Journal of Structural Geology, Vol. 9 No. 1, pp. 87 to 103, 1987
Printed in Great Britain

0191–8141/87 $03.00 + 0.00

Centrifuge modelling of laccolith intrusion

JOHN M. DIXON

Experimental Tectonics Laboratory, Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada K7L 3NG

and

DAVID G. SIMPSON

ESSO Resources Canada, Ltd, 237—4th Avenue, S.W., Calgary, Alberta, Canada T2P OH6

(*Received* 7 *October* 1985; *accepted in revised form* 18 *March* 1986)

Abstract—Laccolith intrusion has been investigated by centrifuge modelling. Silicone putty, representing magma with Bingham rheology, is intruded by overburden pressure through a circular conduit into a stack of paraffin wax layers, which represent sedimentary strata. The model intrusions evolve through a sequence of geometric forms similar to those exhibited by natural laccoliths; the results are also in accord with published mathematical analyses of laccolith formation. The model magma first flows laterally between overburden layers to form a sill. As the sill increases in area, the cover strata are arched upwards into a sinusoidal, 'bending' form. Subsequently, the overburden fails abruptly by kinking above the periphery of the intrusion, and the form changes to a cupola separated from surrounding horizontal strata by a sharp inflection in the layering. Finally, strata on the flanks of the cupola undergo a second episode of localized failure. The top of the dome becomes flat, and the dipping flanks become a monoclinal flexure surrounding this 'kink' form.

A number of variables influence this evolution. Increased overburden strength, thickness of overburden strata, and total thickness of overburden all prolong the bending form to larger intrusion size, delay the localized failure which marks the cupola and kink stages, and reduce the aspect ratio of the intrusion at all stages. Effectively bonded overburden interfaces have a similar effect, but interfaces with sharply defined yield strengths enhance development of the monoclinal flexure. Magmatic driving pressure affects the rate of intrusion, but not the evolution of its form. Intrusion rate is also influenced by magma flow properties, and probably by the form of the feeder conduit. The range of final forms preserved by natural laccoliths probably results from competition between rate of intrusion, controlled by driving pressure and conduit geometry, and rate of chilling of magma in the laccoliths. The model laccoliths form in times that scale to between one and a few tens of years, in agreement with available estimates for natural laccoliths.

INTRODUCTION

"Instead of rising through the beds of the earth's crust, it stopped at a lower horizon, insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds . . . it congealed, forming a massive body . . . the name laccolite . . . will be used." Gilbert (1877, p. 19)

WITH this passage G. K. Gilbert defined the concept of the laccolith and recognized the existence of concordant intrusions other than sills. Prior to Gilbert's investigation of the Henry Mountains of Utah, there had existed considerable reluctance to admit that igneous intrusions of large dimensions could occur. Indeed Hunt (1953, p. 86) noted that "during the 1870's . . . the stocks of western Utah . . . (were interpreted) . . . as protuberances of the crystalline basement overlapped by the sediments around them". Gilbert's report contained sufficient evidence to convince most geologists of the time that such large crystalline masses could indeed be intrusive in origin, and that they could deform the rocks into which they are intruded. Hunt (1980) has eloquently documented the features of Gilbert's original work that render it one of the classics of the geological literature on igneous structures.

General acceptance of the igneous origin of laccoliths led to intense interest in intrusive bodies, and to a vast volume of literature devoted to their description and classification. Several authors offered explanations of the development of laccoliths, most considering the properties of the magma itself or its mode of injection as the dominant factor (Gilbert 1877, Paige 1913, Darton & Paige, 1925, Barksdale 1937, Hurlbut & Griggs 1939). The overburden was commonly treated as a passive factor in determining the final form of the body. In his original report Gilbert explained both the presence and form of laccoliths through an analogy with a simple hydraulic press, although thickness and cohesive strength of the overburden control the size and domal curvature of laccoliths in his model.

Hunt's 1953 paper is a detailed investigation of the type area for laccoliths that has provided many of the data used by later workers. He suggested that laccoliths form as protuberances from the margins of stocks. Mudge (1968) considered conditions that appear to favour intrusion of concordant igneous bodies into flat-lying layered rocks. He found that such bodies typically form beneath 900–2300 m of overburden, and at a stratigraphic level characterized by a prominent parting surface and overlain by a ductile unit that may have acted as a 'crack-stopper'. This concept of termination of an upward-propagating, fluid-filled crack by a horizontal plane of weakness has been further analysed by Weertman (1980).

Pollard and his co-workers (Pollard 1968, Johnson 1970, Johnson & Pollard 1973, Pollard & Johnson 1973, Pollard & Holzhausen 1979, Koch *et al.* 1981) presented detailed mechanical analyses of the evolution of laccoliths. They investigated the effect of magma rheology and driving pressure on the intrusion process, and analysed the deformation of the host rocks in terms of elastic plate-bending theory. They concluded that overburden properties are the dominant factors controlling laccolith development, the magma acting only as a pressurized fluid.

Scale models of laccoliths have been constructed by several workers (Howe 1901, MacCarthy 1925, Hurlbut & Griggs 1939, Pollard 1968). All involved bench-top experiments performed at 1 **g**, with the inherent limitations on scaling body and surface forces, material properties and time that this condition imposes. In early experiments (Howe 1901, MacCarthy 1925) the stratified overburden was simulated by sand, marble or coal dust, and plaster, deposited in a water-filled tank. The magma, simulated by plaster–water slurry or molten wax, was injected into the stratified sediment column with a piston-cylinder device. Hurlbut & Griggs (1939) made similar experiments with solid and fluid plaster, and with stearic acid magma intruded into stratified 'plastiline'. None of these experimental studies focused on evolution of the structures; rather they sought to reproduce the final geometry of laccoliths. Some superficial resemblance was achieved, but scaling was haphazard.

Pollard (1968, Pollard & Johnson 1973) employed photo-elastic gelatin to model the stratified rocks and grease for the magma. His experiments differed from those of the earlier workers in that the deformation of the overlying strata was elastic rather than ductile or brittle. He focused on the stress distribution in the cover due to its deflection by the intrusion, and compared the experimental results with his mathematical analysis based on plate-bending theory. As his experiments were performed at 1 **g** on the laboratory bench, body forces were not scaled in proportion to surface forces.

In this paper we present results of an experimental study (Simpson 1980) of the evolution of laccoliths. We have employed the technique of centrifuge modelling and have attempted to apply the appropriate scaling relationships so that the experimental results can be compared with natural laccoliths and with the mathematical analyses of Johnson & Pollard (1973), Pollard & Johnson (1973) and Koch *et al.* (1981), and the analogue experiments of Pollard & Johnson (1973). The experiments successfully reproduce the principal characteristics of natural laccoliths, including the geometric form and its temporal evolution, and the localized failure of the cover strata that has been observed around the periphery of the intrusions. By varying the appropriate parameters, we have investigated the influence of overburden strength and properties of overburden interfaces, total overburden thickness, overburden layer thickness, and magmatic driving pressure on the intrusion process. Unfortunately, many of these variables are ill-defined for natural laccoliths, so quantitative evaluation of the experimental results is difficult at the present. It is our hope that natural laccoliths will be re-examined in the light of our experimental results, with appropriate attention being paid to the variables that we have studied. Two aspects of the intrusion of natural laccoliths are specifically not modelled in this study. One is the progressive increase of magma viscosity (strength) associated with its cooling and crystallization, and the other is brittle failure of the cover strata that may lead to formation of a peripheral fault.

