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A new apparatus for analog modeling of clay smears

Moses Karakouzian*, Nick Hudyma

Department of Civil and Environmental Engineering, Howard Hughes College of Engineering, University of Nevada, 4505 Maryland Parkway, Box 454015, Las Vegas, NV 89154-4015, USA

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Abstract

An apparatus has been developed for analog modeling of clay smears. This rather simple apparatus compliments the more sophisticated but less common geotechnical engineering ring shear apparatus that has been used in previous studies of clay smear formation. The new apparatus provides analog modelers with the ability to view and record soil deformation and formation of clay smears. The laboratory produced deformations and clay smears are very similar to those found in nature. A complete deformation history and clay smear formation process is documented.

Keywords: Analog modeling; Clay smears; Shear bands; Deformation history

1. Introduction

Structural discontinuities within the subsurface usually cause differences in permeability from the surrounding formation. For petroleum geoscientists, one structural discontinuity of importance is clay smears. This paper presents a newly developed apparatus that can be used in conjunction with analog modeling to follow the development of clay smear formation. The apparatus could be used to study the effects of stratigraphy and material properties on the formation of clay smears as well as the development of fabrics, permeability evolution and defraction of fractures. The purpose of this paper is to describe the apparatus and demonstrate through a limited number of tests, the viability of using the apparatus to study clay smears.

Clay smears are thin layers of clay or shale that separate sand layers juxtaposed across a fault (Lindsay et al., 1993). Clay smears are important structures because they may act as barriers to fluid flow across a fault. It is important, especially in the field of petroleum geology, to understand how clay smears are formed.

Clay smear formation has been inferred from field studies (for example, Lehner and Pilaar, 1991; Aydin and Eyal, 1996), laboratory studies (for example, Weber et al., 1978; Sperrevik et al., 2000) and from quantitative prediction models (Yielding et al., 1997). This paper presents an analog modeling technique that was developed to study the formation of clay smears within a layered system. The system that was modeled for this study consisted of alternating layers of sandstone and shale.

2. Analog modeling

Analog modeling is a technique where deformations seen in the field are experimentally duplicated in the laboratory. Koyi (1997) presented an excellent overview of the history, materials, difficulties, techniques and future trends of analog modeling.

There are several drawbacks to analog modeling, which include:

- there are limited analog materials that can simulate the whole range of rock properties and behaviors,
- it is not possible to simulate any chemical reactions which may occur during deformation and
- the in situ properties of rocks are not always well known (Koyi, 1997).

Despite these drawbacks to analog modeling, there is one very important advantage of analog modeling over observing field deformation; analog models are usually set up to allow the recording or observation of the complete deformation history during a short time interval.

The input data to an analog model, most importantly for in situ rock properties, is often defined qualitatively, based on material behavior, and modeling materials are chosen

* Corresponding author. Tel.: +1-702-895-0959; fax: +1-702-895-3936.
E-mail address: mkar@unlv.edu (M. Karakouzian).

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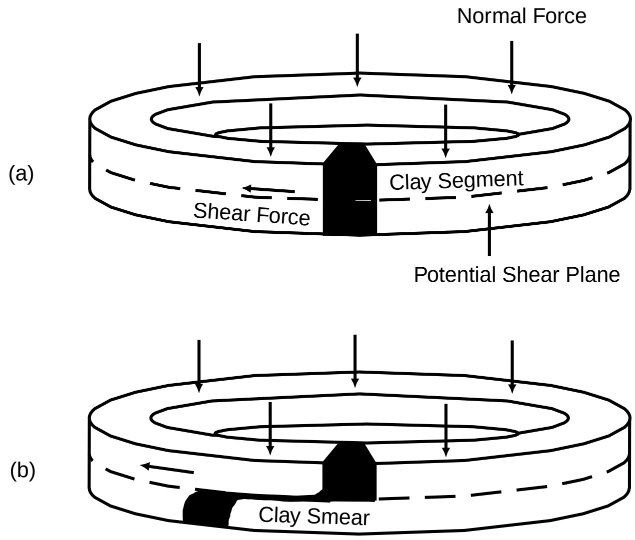

Fig. 1. Schematic diagram of a ring shear apparatus. (a) components and forces. (b) Clay smear.

accordingly (Koyi, 1997). For example, the system that was modeled in this study consists of alternating layers of sandstone and shale. The materials chosen for this study consists of clay to represent the shale layers and a fine silica sand to represent the sandstone layers.

