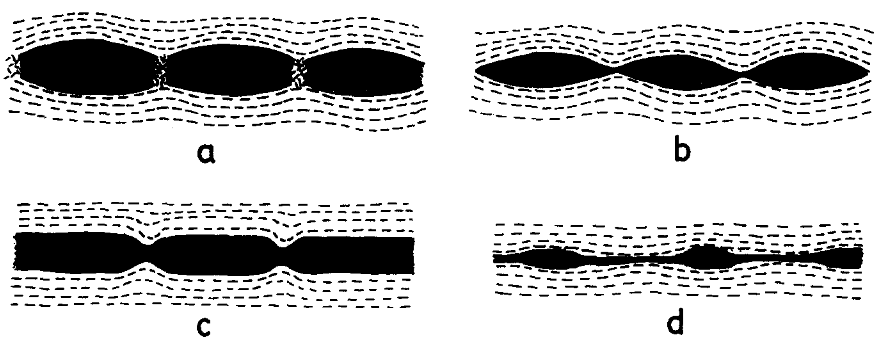



Fig. 1. Illustrations of some common natural pinch-and-swell structures.

observed to be mobile (Schlipf 1989). This sort of strain localization is also observed in the development of geological structures, such as kink bands and small-scale shear zones (Cobbold 1977a,b). The tensile experiments of metal rods exhibit such instabilities through initiation of necking. These neck zones are the localities of high plastic strain. Such a necking produces a structure very similar to a natural pinch-and-swell structure.

The present study is an experimental investigation of the development of exceptionally wide-necked pinch-and-swell structures with a few natural examples as supplements. The experimental results reveal the following features of the evolution of pinch-and-swell structures: (1) spreading of neck zones in the extension direction immediately after its initiation; (2) continuous propagation of neck profiles at a constant neck-thickness (defined as a stable neck) as a mechanism of development of wide-necked pinch-and-swell structures; (3) the linear relationship between propagation velocity of neck profiles and bulk elongation rate; and (4) decrease in the swell's size and its subsequent dying out in the course of widening of neck zones.

## FIELD OBSERVATIONS

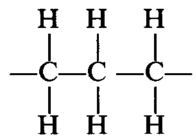
Pinch-and-swell structures have been studied in the Precambrian granite gneiss of Purulia District, West Bengal, India. These structures occur in quartz veins, parallel or subparallel to E–W-striking subvertical foliation. The pinch-and-swell structures of this area are exceptional in the sense that their neck zones are extremely wide, many times the swell's width and thickness (Fig. 3a). One of the characteristic features of these structures is that such a wide neck is not torn out along its central part, but a uniform neck thickness is roughly maintained. Often, in the same pinch-and-swell structure, a long neck has a thickness at its central part equal to that of an adjacent short neck (Fig. 3b). The structure implies that the broader neck zone has undergone widening with a thickness attained at its initial stage.

The successive stages of development of neck zones have been studied from different quartz veins from a single locality. Figure 3(c,i) shows the stage of nucleation of a sharp narrow neck with uniform swells. The geometry of somewhat wider necks (Fig. 3c,ii) is characterized by a central zone of uniform neck thickness connected to the swells by a curvilinear neck profile. At this stage the curvilinear regions occupy a greater part of the neck zones. In the pinch-and-swell of very wide neck zones, the regions of uniform neck-thickness are much longer than the connecting curvilinear neck profiles (Fig. 3c,iii).

## EXPERIMENTAL STUDY

### Method

*Material properties*. Polyethylene has been used as the experimental model material. It is a partially crystalline polymer with a melting temperature of 137°C and has the following chemical structure (Suh & Turner 1975).



Polyethylene shows a complex viscoelastic plastic behaviour at room temperature. Under a stress below the yield point ($0.68 \times 10^8$ dynes $cm^{-2}$) it undergoes time-dependent elastic deformation in the viscoelastic region. With the increase in stress there is a transition from viscoelastic to plastic behaviour. In the plastic region the material undergoes permanent deformation. At the transition of the two deformational regimes (near the yield point) plastic deformation is localized inhomogeneously within the material. These plastic zones expand laterally under a constant load.

*Model construction*. Uniform tubes of polyethylene have been used as experimental models. The tubes were 14 cm long with a cross-sectional area of 0.112 $cm^2$. Some of the experiments have been done with short tubes. The two ends of the tubes were inserted into two metallic holders and were rigidly fixed to them so that there was no slip when the tube was under a tension. Since the tubes are translucent it is difficult to take photographs of the models. To overcome this problem their surfaces were painted to make them opaque.

