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NETWORKS OF SHEAR FAULTS IN THE FIELD AND IN EXPERIMENTS.

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ABSTRACT

Networks of faults in the field are characterized by the organization in one or more sets of faults, by the generation of large faults zones from many segments and by the power distribution of the lengths of fault traces. The growth of fault networks in wet clay samples during laboratory experiments is described here. The experiments show three mechanisms of growth of individual faults: in-plane propagation, off-plane propagation and coalescence. Networks grow in the experiments by superposition of many non simultaneous faults arranged in two sets. In some experiments the distribution of the lengths of the fault traces changes with the deformation from power to lognormal distribution.

INTRODUCTION

Fractures in rocks are divided into two general classes: extension fractures or joints, with motion normal to the fracture surface, and shear fractures or faults, with slip along the fracture surface. The development of networks of faults is the subject of the present study.

Networks of faults range from microscopic scale to continental dimensions and have strong effect on the mechanical and the hydrological properties of the host rock. These effects are usually analyzed by assuming an average or a statistical network of faults, rather than examining an accurately determined fault network. Average networks are used to avoid difficulties encountered in determining the complete geometry of faults in the field as well as the additional problem of analyzing such a complete geometry, even if it were known. It is not even clear if the analysis of an accurate network could yield better predictions than the analysis of the statistical one. The present study outlines some characteristics of networks of faults that were mapped accurately in the field; these networks can serve as a basis for deterministic analysis.

The growth of a network of faults in a rock unit is a long process that initiated during the formation of the rock. One usually attributes the observed faults to a few, separate phases and assumes that each phase generates a relatively simple network that can be correlated with experimental results and theoretical models. However, it appears that the growth process of a network can be best studied in experiments. Such experiments of the growth of networks samples of wet clay are described here, and their possible implications to field cases are discussed.

NETWORKS OF FAULTS IN THE FIELD

The characteristics of fault networks for three cases with detailed field mapping are outlined here. The first case includes wrench faults in a granitic body in the Sierra Nevada, California[1], the second case includes wrench faults and extension fractures in a limestone layer in southern Israel[2] (Fig. 1) and the third case includes normal faults in sandstone layers in the San Raphael Swell, Utah[3].