3. Previous laboratory studies of clay smear formation

Two previous studies have investigated the formation of clay smears in a laboratory setting. Both studies used a ring shear apparatus. Mandl et al. (1977) designed a special ring shear apparatus to investigate the development of shear zones in granular materials. During their study, they also conducted experiments on specimens that contained zones of sand alternating laterally with vertical bands of clay. The specimen was sheared under various simulated overburden pressures along a median slip plane. A schematic diagram of a ring shear apparatus is shown in Fig. 1.

They found that the deformed specimen contained one continuous, multi-layered clay smear, which formed along the median slip plane. The clay smear contained sand grains but it still provided an effective seal to water flow (Weber et al., 1978). The geometry of the clay smears were compared with clay smears found in a lignite mine near Frechen, Germany. The clay smear formed in the laboratory closely resembled the geologically formed clay smear (Weber et al., 1978).

Sperrevik et al. (2000) also used a ring shear apparatus to investigate the formation of clay smears. The goal of their experiments was to determine the influence of different stress conditions, clay properties and clay percentage in the formation of clay smears. They found that the development of a clay smear was dependent on the competence contrast between clay and sand. When the clay was less competent than the sand, the clay exhibited ductile behavior, and a clay smear formed. When the clay was more competent than the sand, the clay exhibited brittle behavior, and the clay was fragmented and distributed over the shear surface.

4. Deformation apparatus and specimens

The ring shear apparatus used in the previous laboratory studies on clay smear formation is a very specialized piece of geotechnical engineering testing equipment. Such equipment may not be available to researchers interested in petroleum geology and engineering. One of the driving forces behind this research was to design an apparatus that could be easily constructed, that was easy and fast to operate and would provide analog modelers insight into the formation of clay smears.

A cross-sectional sketch of the deformation apparatus is presented in Fig. 2a and b. The outer tube is a steel cylinder that has an inside diameter of 57.2 mm, is 230 mm tall and 10 mm thick. A bottom stage is connected to a plunger that ensures the top and bottom movements of the specimen are synchronous. The bottom guide ensures that the bottom stage will remain perpendicular to the shearing direction. An elliptical viewing window has been cut into the outer tube. At its widest and longest axes, the window measures 50.8 and 102 mm, respectively. The centerline of the window is in line with the centerline of the specimen. The viewing window allows video recording of the specimen during deformation.

4.1. Specimens

The specimens were produced in a clear acrylic tube that was 102 mm in length and had a diameter of 50.8 mm. Each of the two specimens had a bottom clay layer that ensured the specimen did not fall out of the acrylic tube. The specimens were deformed to a slip of 50 mm. The first specimen was used to compare the clay smears formed in the laboratory with clay smears formed geologically. This specimen consisted of sand layers that were approximately 15 mm thick and clay layers that were approximately 10 mm thick. The second specimen was deformed so that its complete deformation history could be described using both photographs and the video recording. The specimen consisted of sand layers that were approximately 6 mm thick and clay layers that were approximately 10 mm thick. The specimens used in this study consisted of horizontal layers and deformation took place perpendicular to the layering. It is possible to produce specimens with inclined layering.

4.2. Materials

Two types of materials were needed to produce the layered soil specimen, a granular (sand) and a cohesive