CHARACTERISTICS OF NATURAL LACCOLITHS

Gilbert (1877) described the ideal laccolith as being a concordant, dome-shaped intrusive body with a nearly flat top and steeply dipping sides (see Figs. 1a & b). The ideal intrusion would be circular in plan, although variations in the resistance to magma penetration and layer bending could cause deviations from the circular form. The magma would have been introduced from below through a feeder pipe or dyke. Such feeder conduits are rarely exposed (Hurlbut & Griggs 1939, Johnson & Pollard 1973), although McBride (1979) has described small laccoliths intersected by feeder dykes in the northern Adel Mountains of Montana. Hunt (1953) visualized laccoliths as horizontal offshoots from a central stock (see Fig. 1c). A laccolith may evolve during continued intrusion to a fault-bounded 'sphenolith' (Cross 1894) or 'bysmalith' (Iddings 1898), the roof strata being tilted like a trap-door or lifted as a rigid plug relative to the surroundings (see Figs. 1d & e).

Most laccoliths appear to have been intruded into flat-lying sedimentary strata at a depth ranging from 1 to 3 km below the ground surface (Hunt 1953, Barksdale 1937, Mudge 1968, Johnson & Pollard 1973). The host rocks may be any sort of sediment, although sandstone–shale sequences are the most common. Small, near-surface laccoliths also form in stratified volcanic rocks, such as in Hawaii and Iceland. The horizons at which laccoliths form are generally well-defined stratigraphic boundaries, such as contacts between sandstones and shales, or zones of weakness, such as interfaces between sandstone beds or lava flows. Most laccoliths are only generally concordant, the lower contact often cutting upwards through a few tens of metres of stratigraphic section from the centre towards the periphery of the intrusion.

The deformation of overburden strata due to the intrusion is commonly limited to that portion of the overburden immediately surrounding and overlying the laccolith. The strata remain essentially undeformed to

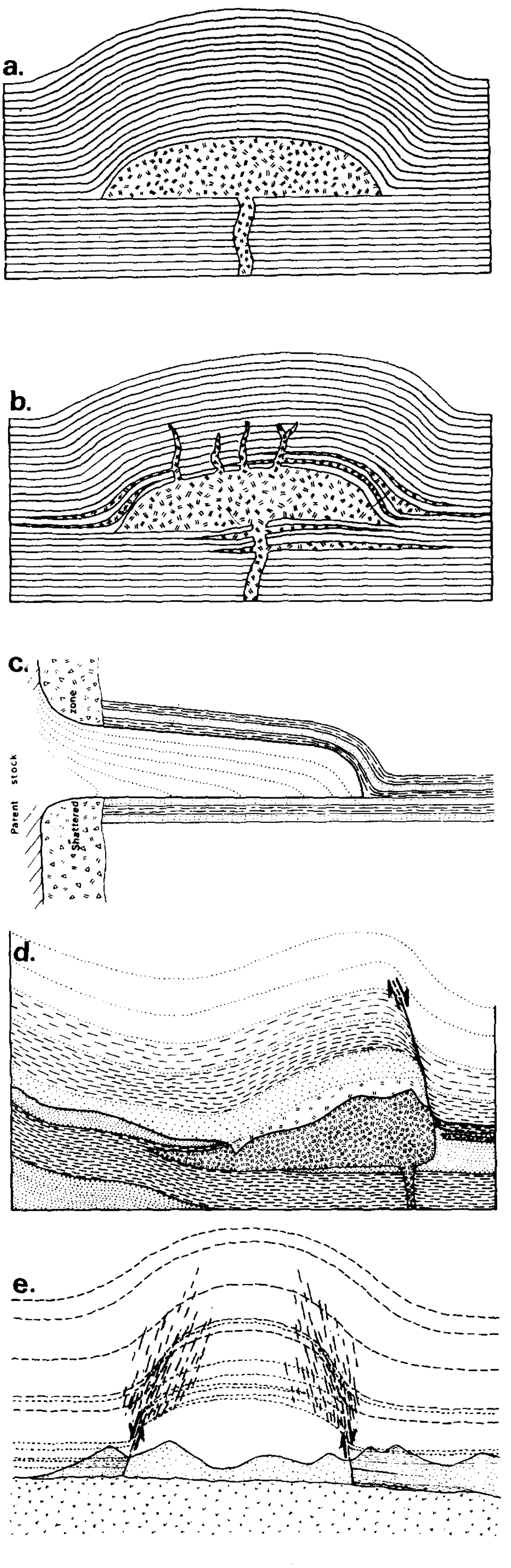


Fig. 1. Concepts of the laccolith. (a) and (b) from Gilbert (1877). (c) Hunt's (1953) concept of a laccolith as a lateral protuberance from a stock. (d) Peripheral faulting produces a sphenolith (from Cross 1894) or (e) a bysmalith (from Iddings 1898).

within a few tens of metres of the intrusion periphery. Here the beds exhibit a sharp upward flexure, parallel to the flank of the intrusion. Angles of dip range from 30 to 90°. The top of the intrusion and the overlying strata are nearly horizontal. Although some laccoliths exhibit gentle flexures of the overburden over the entire body, the steep-sided, flat-topped form bounded by a double monoclinal flexure apparently represents the most common final stage in the formation of a laccolithic intrusion.

Laccolithic bodies are typically a few hundred to several thousand metres in horizontal extent and a few tens to a few hundreds of metres in thickness at the centre. Natural laccoliths tend to have aspect ratios (amplitude/diameter) of approximately 0.1. The laccoliths of the Henry Mountains average 3.67 ± 1.72 km long by 1.79 ± 1.01 km wide by 370 ± 210 m in maximum thickness, with volumes estimated at 0.96 ± 0.67 km^3. These figures represent the mean ± one standard deviation calculated from the figures given by Hunt (1953). Johnson & Pollard (1973) cite 1 km^2 as the minimum size of laccoliths in the Henry Mountains; they classify intrusions smaller than this as sills, which have considerably lower aspect ratios. Shonkin Sag laccolith, in the Highwood Mountains of Montana (Weed & Pirsson 1901, Barksdale 1937, Hurlbut & Griggs 1939), is an example of a circular, flat-topped laccolith. It measures approximately 3.75 km in diameter and up to 75 m in thickness. This is about the middle of the size range of the laccoliths in the Highwood Mountains.

Laccolithic intrusions form from a variety of magma types, typically alkalic in character. The Colorado Plateau laccoliths are dominantly diorite porphyry (Hunt 1953), while those of Montana vary from shonkinite (mafic-rich nepheline syenite) to quartz monzonite and granite porphyry (Larsen 1940). Available evidence indicates that the magmas forming most laccoliths were of relatively high viscosity, perhaps even having a finite yield strength (Johnson & Pollard 1973). This evidence includes blunt terminations of associated sills and dykes; the crushing of phenocrysts; the slickensiding and brecciation of surrounding rocks (Hunt 1953, Pollard & Johnson 1973); the dominantly porphyritic character of the intrusive rocks, with up to 50 volume-per cent of phenocrysts (Johnson & Pollard 1973); the large size of xenoliths supported by the magma in some of the Henry Mountains laccoliths (Johnson & Pollard 1973); and thermodynamic investigations (Nash & Wilkinson 1970) which indicate that the magmas in the Highwood Mountains, at least, consisted of a low-temperature crystal mush. Furthermore, the contact–metamorphic effects of the majority of laccoliths are relatively minor, rarely extending more than a few metres from the contact (Barksdale 1937, Hunt 1953, Johnson & Pollard 1973).

The formation of laccolithic intrusions involves uplift of the cover strata against the force of gravity and implies that the magmatic pressure in the intrusion exceeds the local lithostatic pressure. The magmatic driving pressure (defined as the excess of the magmatic pressure over the lithostatic pressure at a given depth) can be calculated, assuming that the magma is not tectonically pressurized, if the density of the magma, its source depth, and the density distribution in the crustal column are known. Johnson & Pollard (1973) estimated that the magmatic driving pressure of the Henry Mountains laccoliths could have been as high as 70 MPa if the magma had a specific gravity of 2.65 and originated at a depth of 40 km. The driving pressure would have been lower if the density was higher, the depth of origin shallower, or if the magma had a finite yield strength.