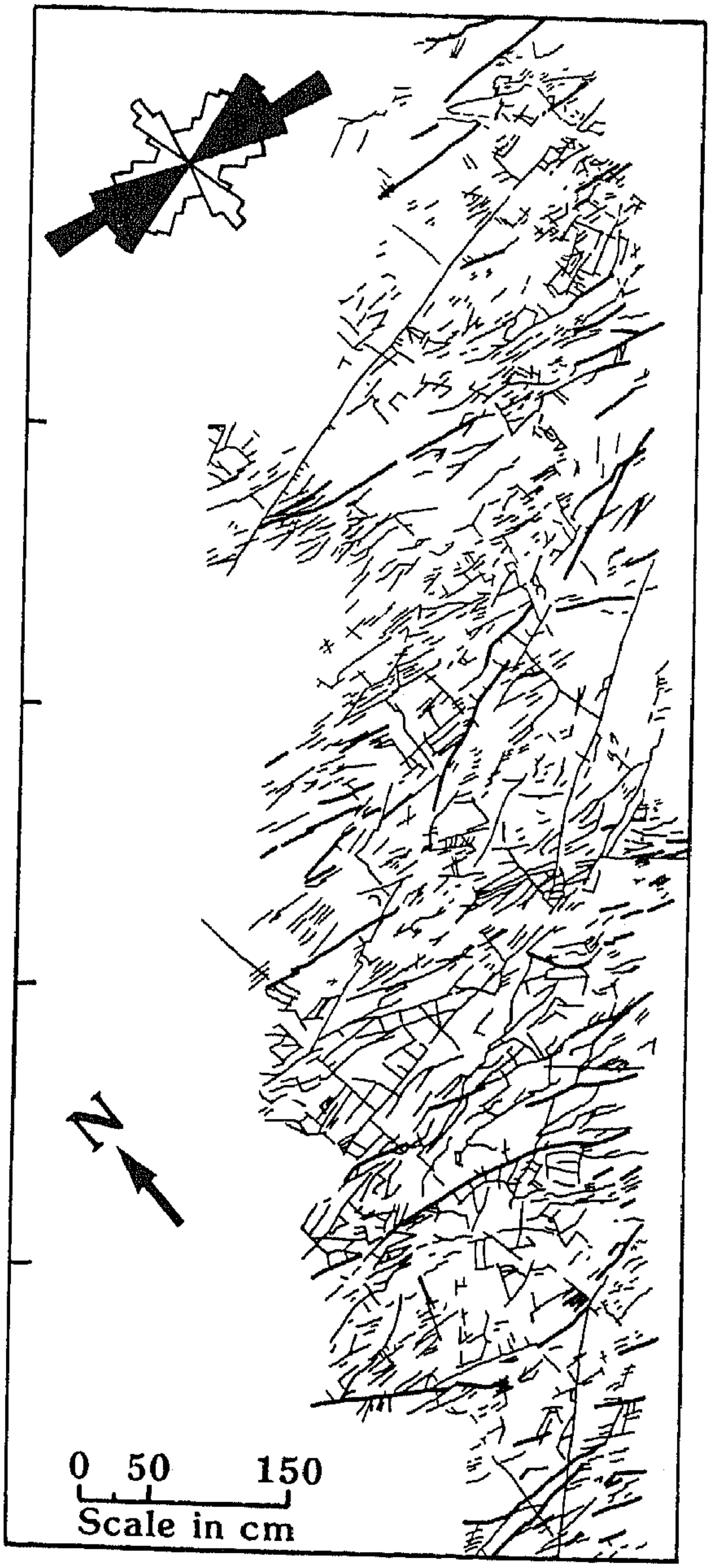

Fig. 1 A map of wrench faults in a dolomitic limestone layer in southern Israel[2]. Heavy lines-faults with measured slip; rose diagram in upper corner-summary of orientations of all fault traces; black sections-the conjugate set of faults trending ENE to ESE.

The types of faults mentioned relate to the sense of slip along an inclined fault surface: normal faulting indicates downward slip of the upper block, reverse faulting indicates upward slip of the upper block and wrench faulting indicates that the slip between the blocks is in the horizontal direction.

The three cases were chosen because they incorporate detailed field measurements at large scales and they display relatively simple networks. The main properties of the faults in these cases are the following:

A. Sets. A network of faults frequently can be divided into a few sets of similar orientations (Fig. 1). In each set the orientations have normal distribution in two dimensions[2] and spherical-normal distribution in three dimensions[3]. Commonly, faults occur in a conjugate set which is a system of two separate sets with complementary sense of slip that bound a dihedral angle of 30° to 60° (Fig. 1). Individual faults of the two sets may displace each other, and thus, are usually attributed to a single deformation event.

Some areas display three, four or more sets of faults[3]. These patterns may suggest multiple deformation events or, as proposed by Aydin and Reches[3], one deformation event. The occurrence of a single set of faults in the field is relatively rare and requires some special conditions. For example, Segall and Pollard[1] deduced from field observations that two separate deformation events, extension fracturing followed by rotated shear, were required to form the single set of faults which they found.

B. Fault zone. Faults may be surfaces of physical discontinuity between two blocks, with clear aperture[2]; but in most cases they are continuous zones of finite width separating two blocks. Fault zones are composed of crushed host rock[4] or material added from external sources[1]. Aydin[1] and Segall and Pollard[1] demonstrated that while intense fracturing and shear occurred inside the fault zones, the host rocks remained almost undeformed.