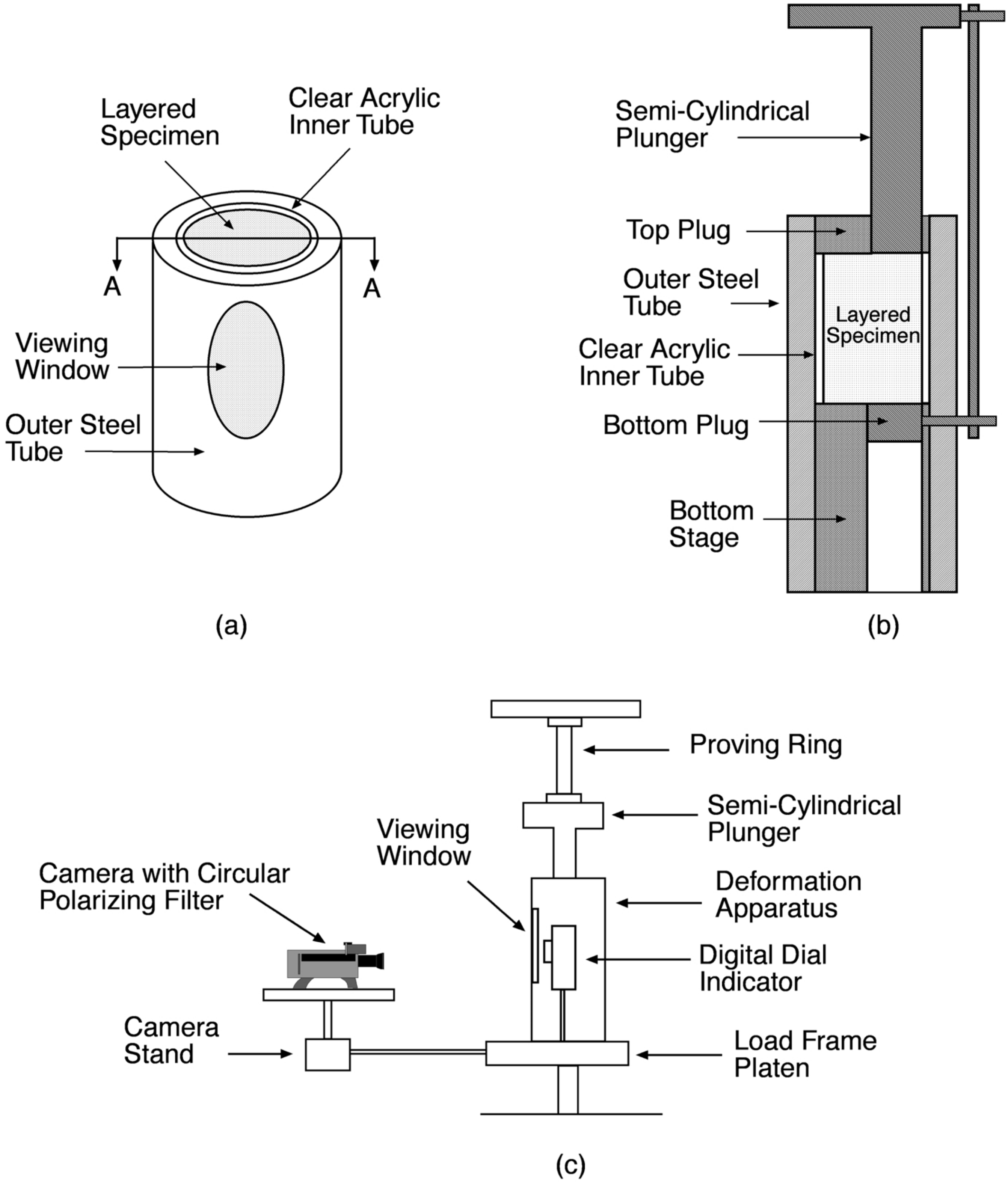

Fig. 2. Deformation apparatus. (a) External view of outer steel tube showing the viewing window. (b) Cross-section of the deformation apparatus. (c) Deformation apparatus set-up. Drawings are not to scale.

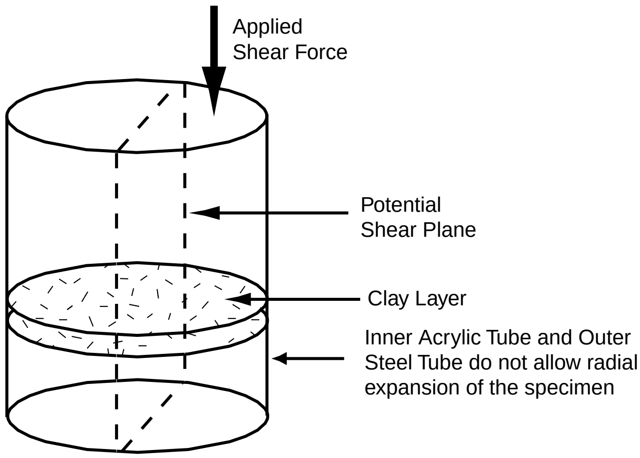

Fig. 3. Applied forces in the new apparatus.