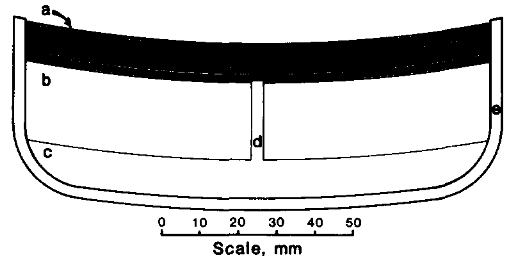


Fig. 2. Dimensions and initial geometry of laccolith models of this study (longitudinal section; the model extends 76 mm perpendicular to the plane of the figure). (a) Multilayered wax–vaseline overburden (specific gravity approximately 0.95). (b) Plasticine (sp. gr. 1.77) substrate that supports overburden strata and pressurizes the model magma. (c) Silicone putty (sp. gr. 1.15) in the model magma chamber. (d) Silicone putty in the 3-mm diameter magma conduit that terminates at the top of the lowest overburden stratum. (e) Plasticine casing surrounding the model.

SCALE MODELLING

Model geometry and rheological characteristics

In this study we constructed scale models in which a pressurized fluid intrudes upwards through a circular conduit into a horizontally stratified overburden. The models have dimensions and initial geometry as shown in Fig. 2. We focused on the geometric evolution of the intrusion, and also investigated the influence of parameters such as overburden thickness, layer strength and layer thickness, nature of the layer interfaces, and fluid driving pressure on the intrusion process. We employed the centrifuge technique (Ramberg 1967, 1981) so that models can be constructed of conveniently stiff materials which do not deform under their own weight at 1 **g** on the lab bench. The experiments were carried out at 2000 **g**, using the centrifuge (described by Dixon & Summers 1985) in the Experimental Tectonics Laboratory at Queen's University. The models are scaled after natural prototypes according to the model ratios listed in Table 1.

The magma is simulated by silicone putty (obtained from Marketing, Inc., New Jersey, in 1977), which has a specific gravity of 1.15. Similar material, manufactured by Dow-Corning Chemical Co. as Dilatant Compound No. 3179, has since been subjected to rheological testing (Dixon & Summers 1985). This material exhibits complex rheological properties: it is elastic under short-term, high-stress conditions, approximately linearly viscous at strain rates between 10^1 and 10^{-1} s^{-1}, but increasingly non-linear at lower strain rates. Its behaviour approximates power-law flow with stress exponent n equal to 7 ± 2 at strain rates of 10^{-3}–10^{-5} s^{-1}; this high stress exponent means that it closely approximates plastic behaviour (Chapple 1978). It has an effective yield strength of about 300 Pa below 10^{-5} s^{-1} (Dixon & Summers 1985). With this complex rheological behaviour, the Dow-Corning silicone putty is intermediate between Bingham and pseudoplastic substances (see Fig. 3). Its behaviour is similar to a Bingham material with a yield strength of 325 Pa and a Bingham viscosity of 1.82×10^4 Pa s^{-1} (Dixon & Summers 1986). The Bing-

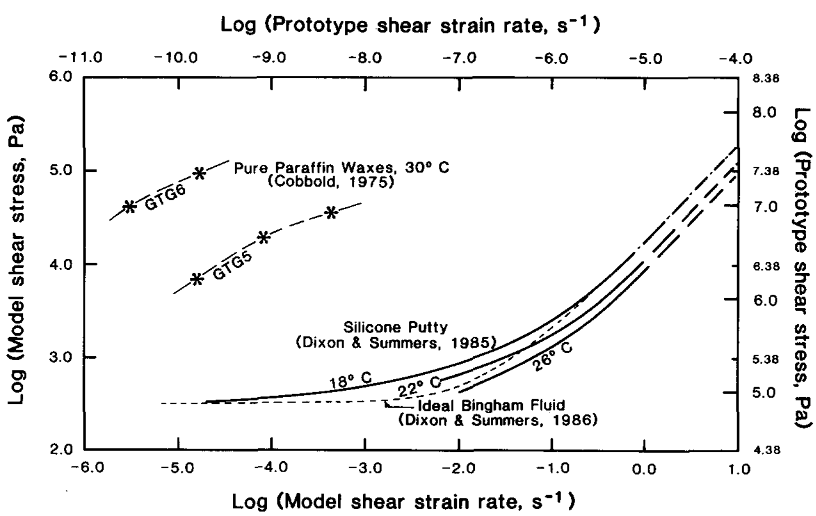


Fig. 3. Log (shear stress) vs log (shear strain-rate) relationships for silicone putty at 18, 22 and 26°C (from Dixon & Summers 1985) and pure paraffin wax at 30°C (from Cobbold 1975). The left-hand and lower axes are calibrated in units that apply to the model materials; the flow curves are transformed into descriptions of the equivalent prototype materials by application of the appropriate model ratios (Table 1), as shown on the right-hand and upper axes. Paraffin wax exhibits power-law behaviour with stress exponent, $n = 2 \times 0.5$. Addition of vaseline lowers the strength of the wax, but our centrifuge experiments were run at temperatures of 22–25°C, rather than 30°C; the wax curves shown therefore approximate the range of behaviour of the wax–vaseline mixtures employed in our models. Silicone putty approximates ideal Bingham behaviour (as shown by the light dashed curve; see text and Dixon & Summers (1986) for discussion).

Table 1. Model ratios applicable to the present study

Quantity	Model ratio	Scaled equivalents
Length	$l_r = 5 \times 10^{-6}$	10 mm in model = 2 km in prototype
Specific gravity	$\rho_r = 4.2 \times 10^{-1}$	1.15 in model = 2.75 in prototype
Acceleration	$a_r = 2 \times 10^3$	2000 g in model = 1 g in prototype
Time	$t_r = 10^{-5}$	1 s in model = 27.8 h in prototype
Stress	$\sigma_r = 4.2 \times 10^{-3}$	1 Pa in model = 238 Pa in prototype

ham and pseudoplastic rheological models have been applied as possible descriptions of the behaviour of the magma during laccolith intrusion (Johnson & Pollard 1973). The silicone putty employed in the models described in this paper appears to be very similar to the Dow-Corning material, but we have not carried out a detailed study of its rheology.

The 'magma reservoir' of silicone putty is lithostatically pressurized by an overlying block of Plasticine (Harbutt's Gold Medal Brand) which acts as a quasi-rigid substrate to the intrusion. The plasticine has a specific gravity of 1.77. A vertical, circular conduit, 3 mm in diameter and initially filled with silicone putty, allows the model magma access through the plasticine to the base of a stratified cover sequence composed of thin layers of a mixture of paraffin wax (ESSO Parowax) and vaseline (Yellow Protopet—Witco Chemicals Ltd). Intrusion takes place between the two lowest layers of the overburden stack. The wax–vaseline overburden strata do not fracture readily; they act as a 'crack-stopper' (Mudge 1968, Weertman 1980) which localizes the lateral spread of the silicone putty.