*Model deformation*. The model was deformed with the help of an apparatus (Fig. 2) in which one block slides over a horizontal rail. One of the terminal holders of the model tube was fixed with the movable block and the other end was held at a fixed wall at the opposite end of the machine. The sliding block was connected to a strong metallic wire which can withstand a high tension. The wire ran over a wheel fixed at the end of the base of the machine and terminated against a plate on which load was applied. Under a load on the plate, the sliding block tended to move, giving an equal amount of tension on the model tube. The load was increased until necks were initiated in the polyethylene tube. As soon as necks were initiated the tube was allowed to extend at a constant load. Different stages of deformation of the model were photographed by restricting the motion of

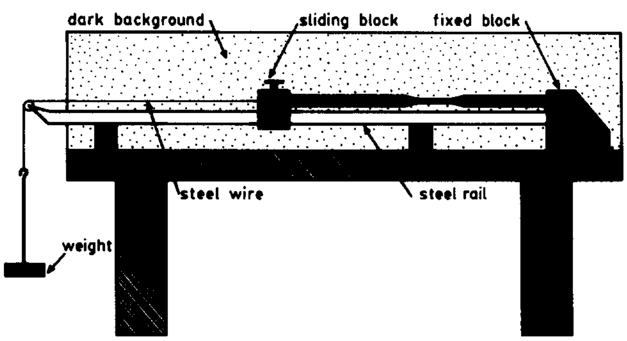



Fig. 2. A schematic sketch of the deformational set-up.

the sliding block with the help of a screw on its top. One side of the apparatus was walled with black paper to obtain a good contrast in the photographs.

*Experimental results*

*Development of wide-necked pinch-and-swell structures.* Necking at several points over the tube at bulk elongation of about 33% produced a structure very similar to natural pinch-and-swell structures (Fig. 4a,i). The neck zones propagated in the direction of extension. As a result, neck zones were widened with progressive deformation (Fig. 4a,ii). Consequently, the overall structure (Fig. 4a,iii) acquired a geometry of a wide-necked pinch-and-swell structure very similar to that shown in Fig. 3(a). It is of note that the continuously widening neck zones did not undergo thinning in the course of their subsequent propagation. That is, their propagation took place at a constant thickness of the necks (here defined as stable necks). In the course of deformation a very wide, uniform neck was left behind the propagating neck fronts (Fig. 4e). Such a neck geometry is very similar to the necks of a natural pinch-and-swell (Fig. 3c,iii).

During neck propagation the swells did not undergo overall thinning but were reduced in size by width. On the other hand, the neck zones were widened at the expense of the swell zones (Fig. 4a). As a result, the increment in bulk extension of the pinch-and-swell structures has been accommodated by the widening of the neck zones accompanying a reduction in width of the swell zones while thicknesses of both remained constant throughout the course of deformation.

*Progressive changes over swell zones.* In the course of evolution of the experimental wide-necked pinch-and-swell structures, while the older necks were widened by continuous propagation in the extension direction, new necking took place over the swell zones elsewhere. As a result, there were sharp narrow necks within a wide swell in the neighbourhood of a very long uniform neck zone (Fig. 4b,i & ii). At this stage the structure had short swells containing sharp necks adjacent to wide uniform thin zones (cf. Talbot 1970). Successive necking over the swells made them progressively smaller in size.

The swell zones occurred as islands when the neck zones were considerably widened (Fig. 4b,iii). Such swells died out completely when the two neighbouring necks coalesced with each other in the course of their propagation. Such a coalescence of neck zones led to formation of a single wider neck. After stretching of the model tube to about 77% elongation all the swell zones died out leaving a homogeneously thinned layer (Fig. 4b,iv). This indicates that a pinch-and-swell structure may be completely destroyed in the course of its evolution.

*Neck propagation and bulk elongation.* Stretching of a short tube with a single neck development (Fig. 4c) provided a convenient and simple way to measure the amount of neck propagation with bulk elongation of a pinch-and-swell structure. Data of the experiment shown in Fig. 4(c) show a linear relationship between increase in width of the neck zone and increase in length of the tube (Fig. 4d).

It is important to note that, when the middle part of the neck acquires a linear geometry (Fig. 4c), the curvilinear neck fronts migrate in the extension direction keeping the same geometry. During migration the front leaves behind a linear neck zone of uniform thickness. This indicates that the strain profile from swell to neck zone remains stationary and it is bodily shifted towards the undeformed part, i.e. swell zones. The migration of this profile leaves behind a stationary finite strain at the neck zone.

With the help of a theoretical analysis it will be shown in the succeeding section that the linear relationship between neck widening and bulk elongation of a segment of a pinch-and-swell structure can hold only if the curved neck fronts acquire a stable geometry and migrate with a finite stationary strain at the neck zone.