(clay) material. The granular material that was chosen was Ottawa Foundry Sand F-110. It is silica sand that is available from the U.S. Silica Company. The grains are rounded and have a specific gravity of 2.65. The classification (USCS) of the sand is SP, a poorly graded (well sorted) sand. The sand was dyed pink, gray and blue using stamp pad ink. Using dyed sand allowed easy identification of sand layers across the slip plane of the deformed specimen.

The cohesive material that was used to produce the specimen was specially blended clay. The clay was a mixture of kaolin clay (50%), pyrophyllite clay (20%) and feldspar particles (30%). These materials were mixed together at a water content of approximately 23%. The clay mixture had a liquid limit of 42% and a plastic limit of 22%. The mixture produced an off-white colored cohesive material that could easily be trimmed with a wire saw.

4.3. Apparatus set-up

The specimen was sheared perpendicular to layering. The half of the specimen that was held in place during shearing is referred to as the passive side (hanging wall) and the side that was subjected to the force of the plunger is referred to as the active side (footwall).

A small load frame was used to provide the force to shear the specimen. The deformation apparatus was placed on the platen of the load frame. A variable rate motor controlled the movement of the platen, which was kept constant at $1.6\ \text{mm min}^{-1}$. A digital dial indicator was attached to the load frame. The indicator measured the movement of the platen, which indirectly measured the displacement of the plunger into the soil specimen.

A camera stand was constructed and attached to the platen of the load frame. An 8-mm camcorder was used to record the specimen deformation and the digital dial indicator. The dial indicator was recorded so that deformation events could be linked to the displacement of the plunger. A circular–polarizing filter was added to the camcorder. The filter reduced or eliminated the glare produced by light reflecting from the surface and/or scratches on the acrylic tube. Fig. 2c contains a sketch of the deformation apparatus, load frame, camera stand, camcorder and digital dial indicator.

4.4. Comparison of the ring shear apparatus with the newly designed apparatus

There are two main differences between the ring shear apparatus and the newly designed shear apparatus: stress conditions during shearing and data collected during shearing. The ring shear apparatus is a doughnut shaped vessel that is split in half horizontally along the median plane. The upper half of the apparatus is fixed and the lower half of the apparatus is able to rotate. For the clay smear studies using the ring shear apparatus, the apparatus was filled with alternating zones of sand and clay. The specimen is confined in both the radial and vertical directions. A normal load is applied in the vertical direction, parallel to the layering while the specimen is sheared perpendicular to the layering (Fig. 1).

The goal of the newly designed shear apparatus is to shear the specimen perpendicular to the layering with one side, the passive side, having little or no deformation vertically or radially and the other side, the active side, sliding past the passive side, deforming vertically but not deforming radially. This stress condition is referred to as a K_o stress condition, which is the predominant state of stress of sediments undergoing burial in the presence of uniform gravitational loading (Maltman, 1994). Unlike the ring shear apparatus, the only applied force acting on the specimen is the shearing force (Fig. 3).

There is also a difference in the data collected during shearing between the two specimens. The ring shear apparatus is a geotechnical engineering testing apparatus that is typically used to determine shear strength parameters of soil samples. Thus, shear stress, displacement, sample height and other parameters can easily be determined from instrumentation used in conjunction with the ring shear apparatus. These measurements are typically plotted as stress–strain curves.

Such precise measurements may not be needed for studying the formation of clay smears in the laboratory. Stress–strain curves from geotechnical testing reflect the bulk behavior of the deforming specimen. The formation of a clay smear is a complex phenomenon and the ring shear apparatus provides no visual record to indicate what deformation events accompany the various anomalies in the stress–strain curves. Thus, the stress–strain curves may not aid in describing the formation of clay smears.