C. Fault growth. Segall and Pollard[1] showed that faults initiated as shear occurred along preexisting extension fractures and grew longer primarily by coalescence with other subparallel faults. Locally, the shear along the preexisting fracture caused extensional fracturing at termination regions. Aydin[4] showed that faults in sandstone initiate as narrow deformation bands which are zones of crushed sand grains. These bands grow up to a few meters length by propagation into undeformed rock. Further lengthening of the fault zone occurs by coalescence with other deformation bands.

D. Length of fault traces. The frequency-length relation of the fault traces of Fig. 1 are shown in Fig. 2. This relation appears to fit a power distribution: frequency=A*length^{B}, where A and B are constants (here B=-1.930). The power

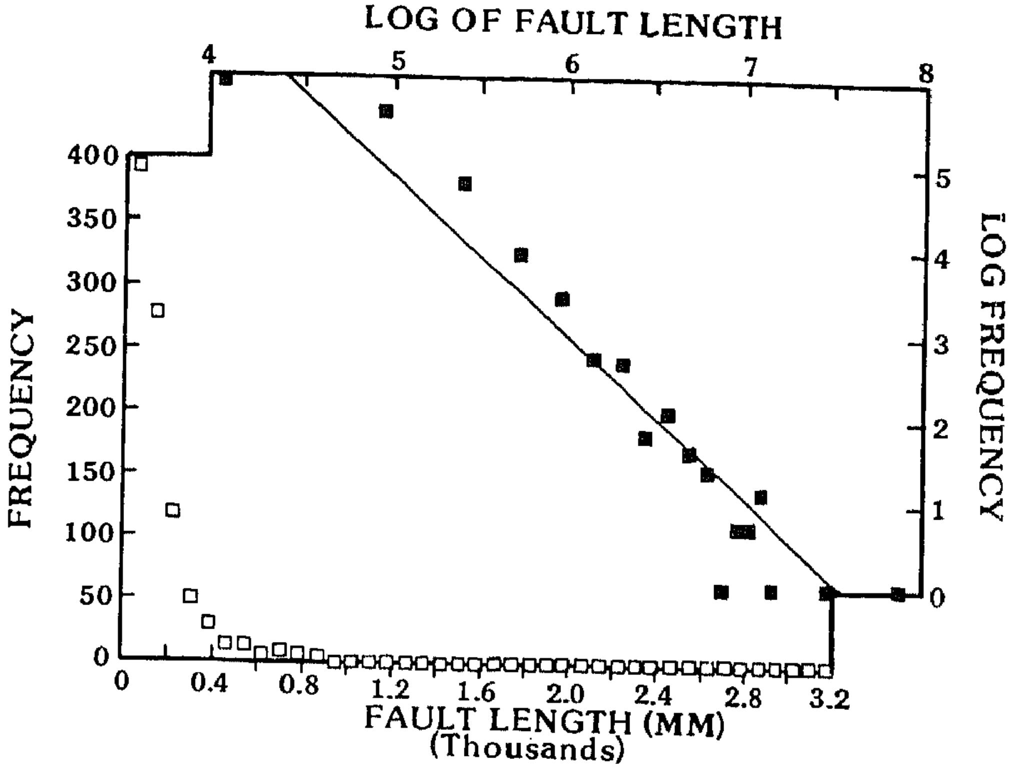

Fig. 2. Frequency of lengths of fault traces in the map shown in Fig. 1 in lower left. The natural log plot with best power law regression line in upper right. The data points indicate top of columns of the histogram.

distribution and the similar truncated exponential decay curve, fit other cases of fracture length[5,6]. The observed frequency values of the short faults are usually lower than the values expected by the power and exponential distribution. The lower frequency of short faults may be attributed to resolution limits and sampling difficulties. On the other hand, Barton and Larsen[7] demonstrated a lognormal distribution of length of fracture mapped in the field. They claim, that the low frequency of the short fractures is a real feature and not the result of insufficient sampling.