Paraffin wax is a polycrystalline aggregate composed of various hydrocarbon species; vaseline is readily soluble in any proportion. Pure paraffin has a specific gravity of 0.95. Its rheological properties make it a suitable rock-analogue. Addition of vaseline to the wax inhibits brittle behaviour; the ratio of these constituents can be varied to alter the strength of the overburden strata. On the basis of unconfined uniaxial compression tests done in our laboratory, a 95/5 weight-per cent (wax–vaseline; compositions of wax–vaseline mixtures will henceforth be designated, for example, W95/V05) mixture exhibits Young's modulus (E) between 10^7 and 2×10^6 Pa at 24–27°C. Addition of more vaseline systematically reduces the Young's modulus: W75/V25 has E between 5×10^6 and 10^6 Pa in the same temperature range. With the model ratios specified (Table 1) these values are equivalent to prototype modulus of 2.4×10^9–4.8×10^8 Pa and 1.2×10^9–2.4×10^8 Pa, respectively, that is, about two orders of magnitude softer than most rock types. Elastic strains produced at model creep stresses are very low (<1%), and the contribution of elastic strain to model deformation is thus relatively small, but this flaw in the scaling may be partially responsible for the relatively larger sizes of our model laccoliths in comparison to natural intrusions (see Discussion below). Beyond the yield point paraffin waxes exhibit power-law flow with stress exponent n equal to 2.6 (Cobbold 1975; see Fig. 3). The influence of vaseline on the yield point and flow characteristics of paraffin has not been tested quantitatively; qualitatively, vaseline promotes ductile behaviour and suppresses brittle failure in the models.

Thin layers of wax (or wax–vaseline mixtures) of any desired thickness can be conveniently prepared in quantity by pouring a measured volume of molten wax onto the surface of hot water in a shallow pan of known area and allowing the water to cool below the freezing temperature of the wax (Summers 1979).

The flow characteristics of Dow-Corning silicone putty (Dixon & Summers 1985) and pure paraffin wax (Cobbold 1975) are illustrated in the log (shear stress) vs log (shear strain-rate) plot in Fig. 3. The bottom and left-hand axes are calibrated in units relevant to the experiments. The upper and right-hand axes are calibrated in units that apply to the equivalent prototype. The two sets of axes are related by the model ratios listed in Table 1. Thus, with the chosen ratios, silicone putty represents a Bingham magma with a yield strength of 7.0×10^4 Pa and a Bingham viscosity of 2.3×10^{11} Pa s^{-1} (see Dixon & Summers 1986 for discussion). Pure paraffin wax at 30°C would represent a relatively weak rock which exhibits power-law flow and a strength of at least 2.3×10^6 Pa (at a nominal strain rate of 10^{-10} s^{-1}). The wax–paraffin mixture that we employ represents a weaker prototype material, but our models were run at 22–25°C; thus the plotted wax curves probably span the range of behaviour of our wax–vaseline mixtures.

Geometric evolution of the model laccoliths

Several initially identical models, with geometry as in Fig. 2 and with overburden comprising 20 layers of W95/V05, each 0.5 mm thick, were subjected to 2000 g in the centrifuge for various lengths of time. Three models, designated DF0a, b and c, were run in stages, and their geometry carefully recorded as a function of time. Four others, designated DF4, DF7, DF9 and DF10, were run for extended periods, to different stages of completion, so that their final geometry could be compared with that of models from interrupted runs. In general it was found that the two types of deformation history produced similar evolutionary sequences of geometric form, but models from uninterrupted runs evolved slightly faster.

The geometric evolution of the model laccoliths (Fig. 4) can be divided into four stages, here named the *sill*, *bending laccolith*, *cupola* and *kink laccolith* stages. The silicone putty initially spreads laterally from the vertical conduit, forming a concordant intrusion with a low aspect ratio (amplitude/diameter) that resembles a sill (Figs. 4a–c). We apply the name sill to this form even though the intrusions are not strictly symmetrical (Pollard & Johnson 1973, Pollard & Holzhausen 1979) about the horizontal plane. In our experiments the sill form is distorted by the relative rigidity of the Plasticine substrate. As the model magma spreads laterally the surface area of the intrusion increases; it is eventually large enough that the upward force exerted by the magma can raise the overburden strata against the force of 'gravity'.

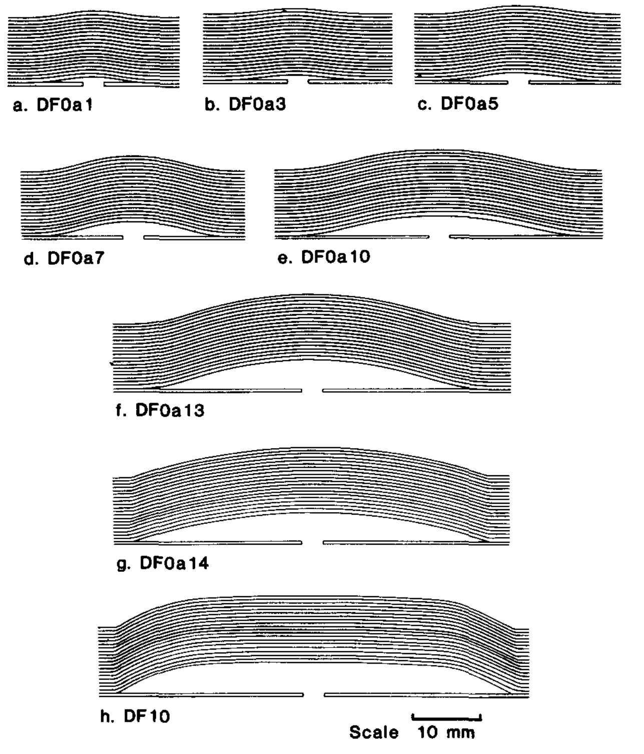


Fig. 4. Geometric evolution of laccoliths of the standard DF series. (a)–(c) Sill stage. (d)–(f) Bending laccolith stage. (g) Cupola stage. (h) Kink laccolith stage.

This point marks the onset of the bending laccolith stage, during which the aspect ratio increases, albeit subtly, and the intrusion develops a sinusoidal profile (Figs. 4d–f and 5). This stage resembles the form derived by Pollard (1968) and Pollard & Johnson (1973) from elastic plate-bending theory.

Next, the sinusoidal profile changes suddenly to a form with a domed top but a relatively sharp kink around the lateral tip of the intrusion (Figs. 4g and 6). During this cupola stage the intrusion continues to increase both in diameter and amplitude, and the hinge line of the kink-like deflection in the overburden strata migrates radially outward as the intrusion grows. The kink develops quickly, in less than 120 s in all models, and represents localized plastic failure of the overburden strata. Pollard (1968, Pollard & Johnson 1973) has demonstrated that the differential stress in the sinusoidally deflected overburden reaches a maximum value above the periphery of the intrusion. Thus, this is the most likely locus of failure.

The final, or kink laccolith, stage follows development of a second kink in the overburden strata, this one at the top of the dipping flanks of the intrusion (Figs. 4h and 7). As the second kink forms, the roof of the intrusion changes from a domed to a flat form, and the amplitude actually decreases. The cover strata now have the form of a circular monoclinal flexure with relatively sharply defined kink-like hinges. With continued intrusion the laccolith grows in diameter, its amplitude remains constant or decreases slightly, and the two kink hinges migrate radially through the cover strata. This second episode of localized failure of the overburden occurs once the intrusion reaches a critical size at which the stresses arising from the bending moment due to the weight of the overburden locally overcome the combined bending resistance and resistance to interlayer slip of the cover strata. This event in the evolution of the form of laccoliths is in accord with a mathematical model developed by Pollard (1972) and Koch *et al.* (1981), in which the overburden layer interfaces are treated as having a finite yield strength.