The newly developed apparatus was designed and constructed to allow analog modelers to view and record the formation of shear zones and clay smears at different stages of deformation. For this study, image data and strain

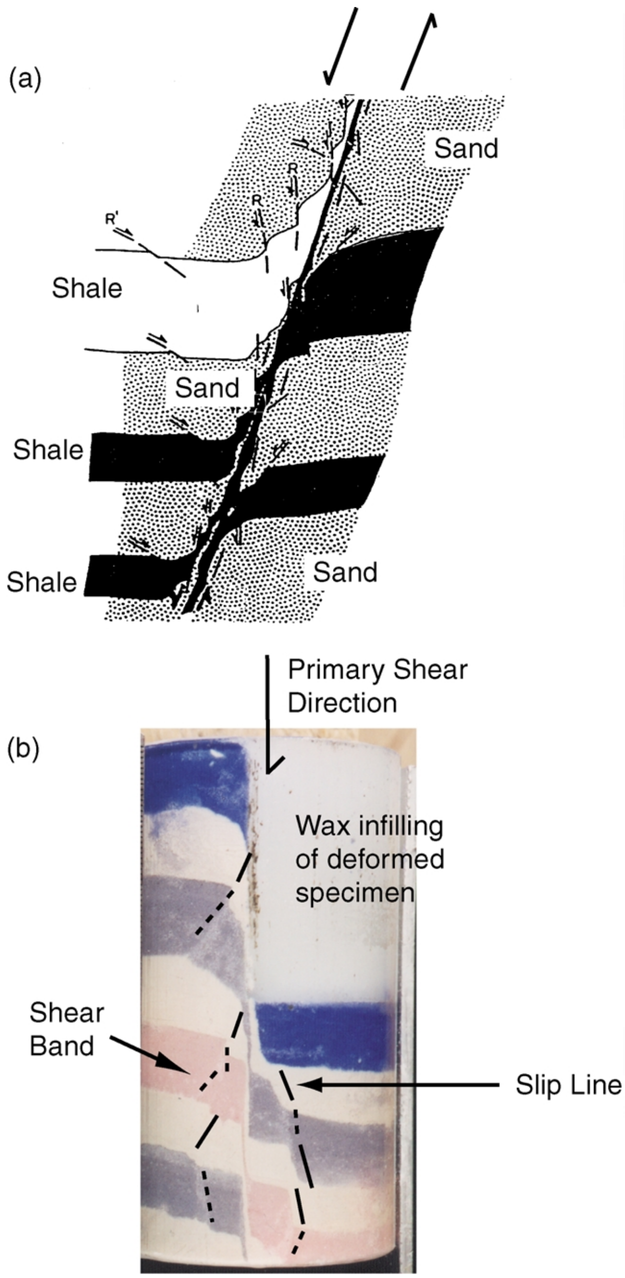

Fig. 4. Comparison of geologically and laboratory formed clay smears. (a) Geologically formed clay smear (after Weber et al., 1978). (b) Laboratory formed clay smear. Sand layers are colored and clay layers are white.

data were collected. The image data tracked the progressive formation of the shear zone and clay smear. The displacement data that was recorded documented the movement of load frame platen, which indicated the movement of the plunger into the soil sample. During this study, the apparatus was not configured to record the shear stresses required to deform the specimen.

Besides allowing video recording of the deformation of the specimen, there are several other advantages of the new apparatus. The apparatus is easy to use, test set-up is fast and simple and a number of experiments can be performed in a relatively short period of time. As mentioned previously, specimens can be made with inclined layering.

5. Comparison of geologically and laboratory produced clay smears

The results of laboratory deformations were compared with a geologically formed clay smear. Weber et al. (1978) described and provided a sketch of a clay smear from a lignite mine near Frechen, Germany. The deltaic sequence that contained the clay smear consisted of alternating well-bedded loose to slightly over-consolidated sands, silts, shales and gravels. The average sand/shale ratio was approximately 75/25. Fig. 4 contains a sketch of a geologically produced clay smear from the lignite mine and a photograph of an experimentally produced clay smear from this study.

