Understanding and modelling brittle deformation in the earth: insight from a novel experimental approach

Anita Torabi[1]* suggests new experiments that can study the fault growth process and answer fundamental questions about material properties such as friction and the stress configuration needed to create brittle and ductile deformation in the Earth.

Abstract

Current experimental approaches on faults provide a significant contribution to our understanding of brittle deformation in the crust. However, they rarely present a multiscale view of fault initiation, propagation and growth or the complex geometry of natural faults combined with other geological features such as folds and flow structures. We suggest new types of experiments that are inspired by the observations of natural phenomena on the water surface of a lake. In order to create similar structure to the nature, we have investigated different possibilities, hence designed and run the first series of novel experiments in a large water tank set-up at the hydrodynamics laboratory of the University of Oslo. The water tank is equipped with cameras to dynamically image the experimental process. Using capillary waves and added impurity (pollen) to the water surface in a controlled laboratory set-up, our experiments created structures similar to faults, folds, and flow structures observed in nature. We suggest that these experiments can be utilised to not only study the fault growth process but also to answer some fundamental questions with regard to material properties such as friction and the stress configuration needed to create brittle and ductile deformation in the Earth.

Keywords: fault, fold, brittle deformation, experiment

Introduction

In geology, faults are brittle deformation structures that form in the upper crust due to changes in the isotropic stress field as described by Anderson (1905). Faults have been studied by researchers from different disciplines due to their popularity and importance in rock deformation, which may result in earthquake (seismic slip) or change of the geometry and petrophysical properties of their host rocks (Martel and Pollard, 1989; Di Toro et al., 2006; Manighetti et al., 2007; Torabi et al. 2013; Loveless et al., 2014; Rohmer et al., 2015). Anderson's theory of faulting (Anderson, 1905) classifies faults in three end-members (normal, reverse, and strike slip) based on the configuration of the three principal stresses assuming that there is no shear stress at the Earth's surface. The fault strikes differently with respect to the greatest and the least principal stress in these three categories. The orientation of the fault plane will always be parallel to the intermediate principal stress and have the smaller angle with the greatest principal stress and be a function of friction (μ) in different rocks. This angle will determine the dip of the fault and in fact its type. Anderson (1905) further explained that if two of the principal stresses are equal, the faulting can occur in any direction.

Faults can be studied through different methods in thin sections, core-samples, well-log images, outcrop and seismic sections, and satellite images, and hence in various scales from microscopic to large scale. Among different methods, studies of outcrops and reflection seismic data are of more interest to geoscientists as they provide information on fault geometry that are not accessible through other approaches.

The fault plane 3D shape is usually reconstructed from interpretation of 2D horizontal and vertical sections of seismic data or vertical sections of outcrops. Using 3D reflection seismic data, which are usually expensive to acquire, it is possible to study fault segmentation and have a better estimate of the fault segments length and displacement (Marchal et al., 2003; Torabi et al., 2019; Roche et al., 2021). Details of fault damage zone and core could be mainly studied in 1D or 2D datasets from outcrops due to the low resolution of seismic data, but usually the fault length and displacement are hard to measure in outcrops. While seismic data can provide both vertical and plain views, outcrops usually provide only one of these views. More recently satellite images have been used to investigate deformation on the Earth's surface in a plain view. These images can provide useful information on large and medium size faults as well as folds and flow structure, for example salt diapirs.