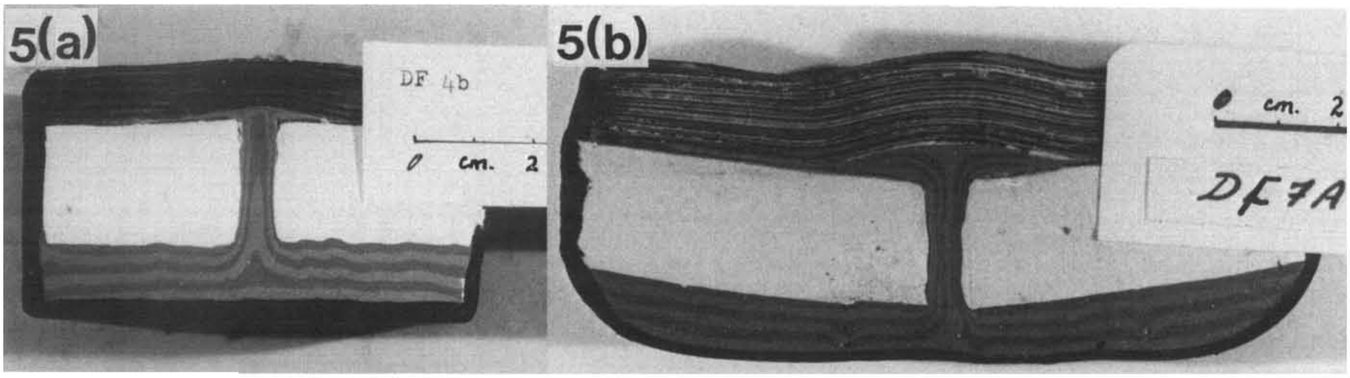
We observed no further changes in form in any of our models. We expect, however, that if the overburden strata were modelled with a more brittle substance, the kink structure might fail in a brittle fashion on a circular, steeply dipping fault; with continued intrusion the structure would assume the form of a sphenolith (Cross 1894) or a bysmalith (Iddings 1898), depending on whether the fault extended partially or completely around the intrusion.

The progressive changes in amplitude, diameter and volume during growth of the model laccoliths of series DF0 (solid circle, square and triangle symbols) and the final forms of models DF4, 7, 9 and 10 (numbered open circles) are illustrated in Figs. 8–11; the measurements on which these figures are based are listed in Table 2. As can be seen from Fig. 8, the rate of intrusion of the model magma in the DF0 series, expressed as volume per unit time, is almost constant throughout the development of the structures, independent of the changing form of the intrusion. A slight decrease in flow rate with time may occur at about 2000 s, which corresponds with the beginning of the final, or kink laccolith stage. The rate of intrusion is largely controlled by the flow of silicone putty through the circular feeder conduit under a virtually constant hydrostatic head. There may be a slight drop in head caused by constriction of the flow as the Plasticine substrate layer sags into the lower reservoir.

Fig. 5. (a) Transverse vertical section of model DF4b, late in the sill stage (the apparent waviness in the reservoir layering is due to deformation arising from sectioning). (b) Longitudinal vertical section of model DF7a, at the bending laccolith stage.

Fig. 6. Model DF9, at the cupola stage. (a) Partially disassembled, showing free surface on the left and top view of first overburden layer above the intrusion on the right. (b) Transverse vertical section, showing domed form of intrusion and peripheral bounding kink in overburden strata. (c) Under-side of overburden, obliquely lighted from the top to emphasize the sharp definition of the peripheral kink and the smoothly domed roof. Note circular outline of the intrusion.

Fig. 7. Model DF10, at the kink stage. (a) Partially disassembled, showing free surface on the left and top view of first overburden layer above the intrusion on the right. (b) Transverse vertical section, showing flat-topped form of intrusion and peripheral monoclinal kink in overburden strata. (c) Under-side of overburden, obliquely lighted from the top to emphasize the sharp definition of the peripheral kinks and the flat roof. Note circular outline of the intrusion.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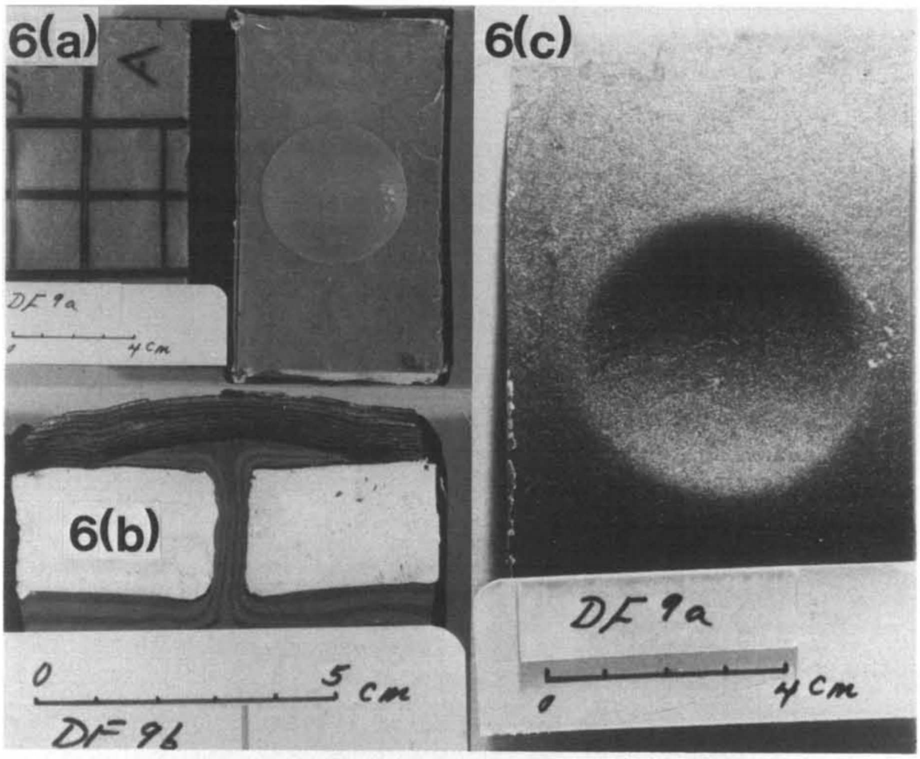
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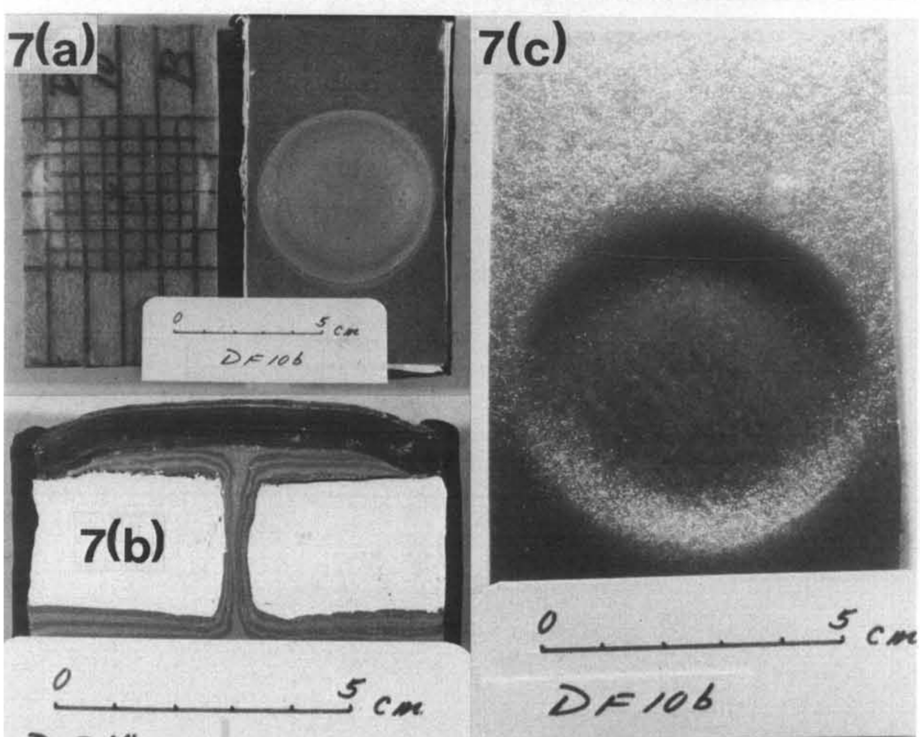
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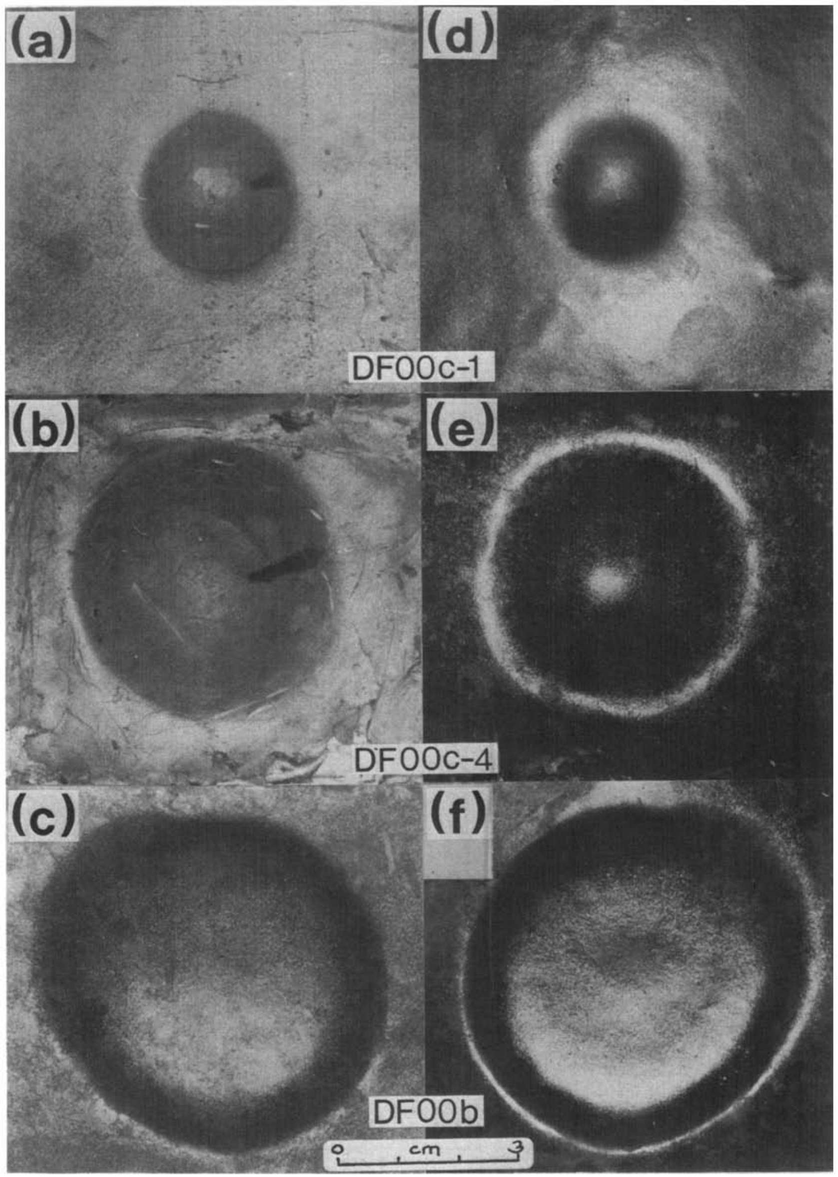