The geologically and laboratory produced smears are similar in terms of the components of the clay smear and deformation features outside of the clay smear. With regard to the composition of the clay smear, both smears include clay from more than one layer. Sand is also present in the clay smears. The sand pinches out in the direction of shearing. The sand appears to be continuous within the clay smear, which could be representative of plastic behavior of the granular material. Since the majority of the materials within the smear are clay, it is likely that the plastic behavior of the clay masks the true behavior of the sand, even though the sand and clay occupy distinct zones.

There are also similarities in the types of deformation that are present outside of the clay smear. Weber et al. (1978) identified three sets of displacement shears in the geologically produced clay smear. They are the fault-parallel principal displacement shears (D-shears), Riedel shears (R-shears) which lie en échelon, inclined at 10–30° to the D-shears with the acute angle pointing in the direction of relative movement of the fault block in which they occur, and the conjugates to the Riedel shears, the R′-shears. It appears from Fig. 4 that the R-shears begin in the sand layers and terminate within the shale layers. The R′-shears appear to begin and terminate in the clay/shale layers.

In the laboratory-formed clay smears there are also three sets of displacement shears. The first set of displacement shears are fault-parallel principal displacement shears, which occur parallel to the primary shear direction. These shears are caused by the experimental testing conditions imposed on the specimen. Since the specimen is sheared vertically, the majority of the deformation takes place vertically along the plane on which the specimen is sheared. However, there are other orientations in which deformation takes place.

A second set of displacement shears occur in the sand layers of the specimens. They are called shear bands, which are well defined narrow regions of intensely sheared