FAULTING IN LABORATORY EXPERIMENTS

Understanding the development of fault networks requires experimental inspection of the process. Unfortunately, it is experimentally difficult to produce networks in rock samples, due to their unstable yielding and high compressive strength[8]. Therefore, I have studied the networks of faults that develop in samples of wet clay[9] and present here part of the results.

The experiments were performed in a biaxial deformation apparatus in which a horizontal plate of wet clay was loaded along its four vertical sides. The plate was deformed at a constant strain rate of about $2*10^{-5}$ sec^{-1}, with continuous monitoring of the stresses within the clay and periodic photography of the faulted surface of the clay sample. Most observed faults are wrench faults, with few normal and reverse ones. The wet clay was deformed up to 25% of shortening, and the first faults appear on the sample surface after 5% to 6%. The observations presented here are based on direct observations during thirty tests and the inspection of photographs of the sample surface. These photographs are two dimensional maps of the fault traces[9].

The networks of faults that developed in the clay samples include the following features (Figs. 3,4):

a. Faults are first detected as tiny, 1 to 3 mm long, linear fractures on the surface of the sample. The resolution limit is about 1 mm, and thus, it is likely that the initial faults are shorter then 1 mm, but invisible. Some faults grew longer while others did not grow or even disappeared with increased deformation (Fig. 4). New, tiny faults developed during the entire span of the tests, but their relative frequency decreases with increasing deformation.

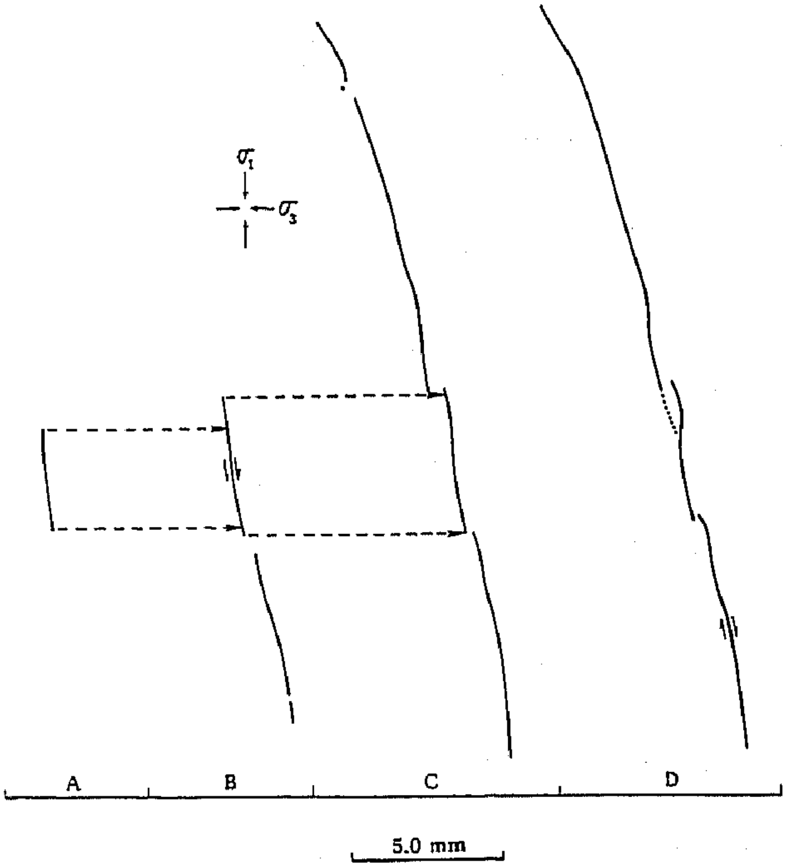

Fig. 3. Map of the fault traces in four stages of the development of an individual fault zone in wet clay. A,B,C and D indicate separate stages; dashed lines connect indentical points in two stages; the orientations of maximum and minimum stress axes are marked. Note: in-plane propagation in B and C and off-plane propagation and coalescence in C and D.