## THEORETICAL ANALYSIS

*Successive stages of development of wide necks*

All the experiments show a continuous amplification of necks at the initial stage of progressive extension of a tube. A stage is then reached at which the neck zone geometry is stabilized. With continued deformation instead of further neck thinning the neck fronts start to migrate laterally and produce a uniform linear neck zone. For example, Fig. 4(e) illustrates a newly formed neck which has just reached the stable geometry.

From the experimental observations the evolution of a wide neck can be modelled in the following stages (Fig. 5).

(1) Initiation of necking (Stage I).

(2) Continuous amplification of the neck with continued extension (Stage II), the unstable state of necking.

(3) Amplification of the neck restricted and attainment of a stable neck geometry (Stage III).

(4) Migration of neck fronts with stable geometry at a constant neck thickness and formation of a uniform wide neck (Stage IV), the stable state of neck formation.

*Propagation of necks in a stable state*

In this section an attempt will be made to relate neck zone widening to the bulk extension of a segment of pinch-and-swell structure in the evolutionary Stage IV. With the help of this relation the rate at which a swell is reduced in progressive extension will also be analysed. Let the overall length of a semi-segment of a pinch-and-swell structure at an instant be $l$ of which the width of the pinch zone is $l_p$ (the pinch width determined by the length up to which there is a presence of necking) and the width of swell is $l_s$ (Fig. 6). Then, $l = l_p + l_s$. The curvilinear front of the neck zone is represented by a function $y_1 = f(x_1)$ in a reference frame moving along the $x$ axis of the stationary reference frame $OXY$. Let the $O_1X_1Y_1$ reference and hence the neck profile move for a small distance $\Delta l_p$ for a bulk elongation $\Delta l$. The areal shortening due to this migration of the neck front can be obtained by the integration of the function as

$$S_p = \int_{A_p}^{A_s} \Delta l_p \cdot dy_1 = \int_{A_p}^{A_s} \Delta l_p \cdot dy \quad (\text{since } y = y_1, \text{ Fig. 6}), \tag{1}$$

where $2A_p$ and $2A_s$ are the thicknesses of the layer at the pinch and swell zones, respectively. If the bulk deformation is assumed to be non-dilatational, $S_p$ can be equated with the bulk elongation as

$$|A_s \cdot \Delta l| = |(A_s - A_p) \cdot \Delta l_p|$$

or,

$$\Delta l = |(1 - A_p/A_s)| \cdot \Delta l_p$$

or,

$$\Delta l = |e_p| \cdot \Delta l_p. \tag{2}$$

The instantaneous rate of bulk elongation, $\dot{l}$ of the pinch-and-swell segment and propagation velocity of the neck can be obtained from equation (2) by differentiating it with respect to time as

$$\dot{l} = |e_p| \cdot v, \tag{3}$$

where $e_p$ is the stationary finite strain (Fig. 5) and $v$ is the velocity of neck propagation of the stable neck profile.

The equation shows that a neck zone will widen linearly with bulk elongation. A neck with a lower $e_p$ will be wider than that with a higher $e_p$ for a unit bulk elongation (Fig. 7). It is important to note here that increase in width of the neck zone will hold a linear relationship with the bulk elongation only if $e_p$ remains constant throughout the course of propagation.

The experiments show that, with progressive extension, the swell segments are reduced in width as the necks widen. The reduction can be equated with the bulk elongation as

$$\Delta l_s = \Delta l - \Delta l_p.$$

By substituting $\Delta l_p$ from equation (2) we get

$$\Delta l_s = -\Delta l(1/|e_p| - 1). \tag{4}$$

Since $e_p$ is always less than 1, and $\Delta l_p$ and $\Delta$l are positive, $\Delta l_s$ in equation (4) is negative, i.e. swell segments will be reduced in width. The reduction will be lower for a high $e_p$ (i.e. in the pinch-and-swell structures with thin necks). On the other hand $\Delta l_s$ will be extremely large when $e_p$ tends to zero. This implies that a pinch-and-swell structure can be persistent only if $e_p$ becomes considerably larger than zero in a short interval of time.

*Propagation of unstable necks*

The unstable part of the evolution of a neck can be analysed by adding a neck thinning component with the widening of neck zones. In this case, the neck profile actually does not bodily move but its lateral extent is widened by increasing its flanks. Let $\Delta L_p$ be the amount of widening of a neck along with a thinning of the early formed part by $\Delta A_p$ for a bulk elongation $\Delta$l (Fig. 8). Then, areal shortening of the neck zone can be equated with the bulk elongation as

$$A_s \cdot \Delta l = \int_{A_p}^{A_s} \Delta L_p \cdot dy + \Delta A_p \cdot \Delta L_p$$

or,

$$\Delta L_p(A_s/A_p - 1 + \Delta A_p/A_p) = (A_s/A_p) \cdot \Delta l$$

or,

$$\Delta L_p\{e_p + \varepsilon_p(1 - e_p)\} = \Delta l$$

or,

$$\Delta L_p = \frac{\Delta l}{e_p + \varepsilon_p(1 - e_p)}, \tag{5}$$

where $e_p$ is a time-dependent finite strain at the neck, and $\varepsilon_p$ is the increment in strain during the propagation of the neck.