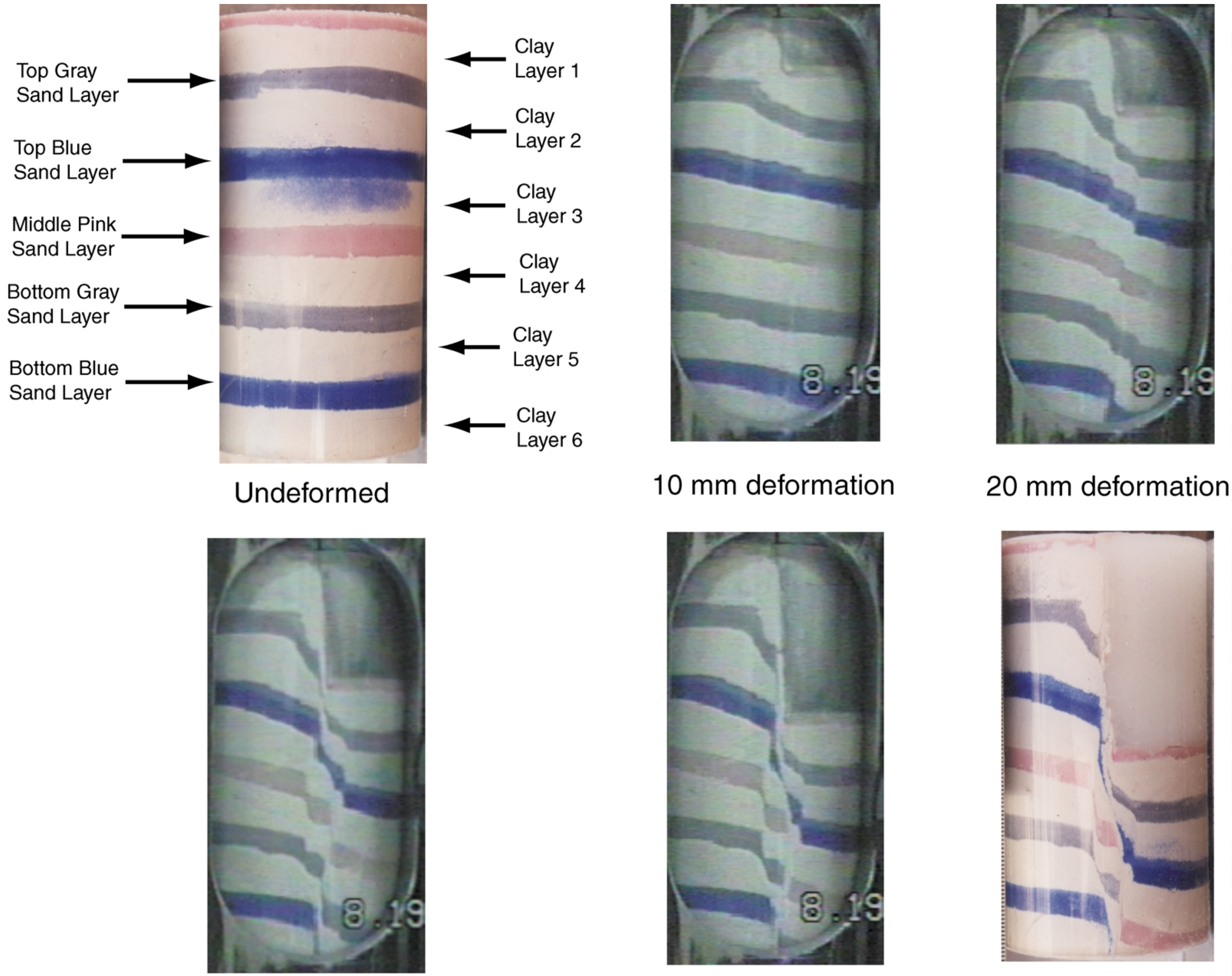

Fig. 5. Photographs and video snapshots of a specimen at intermediate stages of deformation.

material in which significant decreases in density have occurred (Scarpelli and Wood, 1982; Vermeer, 1990). In the photograph, shear bands appear as light colored linear features. The orientation of the shear bands varies from parallel to the primary shear direction to inclined at an angle of approximately 40° to the primary shear direction. Shear bands are not the same as deformation bands. Within deformation bands, pores collapse and sand grains fracture, resulting in the reduction of grain size and an increase in density (Aydin and Johnson, 1978).

A third set of displacement shears identified is slip lines, which are the clay equivalent to shear bands (Vermeer, 1990). Slip lines occur within clay layers. Their orientation is approximately 15° to the primary shear direction.

6. Deformation history of a specimen

In this section, the deformation and smear formation of a specimen will be discussed. The discussion is based on a continuous video recording of the test. The specimen is made up of six clay layers, each approximately 10 mm thick, and six sand layers, each approximately 6 mm thick. The clay layers are white and the sand layers are colored blue, pink and gray. Fig. 5 contains a photograph of the specimen before deformation, video snapshots of the specimen after 10, 20, 30 and 40 mm of deformation and a final photograph of the specimen after 50 mm of deformation. The deformation history is divided into 10 mm segments. Each of the segments are discussed below.

6.1. Plunger displacement 0–10 mm

Deformation begins at the top of the specimen but is also seen at the bottom of the specimen. As expected, deformation is highest at the top and smallest at the bottom. Layers throughout the specimen have changed in orientation, from initially horizontal to dipping on the active side (footwall) of the specimen. This change in orientation can be attributed to frictional forces imposed by the plunger causing the clay and sand layers to be dragged into the forming fault. There are no signs of a through-going fault developing.

6.2. Plunger displacement 10–20 mm

The top gray sand layer exhibits clay-like deformation and is necking or pinching out from the passive side to the active side (footwall). It appears a through-going fault is beginning to develop in the middle of the specimen. This is indicated by the formation of slip lines in clay layers 2, 3 and 4. The bottom blue sand layer is almost truncated. The truncation may indicate the formation of a through-going fault zone. The truncated layer is not dragged into the fault zone because there is no influence of the plunger on this layer.

6.3. Plunger displacement 20–30 mm

The top gray sand layer continues to neck or pinch out until the plunger causes the layer to be cut off at the passive–active interface. The top blue sand layer is now beginning to pinch out across the passive–active interface. The middle pink sand layer and the bottom gray sand layer have been truncated and a smear has formed. The smear is formed by plastic deformation of the clay layer parallel to the primary shear direction.

6.4. Plunger displacement 30–40 mm

The top blue sand layer has pinched out and a seal has formed. An almond-shaped fault zone has formed and movement is beginning to occur along a second plane. This may indicate that strain hardening is occurring within the specimen and a second preferential shear plane has formed. The active side (footwall) is still moving en mass which causes continual pinching out of the top gray and top blue sand layers.