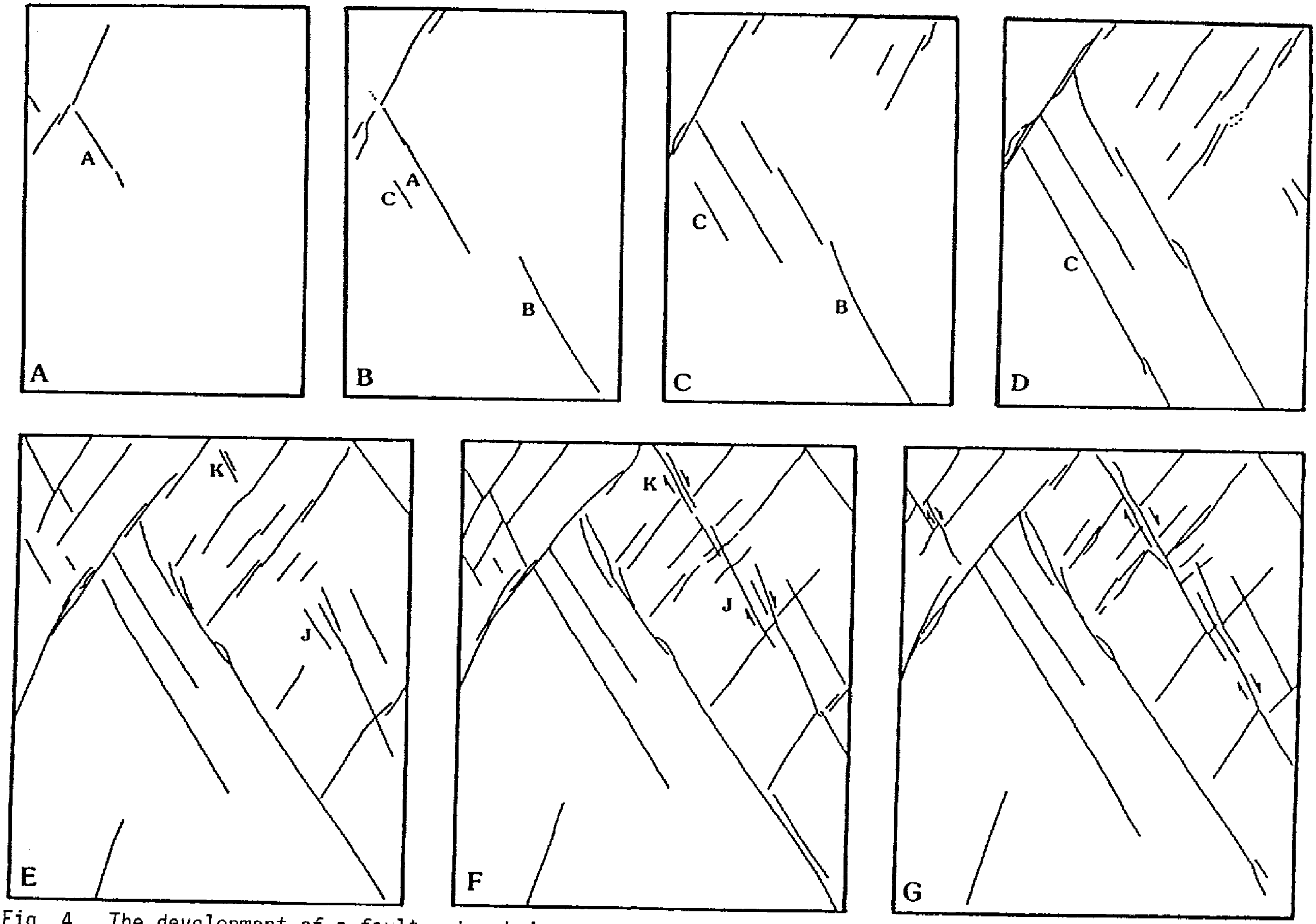

Fig. 4. The development of a fault network in experiment D-204. The figures show the fault traces in seven consequtive stages; the figures are maps of the upper surface of the sample of wet clay. Note: the in-plane propagation of faults A and C, the coalescence within fault zone B and the cross cutting of old sets by the young system K-J. Scale: width of frame E is 45 mm.