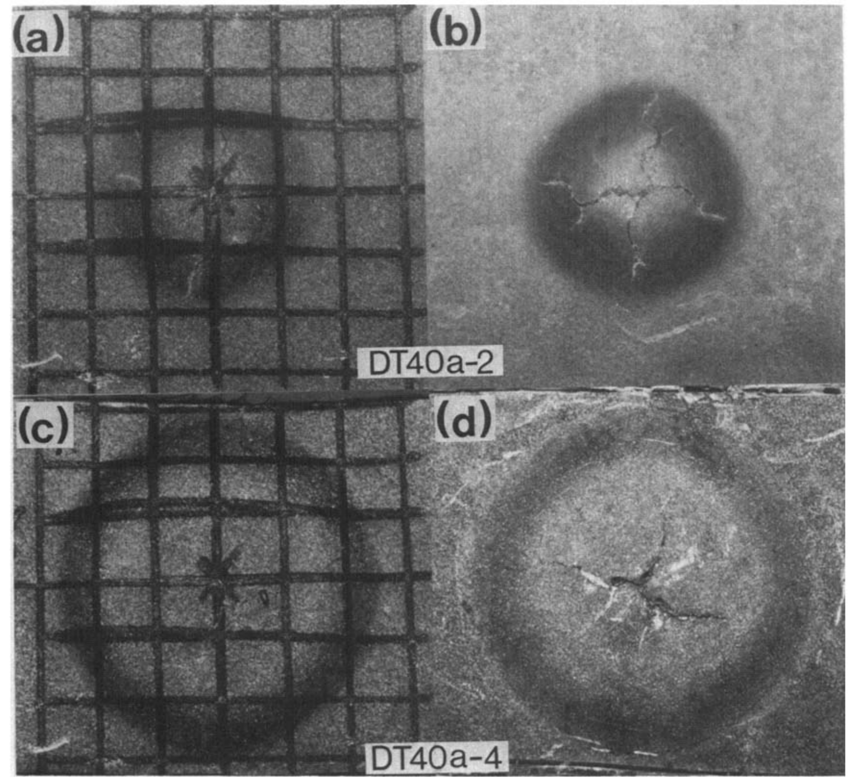
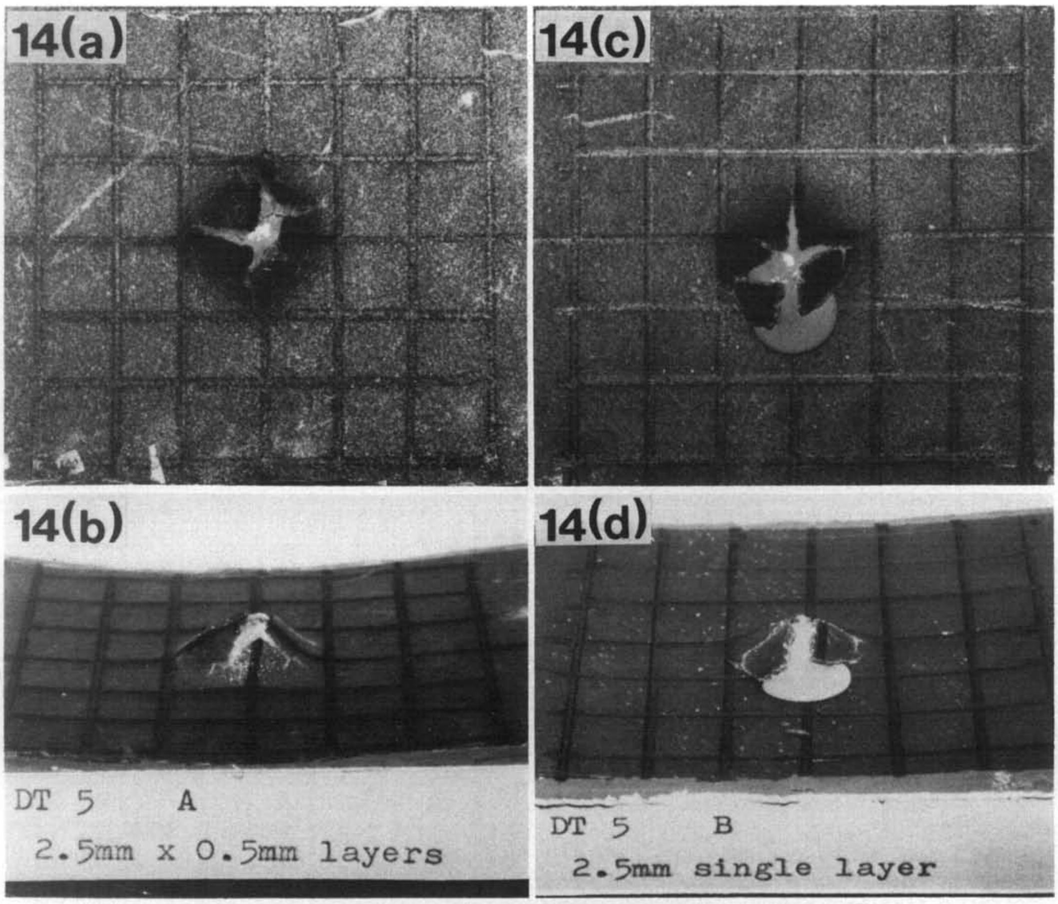
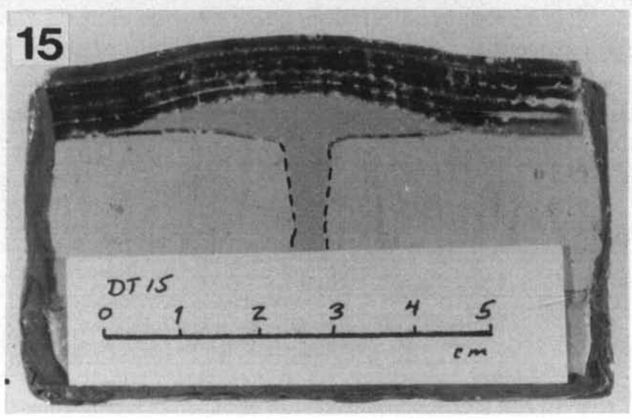