Equation (5) indicates that a neck in this state will be widened non-linearly with the bulk elongation since $e_p$ does not remain constant during the development of the neck zone. If $\varepsilon_p$ is very large, $\Delta L_p$ will be small before the attainment of a stable state. A necking can be stable only if $\varepsilon_p$ tends to zero in the progressive extension. It is important to note that, if a stable state is not achieved by $\varepsilon_p = 0$, with time $\Delta L_p$ will become very small when $e_p$ becomes very large. So, unless a stable state is achieved, a very wide neck is unlikely to form. On the other hand, if an unstable state indeed exists, continuously thinning neck zones may lead to tearing out of the pinch-and-swell structures along their neck lines before the development of wide necks.

## DISCUSSION

The process of neck propagation as revealed from the present experiments is likely to be operative in the development of natural pinch-and-swell structures. The role of such neck widening in the extension direction becomes obvious in the wide-necked pinch-and-swell structures (e.g. Fig. 3a). Both from experimental results and natural observations it stands that pinch-and-swell structures do not always develop solely by amplification of neck amplitudes but may involve a propagation of neck fronts. However, it may not always be possible to assert this from the natural pinch-and-swell structures.

During widening of neck zones in the experimental models, swells are reduced in size by their width and die out when the two neighbouring necks coalesce with each other. Similarly, in the evolution of a natural pinch-and-swell structure, some of the swells may be destroyed leaving no record of their prior existence. Similar to the experiment shown in Fig. 4(b), a layer initially with