Figure 5 presents the frequency-length relations in three stages of experiment D204 (Fig. 4). In the first stage (the lower curve in Fig. 5) short faults are the most common, whereas in the final stage (the upper curve in Fig. 5) longer faults are more common. This trend reflects the growth and lengthening of faults and implies the development of a dominant length of about 10 mm long in this experiment (Fig. 5). The frequency-length analysis has been completed for five experiments; all five show a lognormal distribution (similar to the final stage in Fig. 5); three show transition from short faults in early stages to longer faults in the final stage.

<u>b</u>. The faults are organized in two sets oriented $30^{o} \pm 10^{o}$ on both sides of the axis of maximum compression. These two sets form a conjugate set mentioned above (Fig. 1). The orientations of the newly formed faults do not change during the experiments, whereas the orientations of old faults may change locally due to rotation and interaction with other faults.

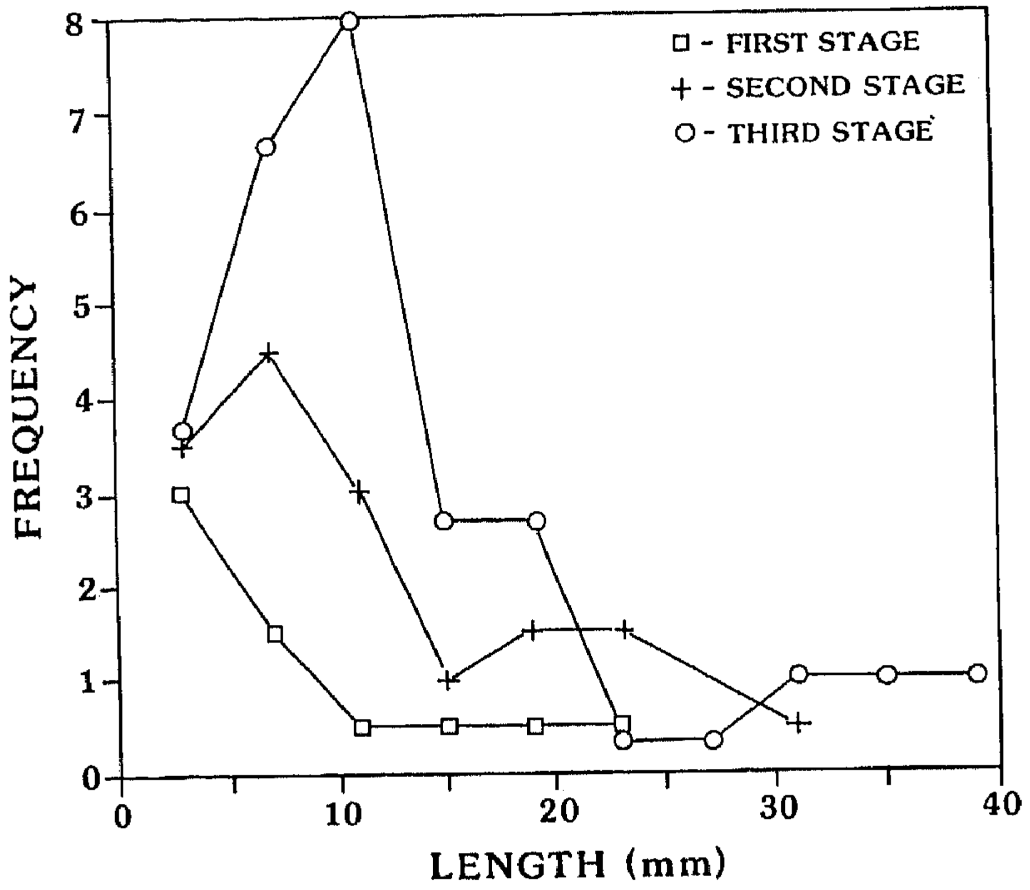

Fig. 5. Frequency versus lengths of fault traces in experiment D-204. Each point indicates top of a column in a histogram; width of column is 4 mm. First stage-mean of A and B in Fig. 4; second stage-mean of C and D in Fig. 4 and third stage-mean of E, F and G in Fig. 4.