As the methods mentioned above provide a snapshot of the faults, the process of faulting is investigated through different types of experiments and numerical models. Over the decades, many experiments have been designed to investigate faults and their associated structures such as fractures, deformation bands, and folds (ductile deformation), etc. Although these experiments have significantly contributed to our understanding of brittle

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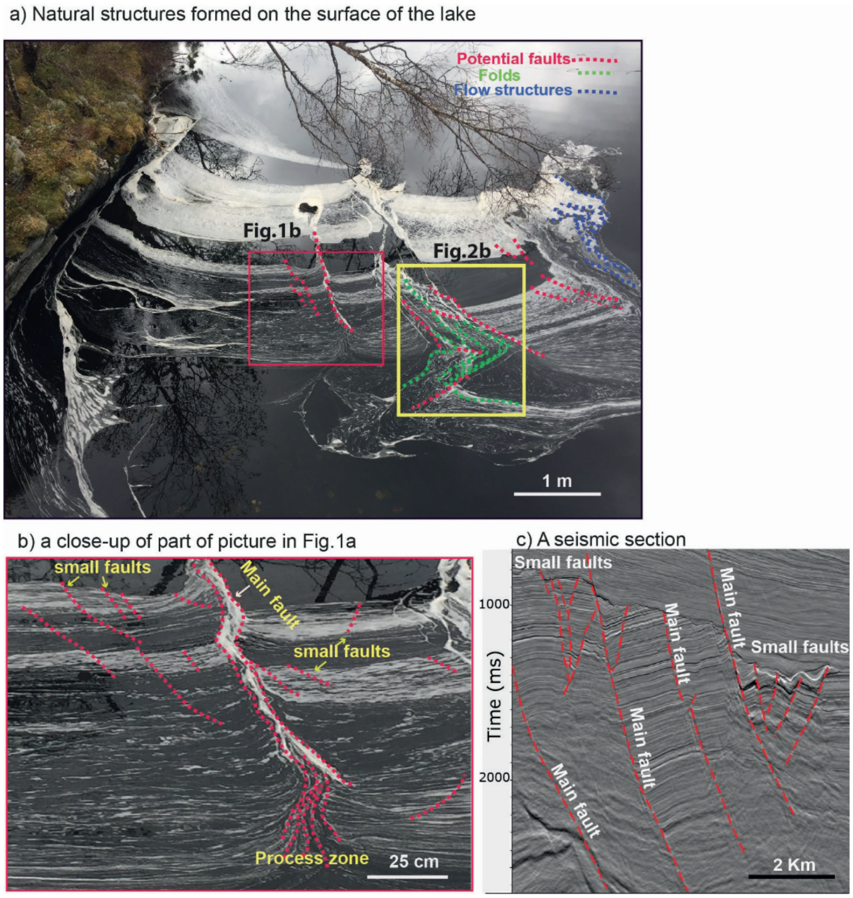
deformation in the crust, there are challenges mainly related to the type of experiments and their boundary conditions. Therefore, they rarely provide a multi-scale view of fault initiation, propagation and growth or the complex geometry of natural faults, which are commonly combined with other geological structures such as folds and flow structures.

Some of the previous experiments were used to study fault nucleation and growth (Buijze et al., 2020) or fracture initiation and propagation as well as rock pulverisation and melt lubrication of faults (Rosakis and Coker, 1999; Di Toro et al., 2006; Doan and Gary, 2009). Other studies investigating faults and shear fractures involve ring-shear and direct shear experiments (Torabi et al., 2007; Bohloli et al., 2021). Seismic and aseismic slip of faults (shear fractures) are studied by direct shear experiments utilising velocity-dependence friction coefficient (Dieterich, 1979; Ruina, 1983). Ring shear experiments were originally designed to study slumps and landslide, but they have been successfully utilised to investigate deformation bands and small faults up to 1 m displacement on a pre-defined shear surface in sand and a mixture of sand and clay (Torabi et al., 2007; Cuisiat and Skurtveit, 2010). Triaxial experiments investigate the process of strain localisation and the interchange between strain softening and hardening in different kinds of rocks and sediments at millimetre to centimetre scales (Alikarami et al., 2013; Skurtveit et al., 2013; Salvatore et al., 2019; McBeck et al., 2022). Recent advances in imaging using synchrotron, CT-scanners, and neutron imaging allow dynamic observation of this process at a small scale during the experiments (Fusseis, et al., 2014; Viggiani and Tengattini, 2019; Cartwright-Taylor et al., 2020). Most of the above-mentioned experiments are performed on small samples of one lithology or a mixture of a limited lithologies, which are either considered homogeneous or include heterogeneity by adding an inclusion or a predefined shear surface. Up to now, only analogue experiments (cm-m scale) have been the most relevant experiments in creating deformation structures similar to nature in terms of the architecture and geometry (Gabrielsen, et al., 2019). Through these type of experiments, it is possible to create both folds and faults. Different types of materials have been used to create such structures, examples are rubber, plaster (gypsum), silicon putty, sand and clay among others (Kuenen and de Sitter, 1938; Storti and Salvini, 1997; Gabrielsen, et al., 2019; Nabavi and Fossen, 2021). However, in these experiments, the samples are not under confining pressure unlike the other experiments explained above and only lateral forces are used to make either extension or compression in the samples. In these experiments, materials of different viscosity are utilised to resemble both brittle (faults) and ductile (folding) style deformation. In fact, the contrast in the viscosity of materials plays an important role in the final product of the experiments. Although designed in 3D, these experiments provide better insight in the vertical sections than horizontal sections (the plain view of faults).