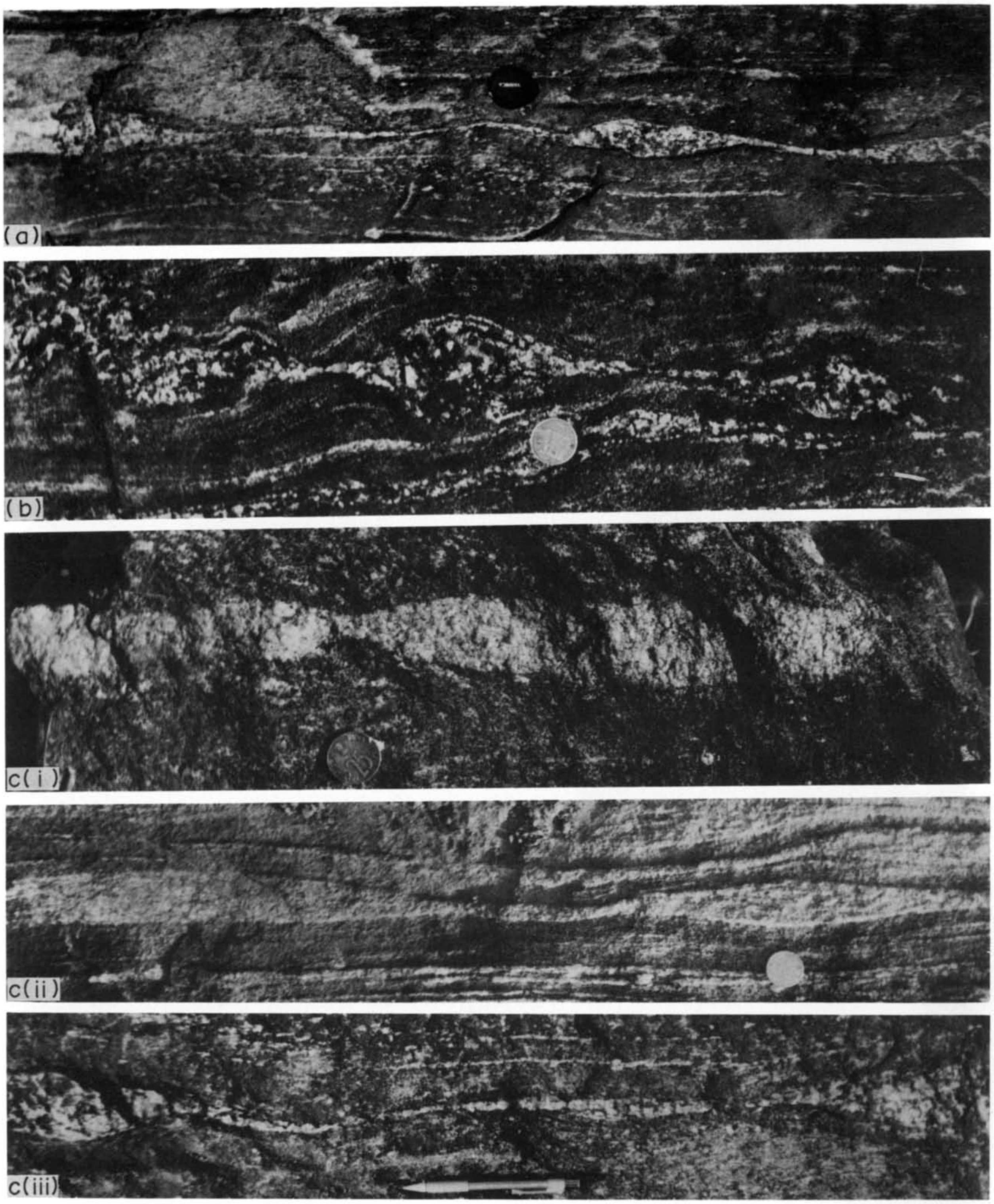



Fig. 3. Pinch-and-swell structures in quartz veins within granite gneiss: (a) wide-necked pinch-and-swell; (b) a short neck (left) and a wide neck separated by a lenticular swell; and (c) pinch-and-swell with increasing width of neck zones in (i), (ii) and (iii).