c. The experiments display details of the process of fault growth. Individual faults grow by three mechanisms that frequently operate in a sequence (Fig. 3). First, they grow by in-plane propagation during which the trace of a fault extends itself in its own direction. This is followed by off-plane propagation during which the fault trace curves out of its original direction. The propagation stage of a fault is followed or is partly accompanied by its coalecensce with other nearby faults (Fig. 3).

The growth process generates a fault zone that is composed of several interconnected segments (Fig. 3). The links between the segments are sites of intense localized deformation[9]. The growing fault becomes wider; it changes from the initial faint trace to a wide, distinct zone. On the other hand, faults that did not grow become less distinct, or even disappear, with increasing deformation. A few fault zones that developed faster then the others become master faults: they are geometrically dominant and they accommodate most of the shear (Fig. 4).

The present study provides the first experimental observations of in-plane propagation of faults under shear conditions. In previous experiments, fault propagation was studied in rock samples or brittle modelling materials[9] that display only off-plane propagation[4]. This mode of propagation reflects the brittle-elastic rheology of the rock samples that yield more easily by off-plane extension fracturing.

d. The networks of wrench faults observed in the present experiments are cumulative features that developed by superposition of many non simultaneous individual faults, as illustrated in Fig. 4. Initially, a few faults organized in two separate sets, appear in the wet clay sample; their locations and order of appearance seem to be independent of each other (Fig. 4a,b). The initial faults are frequently arranged in a domainal pattern (Fig. 4c,d). Each domain includes faults of similar orientations belonging to one set, whereas faults of the second set are essentially absent; the inverted situation appears in the adjoining domain. New faults continue to form and to grow within the domains and some of them, for example fault system J-K in Fig. 4e, grow to dominate the region (Fig. 4e,f). This growth of the new faults forms a conjugate pattern in which faults of two sets have about the same intensity (Fig. 4f,g). Final stages of network development are characterized by the domination of two or three master fault while most smaller faults become inactive (Fig. 4g).

During network development the old, inactive faults are cut and displaced by the young, growing ones (examine the development in Figs. 4e to 4g). Furthermore, the younger faults usually do not change their orientations at the proximity of the older, larger faults. These observations indicate that the young faults cannot "discriminate" between old fault zones and unfaulted medium. This suggests that the networks in the wet clay experiments develop with relatively small interaction between the faults.

DISCUSSION

The geometric similarity between networks of faults mapped in the field and the networks of faults observed in wet clay experiments has been noted for many years[10]. However, the mechanical implications of this similarity are not well understood. Reches[9], for example, argues that the geometric similarity reflects a rheological similarity and bases his argument on the observations[9] that rocks flow in a viscous mode under geologic strain rates. Without raising the details of the proposed mechanical similarity, I discuss here the possible similarity of frequency-length relations in the experiments and in the field.

Figure 5 presents the lengths of the fault traces in three stages of experiment D204. This diagram indicates a development from more frequent short faults, 1 to 3 mm long, in the first stage, to more frequent intermediate faults, about 10 mm long, in the last stage. The curves show a transition from a power distribution in the first stage to lognormal distribution in the last stage. As the scale of mapping and the resolution limits were constant during the experiment, the change of frequency distribution with deformation is not a function of improper sampling of short faults (as was suspected above for field cases). These results may suggest that the frequency-length relations reflect the degree of development of the fracturing, where mature systems display lognormal distribution and developing systems have power distribution. This suggestion would be verified through further experiments and field studies.

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