Inspired by observations of present-day natural phenomena on the surface of a lake (structures in the pictures in Figures 1a, b) and observations of faults in seismic data (Figure 1c) which geometrically are similar to the structures on the water surface in Figures 1a and b, we have studied and investigated different



a) Natural structures formed on the surface of the lake

b) a close-up of part of picture in Fig.1a

c) A seismic section

Figure 1 (a) The picture shows a lake that is used as a supplier for drinking water located in Bergen, Norway. This picture (taken in 2018) was used as an inspiration for this research and the new experiments in the water tank. The structures observed here are similar to deformation structures observed in the Earth's crust (faults, folds, and flow structures). b) The picture is a close-up of Fig.1a (shown by red rectangle), resembling a main fault with a process zone at the tip, as well as smaller synthetic and antithetic faults around it. c) A very good resolution seismic section from the Norwegian Continental Shelf from the Diskos database for a comparison which shows similar fault structures as in Figure 1b but with a lower resolution.

a) Water tank at Hydrodynamics laboratory at University of Oslo

b) Natural structures formed on the surface of the lake c) Pilot study in water tank

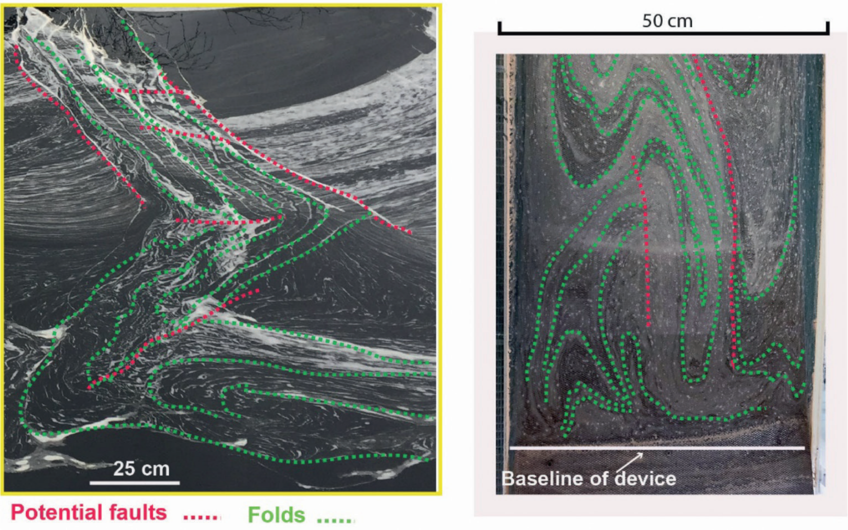


Figure 2 (a) A picture of the water tank in the hydrodynamics laboratory at the University of Oslo. b) A close-up picture of the lake surface (yellow rectangle in Fig.1a) with natural structures that were the inspiration for the experiments as shown in Figure 1a. Both brittle structures such as faults displacing the layers and ductile structures such as folds are observed in the same picture. c) Result from the first series of experiments (pilot study) performed at the Hydrodynamics Laboratory showing folds that are cut by faults formed on the surface of the water tank.