6.5. Plunger displacement 40–50 mm

By 50 mm of plunger displacement, the second shear plane is clearly visible and the almond-shaped fault zone is clearly formed. The top blue and top gray sand layers are strung out across the passive–active interface. The middle pink sand layer has begun to pinch out along the second shear plane. It appears the bottom gray sand layer has been truncated for a second time and a sand pocket is now beginning to form. It is interesting to look at the locations of the various sand layers across the passive–active interface. At the top of the fault zone, the strung out top gray sand layer, the top blue sand layer and the middle pink sand layer are now side-by-side with a thin clay layer separating the strung out sand layers. Near the middle of the fault zone, the strung out top blue sand layer is juxtaposed with the truncated middle pink sand layer that is juxtaposed with the truncated bottom gray sand layer. The bottom gray sand layer sand pocket then appears, which is not adjacent to any sand layers on either the active (footwall) or passive (hanging wall) sides. Finally, at the bottom of the fault zone, the truncated middle pink sand layer is juxtaposed with the truncated bottom blue sand layer.

Most of the displacement is along the initial shear plane but there was clearly movement along the second shear plane. The movement along the second shear plane caused a second seal to begin to form that caused the formation of sand pockets. The sand pockets were formed from material belonging to the middle pink sand layer and the bottom gray sand layer.

7. Summary

A new apparatus has been developed for use in analog modeling of clay smears. The two specimens used in this study consisted of alternating layers of sand and clay, which were used to model a faulted sequence of sandstone and shale layers. The apparatus is equipped with a viewing port that allows video recording of the specimen deformation. The geometry of a laboratory-formed clay smear is similar to geologically-formed clay smears. The advantage of incorporating a viewing port into the design of the apparatus was demonstrated by examining a specimen with very complicated deformation structures using only before and after photograph and using video snapshots from intermediate stages of deformation. For analog model studies of clay smear formation, the new apparatus will compliment the more sophisticated but less common ring shear apparatus, a geotechnical engineering testing apparatus.

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References

Aydin, A., Johnson, A., 1978. Development of faults as zones of deformation bands and slip surfaces in sandstone. Pure and Applied Geophysics 116, 931–942.

Aydin, A., Eyal, Y., 1996. Anatomy of a normal fault with shale smear. American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists — Annual Meeting Abstracts, Vol. 5, p. 7.

Koyi, H., 1997. Analogue modeling: from a qualitative to a quantitative technique — a historical outline. Journal of Petroleum Geology 20, 223–238.

Lehner, F.K., Pilaar, W.F., 1991. On a mechanism of clay smear emplacement in synsedimentary normal faults. American Association of Petroleum Geologists Bulletin, 75(3), 619.

Lindsay, N.G., Murphy, F.C., Walsh, J.J., Watterson, J., 1993. Outcrop studies of shale smears on fault surfaces. International Association of Sedimentologists Special Publication 15, 113–123.

Maltman, A., 1994. The Geological Deformation of Sediments. Chapman & Hall, New York.

Mandl, G., de Jong, L.N.J., Maltha, A., 1977. Shear zones in granular material. Rock Mechanics 9, 95–144.

Scarpelli, G., Wood, D.M., 1982. Experimental observations of shear band patterns in direct shear tests. Proceedings of the IUTAM Conference on Deformation and Failure of Granular Materials. Delft, Netherlands, pp. 473–484.

Sperrevik, S., Faerseth, R.B., Gabrielsen, R.H., 2000. Experiments on clay smear formation along faults. Petroleum Geoscience 6, 113–123.

Vermeer, P.A., 1990. The orientation of shear bands in biaxial tests. Geotechnique 40, 223–236.

Weber, K.J., Mandl, G., Pilaar, W.F., Lehner, F., Precious, R.G., 1978. The role of faults in hydrocarbon migration and trapping in Nigerian growth fault structures. Tenth Annual Offshore Technology Conference Proceedings.

Yielding, G., Freeman, B., Needham, D.T., 1997. Quantitative fault seal prediction. AAPG Bulletin 81, 897–917.