Fig. 12. (Left.) Model laccoliths of the DF00 series, constructed with a weaker overburden than those of the standard DF series. (a)–(c) Top surface of the intrusion at the bending, cupola and kink stages, respectively. (d)–(f) Under-side of the overburden stack, lighted to emphasize the form of the intrusion, at the bending, cupola and kink stages, respectively. These models evolved through the same sequence of forms as the standard series.

Fig. 13. (Above.) Model DT40a, constructed with a thinly laminated overburden totalling 5.0 mm thick. (a), (b) Free surface of overburden and top surface of intrusion at the cupola stage. (c), (d) Free surface of overburden and top surface of intrusion at the kink stage. Scale is indicated by 1-cm grids in (a) and (c). Note circularity of intrusion and radial cracks in overburden. Note also the smaller size of intrusion at a given stage in comparison with models of the standard DF series (see Figs. 6 and 7).





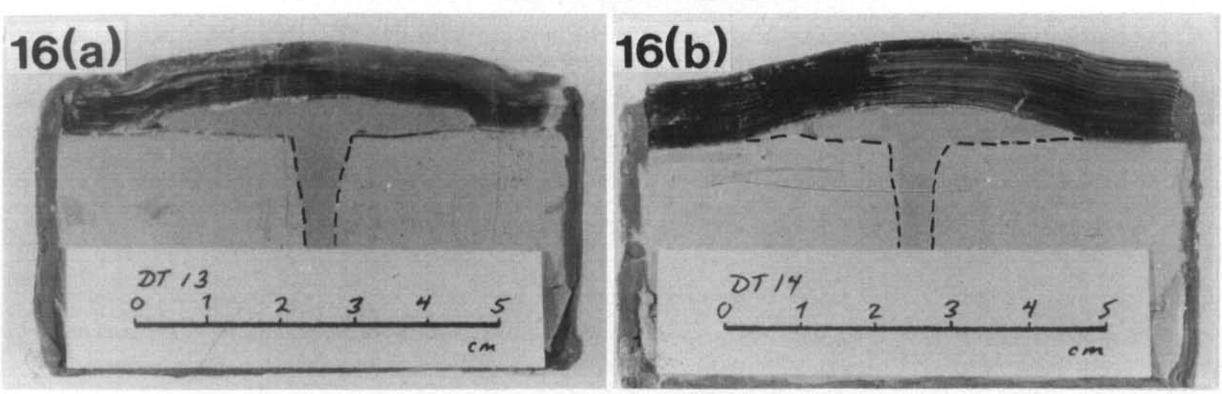
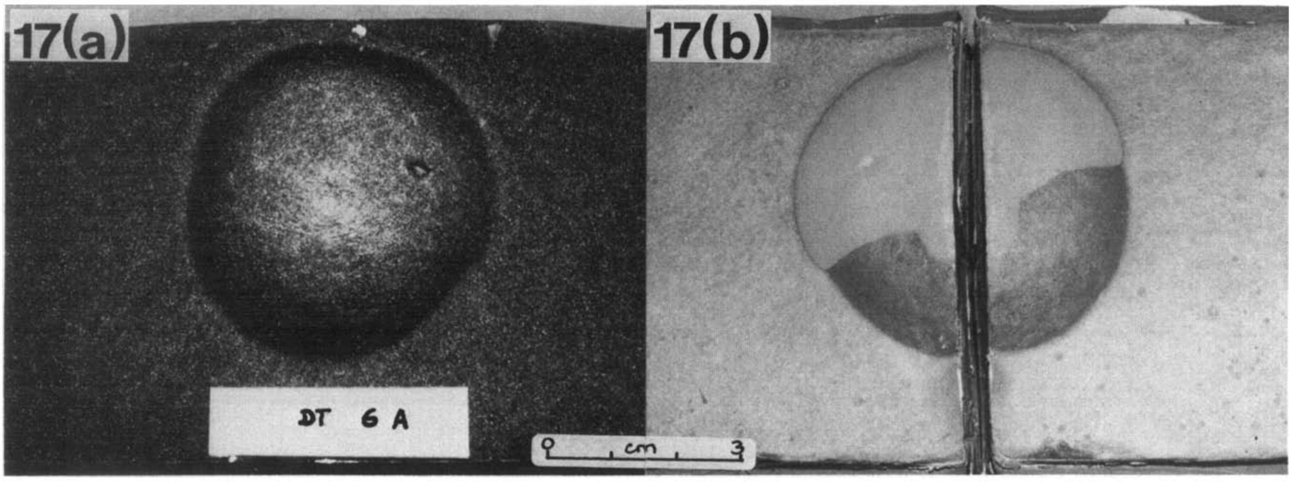


Fig. 14. Models DT5a and b, constructed with overburden stacks 2.5 mm thick (thinly laminated in DT5a and a single thick layer in DT5b). (a), (b) Vertical and oblique views of the top surface of DT5a. Note upward-gaping, radial fractures. (c), (d) Vertical and oblique views of the top surface of DT5b. Note radial fractures through which silicone putty 'magma' has reached the surface. Scale is indicated by 1-cm grids on surfaces of models.

Fig. 15. Model DT15, constructed with a thickly laminated overburden. This model developed an intrusion with the bending form.

Fig. 16. Effect of interlayer properties on the form of the intrusion. (a) Model DT13, with vaseline-coated interlayer contacts, developed a sharply defined, steeply dipping monoclinal flexure (kink laccolith form). (b) Model DT14, with graphite-bonded inferfaces, developed slowly only to the bending stage.