possibilities to design and perform new experiments to reproduce structures similar to nature (Figure 1a and 1b). The best option we found to run these experiments was to utilise a water tank system used for hydrodynamic studies. The structures observed on the surface of the lake are similar to deformation structures observed in the Earth's crust. Both brittle structures such as faults displacing the layers and ductile structures such as folds and flow structures are observed in the same picture (Figures 1a, b). The natural observation occurred during spring in a lake in Bergen, western Norway, where the structures formed on the water surface as a result of the interaction between the capillary forces, pollen, and probably remnants of melted ice at the water surface. The new experiments were performed in a big water tank at the Hydrodynamic Laboratory at the University of Oslo, aiming to produce similar structures to those at the surface of the lake in Figures 1a and b. These experiments were produced by the interaction between added pollen and capillary (lateral) forces to the water tank surface, hence resulting in fault initiation, propagation and growth as part of a complex system that involves interaction with other faults, folded layers and flow structures (Figure 1). We envisage that with detailed dynamic imaging, these experiments could provide a better geometric view of faults and their growth process with regard to other structures and will shed more light on the importance of shear and frictional forces in the faulting process.

The innovative water tank experiments

We have performed several experiments as a pilot (feasibility) study in the hydrodynamics laboratory at the University of Oslo's Department of Mathematics to test the feasibility of running experiments using a mixture of water and pollen in a water tank. A large water tank (25 m long and 0.5 m wide) was used for these experiments (Figure 2a). In order to create capillary waves, airflow or wind at the water surface was produced using construction fans (Heylo FD4000, each with an adjustable flow rate from 0.8 to 1.15m3 s−1 (Vollestad and Jensen, 2021). During some of the experiments barriers were added on the water to damp the waves and affect their geometry. The tank is also equipped with a laser source to illuminate the water surface for imaging both with high-resolution cameras and Particle Image Velocimetry (PIV).

Moreover, ultrasonic wave probes (General Acoustics, Ultralab USS 02/HFP, Kiel, Germany) can be utilised to measure the water surface elevation (Vollestad and Jensen, 2021). However, for these new set of experiments only cameras were used on the top and sides of the tank to image the experiments. This set-up was adjusted to accommodate the above-mentioned experiments. Pollen was added to the water surface under controlled capillary waves in order to create deformation structures similar to the natural examples in Figure 1.

The results show the first deformation structures that are comparable to nature (Figures 2b and 2c). Both pictures and videos of the experiments were captured during the pilot study. The dynamic imaging during the experiments allows for extracting the geometry of faults and other deformation structures in order to study their growth process. We envisage that the suggested experiments can impact our fundamental understanding of deformation (particularly faults) in the Earth and answer many interdisciplinary questions in this regard with respect to the importance of forces, friction and the properties of the material under deformation.

Discussions and further work

Although the initial purpose of this pilot study was to investigate fault initiation and growth, the current experiments go beyond the brittle faults and include fold and flow structures development as well. The results of experiments performed with changing the velocity of fan and the amount of pollen dissolved in the water make very interesting structures on the water tank that are similar to the natural structures on the images of the Earth at different scales, e.g. satellite images, and pictures of outcrop and core samples, respectively (Figure 3). This is the first time that such experiments involving water as the main medium are designed to study the faulting process in high resolution images, although (sea) ice deformation has been previously studied at a larger scale and much lower resolution (e.g. Itkin et al., 2017; Weiss and Dansereau, 2017) for other purposes such as climate change. The assumption that a geological medium can be modelled as a fluid has been used in other disciplines such as physics and geophysics, but has not been employed for experimental studies. An example is in processing (or more precisely migration) of reflection seismic data. The seismic imaging problem is simplified by considering the Earth to be a multi-layered fluid instead of a fully elastic medium (Bleistein et al., 2002). The multi-layer fluid assumption means that the wave propagation is governed by the scalar wave theory (Bleistein et al., 2002). The scalar wave theory considers non-Hertzian waves that are different than vector-type waves and can longitudinally propagate along the interfaces. In the water tank experiments, the capillary waves longitudinally act at the surface similar to scalar waves and therefore might result in coherent reordering of molecular structure of water (Tang et al., 2020). We suggest this reordering of water molecular structure combined with added impurity such as pollen on the water surface creating structures that are similar to the geological features. However, at this stage it is unclear how this interaction physically and chemically happens.