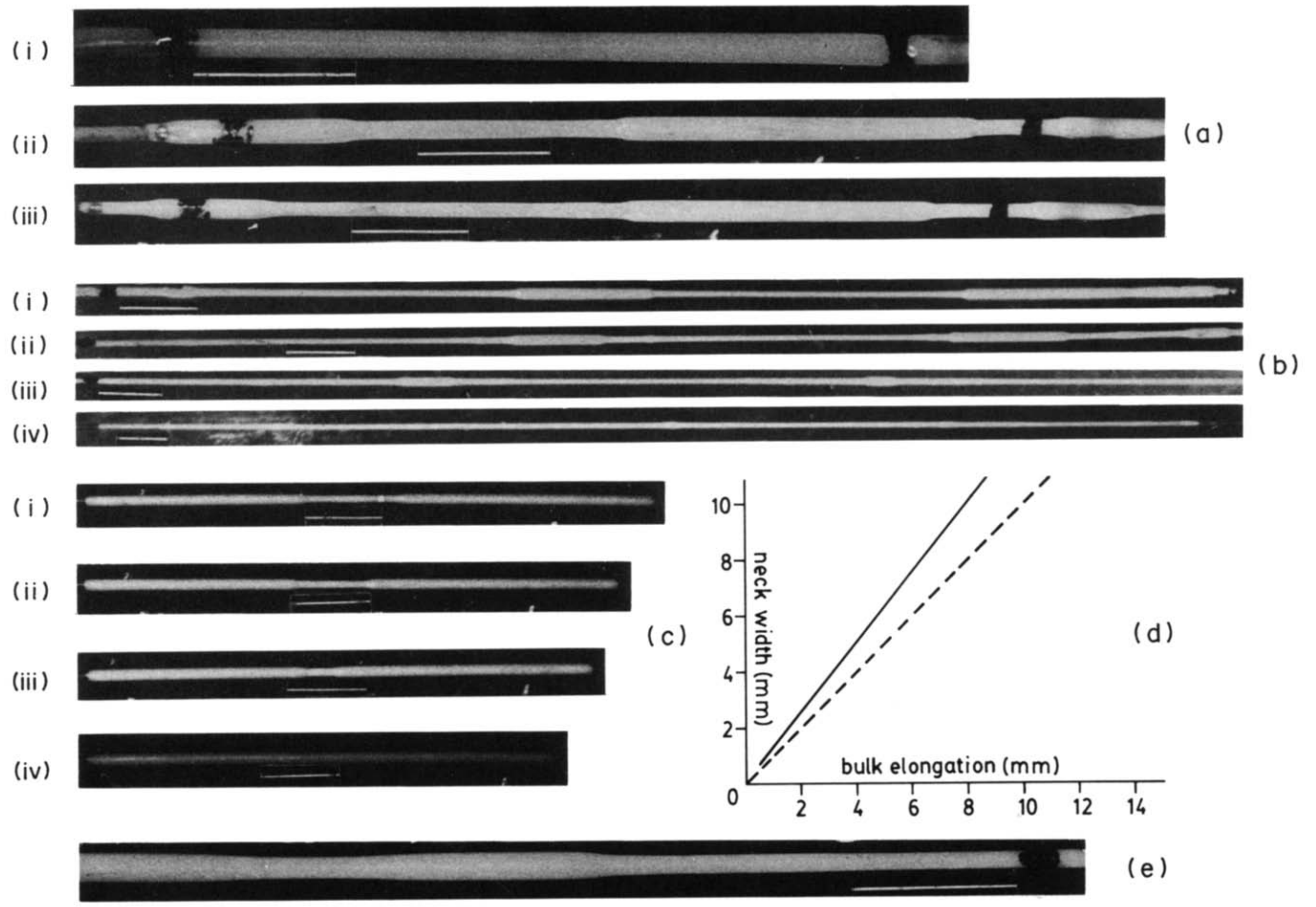



Fig. 4. (a) Successive stages of development of wide-necked pinch-and-swell structures in experimental model. (b) Splitting and progressive dying out stages of swells in (i), (ii), . . . . (c) A short tube with a single-neck initiation and its propagation. (d) Illustration of the linear relationship between neck widening vs bulk elongation of the tube shown in (b). (e) Necking stage of a swell (left) just prior to attaining the stable thickness shown by the neighbouring uniform, wide neck. Bar = 2 cm.

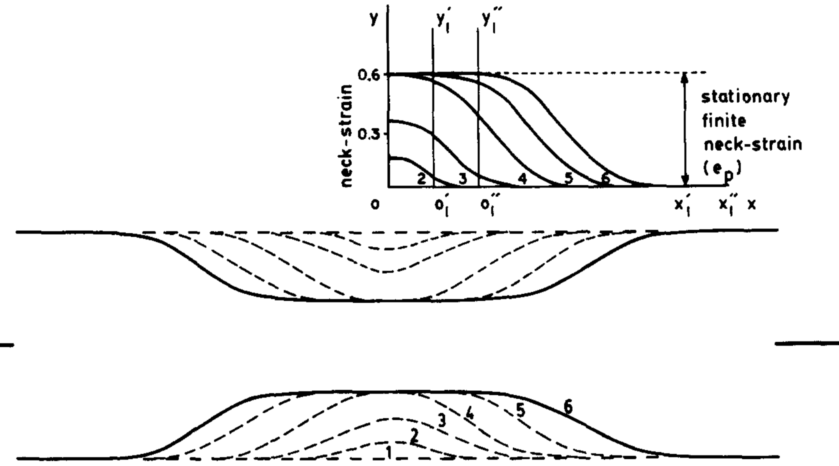



Fig. 5. A model for the evolution of neck; dashed line with 1, 2, . . ., etc., show different positions of the neck profiles with time. The corresponding figure (above) represents neck-strain profiles at those positions. The stable strain profiles start to migrate at 4 with the moving reference frame $O_1X_1Y_1$ in a stationary frame $OXY$; primes indicate different positions.

pinch-and-swell structures may become completely uniform and may appear as a homogeneously thinned layer when all the swells have died out.

*Neck propagation in stable and unstable state*

In the experiments a neck development is observed to attain a stable state in which the neck fronts propagate at a constant neck thickness. In other words, the neck zones have a finite strain which remains constant throughout the course of neck-propagation. Since the experimental models lack embedding medium the results do not give a complete picture of development of natural pinch-and-swell structures in competent layers hosted within incompetent rocks. The extension rate of an experimental model tube is determined by the propagation velocity of the neck front, a parameter dependent on its own constitutive properties. Thus, in a system with a layer undergoing extension in response to flow of its confining medium, a neck may or may not propagate in a stable state depending upon whether extension rate of the confining medium can be balanced by the extension rate determined by the maximum velocity of neck propagation. The following analysis is offered to address the results if the experimental models would have an embedding medium.

Maximum velocity of a deformation band can be obtained from equation (22) of Schlipf (1989) as

$$v = \phi \hat{v}, \tag{6}$$

where $\phi$ is the fraction of actually moving dislocations and $\hat{v}$ is the dislocation velocity. This can be expressed as

$$\hat{v} = \gamma_a \lambda \exp(-U/KT),$$

where $\gamma_a$ is a constant, $\lambda$ is the jump distance and $U$ is the activation energy. Now the maximum extension that can be acquired by the tube at an instant can be obtained from equations (3) and (6) as

$$(\dot{l}_T)_{max} = e_p \cdot \phi \cdot \hat{v}.$$

If the elongation rate of the confining medium ($\dot{l}_s$) is below $(\dot{l}_T)_{max}$ (regime 1, Fig. 9a) the extending tube could adjust with its surrounding by a stable neck propagation. On the other hand, in the situation $\dot{l}_s > (\dot{l}_T)_{max}$ (regime 2, Fig. 9a) the extension rate of the confining medium could not be balanced by the extension of tube by neck propagation. In such cases, the neck would be unstable and would have undergone rapid thinning throughout its course of development. Each of the situations (regimes 1 and 2) will produce a definite type of pinch-and-swell structure in nature (Fig. 9b). In regime