The results of these experiments can be utilised to not only study the fault growth process but also to answer some fundamental questions with regard to material properties and stress configuration needed to create brittle and ductile deformation. Examples are 1. How changing the friction of water change its behaviour manifested in brittle and ductile structures? 2. Can one material (e.g. one lithology in rocks similar to mixture of water and pollen in the experiments) make both ductile and brittle deformation in the same condition? 3. Is deformation dependent on the material properties or just the forces that are important? 4. Do we need both vertical stress and confining pressure (three principal stresses as described by Anderson (1905)) in order to make deformation structures or are only lateral forces (shearing) needed?

We suggest that more experiments of this type under controlled condition should be performed in order to answer some of the above questions and better understand the deformation process in the Earth.

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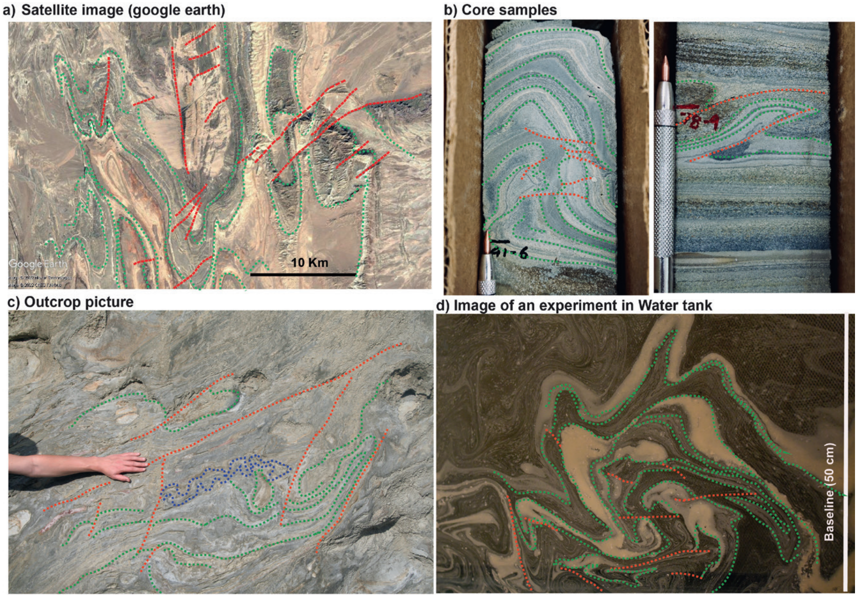
a) Satellite image (google earth)

b) Core samples

c) Outcrop picture

d) Image of an experiment in Water tank

Figure 3 A comparison between natural examples of deformation structures at different scales with the new experimental results. a) A satellite image of Kavir-e-Lut (Iran) showing folds cut by major faults (Google Earth image). b) Images of two core samples from Oligocene Lacustrine strata showing syn-sedimentary faults and folds, courtesy of Applied Stratigraphix by Ali Jaffri. The pens are for scales. c) An outcrop picture showing syn-sedimentary deformation (small faults, folds, and flow structures) in deep-water sediments, Southern Spain. The arm is for the scale. d) An example of new experiments showing folds and faults. The interpretations (drawings) on the images show only the main structures and do not include all the details. Note that faults are shown in red dashed lines, folds in green and flow structures in blue.

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Data availability statement

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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