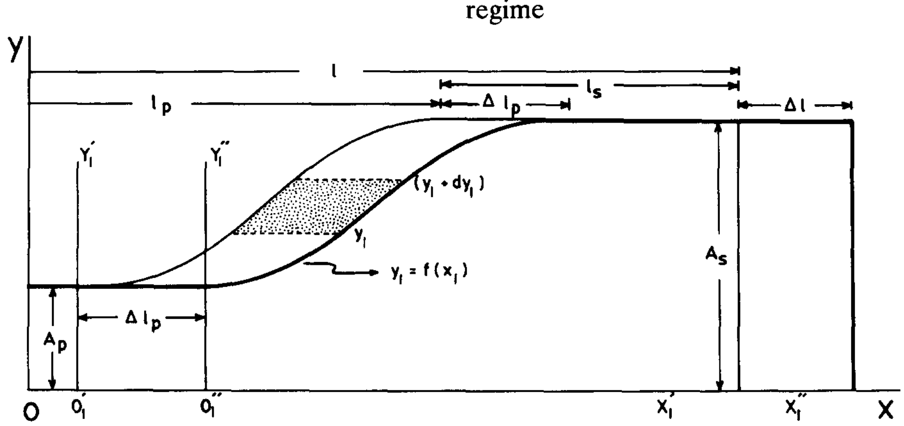



Fig. 6. A schematic illustration of neck-increment ($\Delta l_p$) with bulk elongation ($\Delta l$) of a semi-segment of a pinch-and-swell structure; $A_p$ and $A_s$ being halves of the layer-normal thicknesses at the neck and the swell, respectively.

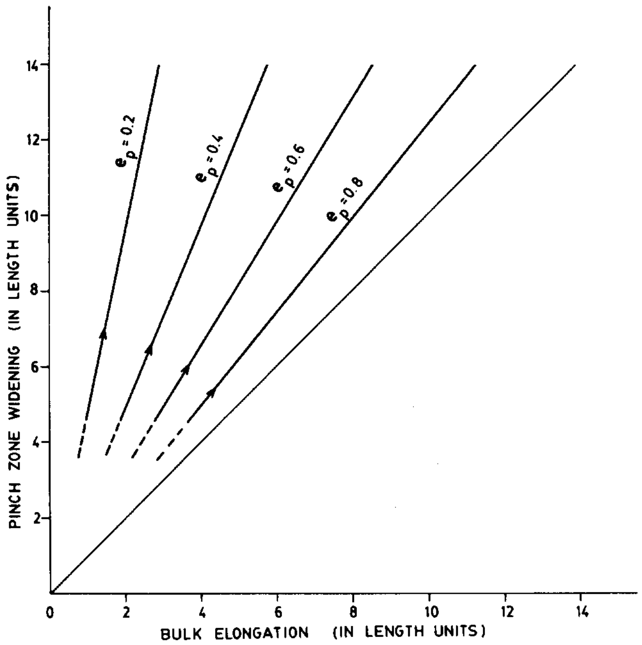



Fig. 7. Theoretical lines of neck zone widening with bulk elongation for different values of stationary finite neck strain ($e_p$).

2 pinch-and-swell structures will have torn narrow neck zones following extreme neck thinning. On the other hand, wide-necked pinch-and-swell structures will be produced in regime 1 where neck zones widen at constant neck thickness. It may also happen that, in a progressive deformation, $\dot{l}_s$ may exceed $(\dot{l}_T)_{max}$. Under these conditions a neck which initially propagated at a stable state would undergo rapid thinning when the unstable state is attained.

### Experimental limitations

The narrow tubes used for these experiments do not perfectly match with the overall geometry of natural pinch-and-swell structures. The reason for using narrow tubes, instead of a plate, is to reduce the cross-sectional area on which the force is applied. As a result, the stress is greatly increased and it has been possible to achieve the yield stress of polyethylene under only about 8 kg load. However, the present series of experiments is intended only to show that neck zones propagate in the extension direction. This propagation would also be similar in a layered model since neck-propagation is not dependent on the geometry of the material body. However, overall cross-sectional profile geometry of the neck fronts would vary depending upon the model geometry. In the experimental tubular model there has been neck thinning in all directions, but in natural pinch-and-swell structures necking generally occurs across the layering. The relation between neck-propagation and bulk elongation will then change accordingly. However, in the present theoretical analysis $e_p$ is given in terms of areal shortening of a cross-section of a neck profile. The analysis can be modified for neck-propagation in layered structures.

## CONCLUSIONS

(1) Spreading of neck zones in the extension direction may be an important process in the development of pinch-and-swell structures in rocks.

(2) Wide-necked pinch-and-swell structures develop in the situations where neck-propagation takes place without accompanying significant overall neck thinning. In other situations there may be neck thinning all along the course of development of the neck zones and the pinch-and-swell structure with narrow, torn neck zones will be produced.

(3) The width of a neck zone is linearly increased with the bulk extension of a pinch-and-swell structure where the neck fronts propagate with a uniform neck thickness.

(4) The bulk extension of pinch-and-swell is accommodated with the increase of neck width accompanying a reduction in swell width while the thicknesses of both remain unchanged throughout the course of the deformation.

(5) In the progressive extension of pinch-and-swell structures, a swell dies out when its two adjacent necks coalesce with each other in course of their propagation.

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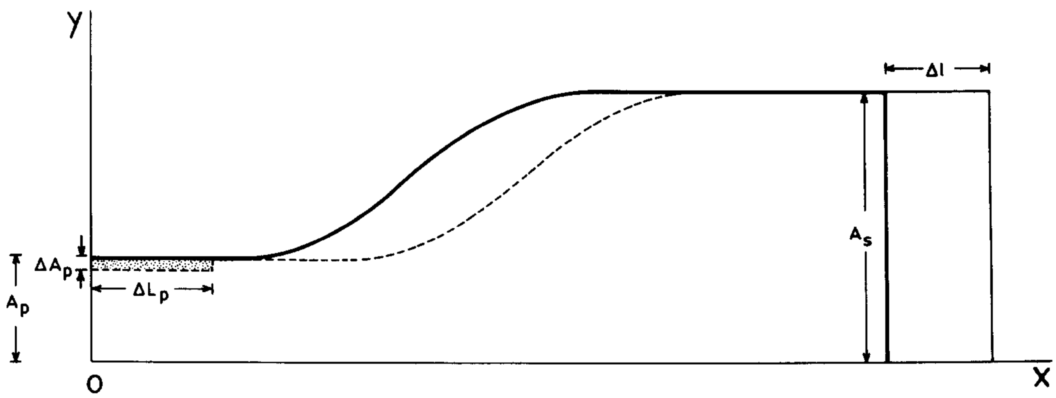


Fig. 8. Neck zone widening ($\Delta L_p$) along with a thinning ($\Delta A_p$) at the initial stage of neck development.

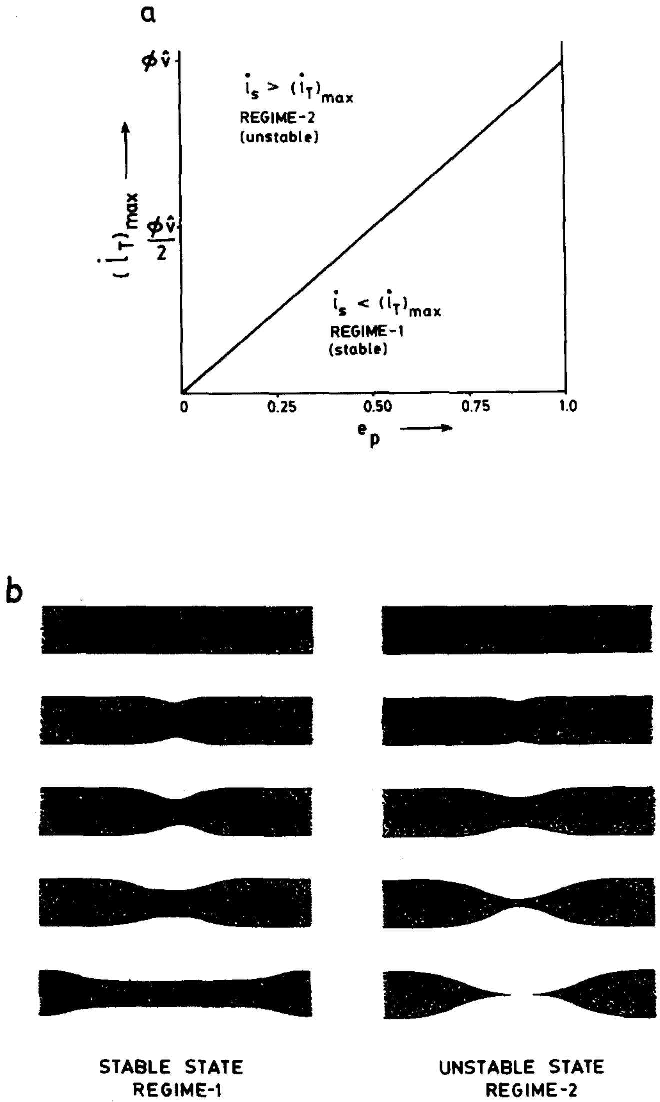


Fig. 9. (a) A schematic graph showing regimes of stable and unstable course of neck-propagation (see text for detail). (b) Two possible modes of evolution of pinch-and-swell structures.

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