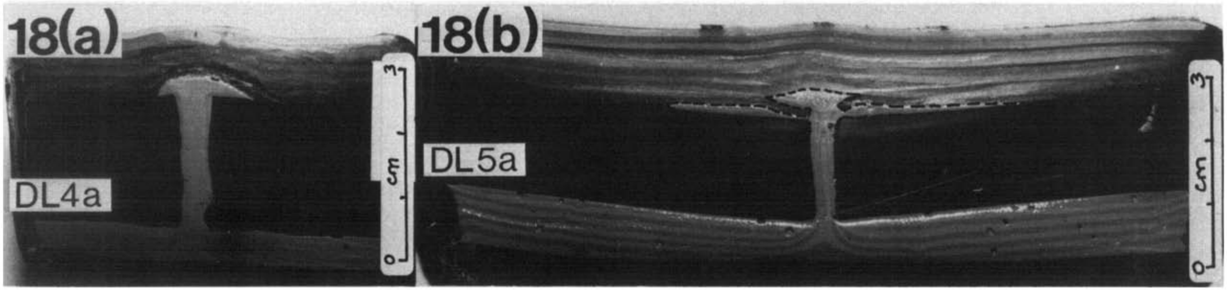


Fig. 17. Model DT6a, in which the spreading silicone putty 'magma' stepped downwards below the lowest overburden wax layer, and therefore encountered greater resistance to bending of the overburden stack. The magma was able to spread further beneath the thinner overburden (towards the top in the figures). (a) Under-side of the wax overburden, highlighted to emphasize the form of the intrusion. (b) Vertical view of the wax layer immediately overlying the intrusion.

Fig. 18. Other intrusion effects observed in the models. (a) Model DL4, constructed with weak overburden strata, each 1.0 mm in thickness, and with the lowest stratum bonded to the Plasticine substrate. Intrusion at the level of this interface met with strong resistance to lateral spreading; the weak overburden allowed formation of a highly domed intrusion. (b) Model DL5a, constructed with weak overburden layers, each 1.0 mm thick. The spreading magma has penetrated between the overburden strata at two horizons, thereby forming a compound intrusion resembling a laccolith underlain by a sill. For clarity the form of the intrusion is outlined in ink in the figure.

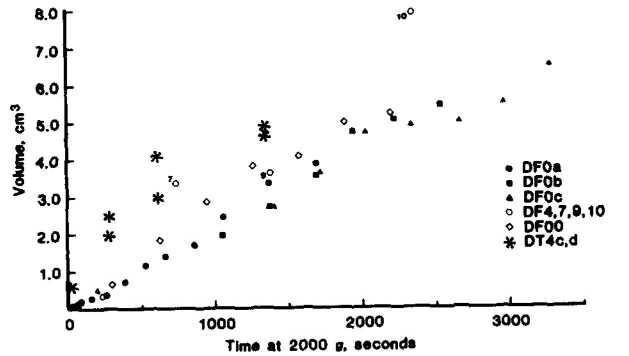


Fig. 8. Graphical representation of the growth of volume of selected model laccoliths as a function of time. See Tables 2 and 3 for estimates of errors associated with volume values.

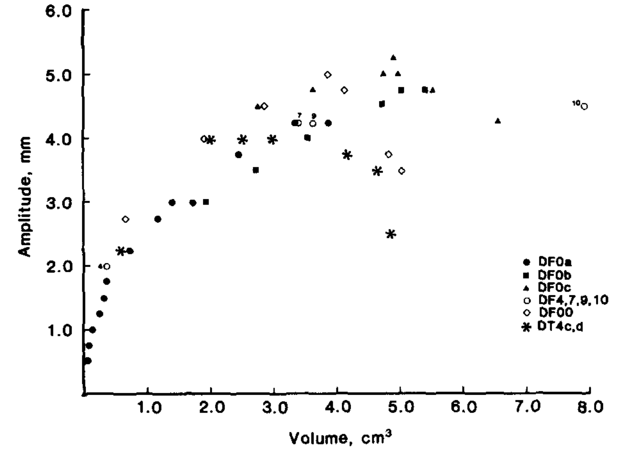


Fig. 11. Relationship between amplitude and volume for selected laccolith models. Open triangle indicates original value; individual models evolve from left to right. Note tendency for amplitude to increase and then decrease; the decrease is associated with flattening of the roof of the laccolith as the kink stage commences. See Tables 2 and 3 for error estimates.

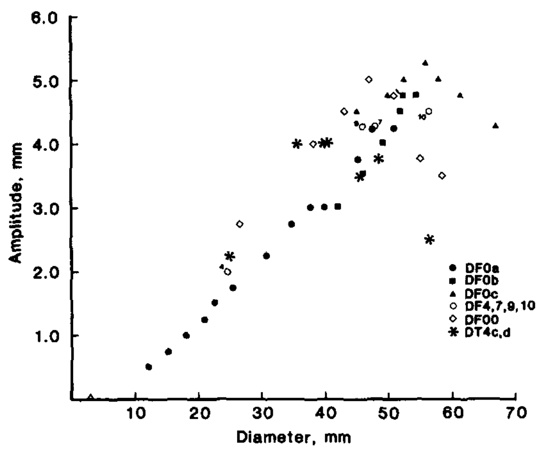


Fig. 9. Relationship between amplitude and diameter for selected laccolith models. Open triangle indicates original value; individual models evolve from lower left towards upper right. Note tendency for amplitude to increase and then decrease; the decrease is associated with flattening of the roof of the laccolith as the kink stage commences. See Tables 2 and 3 for error estimates.

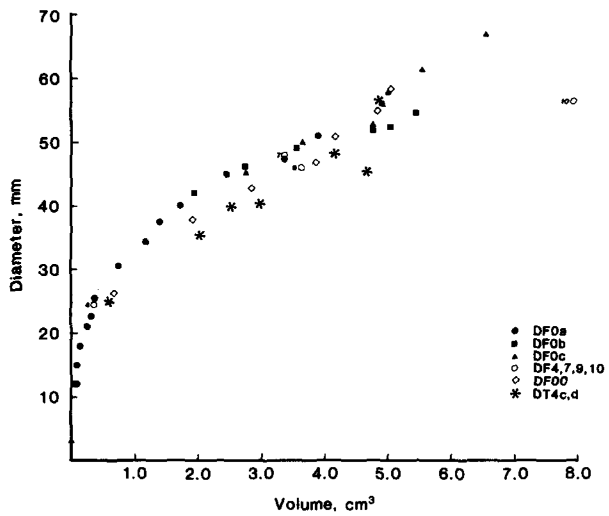


Fig. 10. Relationship between diameter and volume for selected laccolith models. Open triangle indicates original value; individual models evolve from lower left towards upper right. See Tables 2 and 3 for error estimates.

Table 2. Results of DF (Standard) series models

Model No.	Time at 2000 g (s)	Amplitude (mm)	Diameter (mm)	Volume (cm^3)
DF-4	248	2.00 ± 0.25	24.5 ± 0.25	0.36 ± 0.14
DF-7	735	4.25 ± 0.25	48.0 ± 0.25	3.39 ± 0.54
DF-9	1388	4.25 ± 0.25	46.0 ± 0.25	3.62 ± 0.54
DF-10	2348	4.50 ± 0.25	56.5 ± 0.25	7.94 ± 0.79
DF0a 1	20	0.50 ± 0.25	12.0 ± 0.25	0.05 ± 0.03
2	35	0.50 ± 0.25	12.0 ± 0.25	0.06 ± 0.04
3	50	0.75 ± 0.25	15.0 ± 0.25	0.08 ± 0.05
4	65	1.00 ± 0.25	18.0 ± 0.25	0.13 ± 0.07
5	80	1.25 ± 0.25	21.0 ± 0.25	0.23 ± 0.12
6	155	1.50 ± 0.25	22.5 ± 0.25	0.31 ± 0.14
7	251	1.75 ± 0.25	25.5 ± 0.25	0.37 ± 0.17
8	386	2.25 ± 0.25	30.5 ± 0.25	0.74 ± 0.26
9	522	2.75 ± 0.25	34.5 ± 0.25	1.18 ± 0.34
10	658	3.00 ± 0.25	37.5 ± 0.25	1.40 ± 0.38
11	853	3.00 ± 0.25	40.0 ± 0.25	1.72 ± 0.41
12	1049	3.75 ± 0.25	45.0 ± 0.25	2.45 ± 0.49
13	1365	4.25 ± 0.25	47.5 ± 0.25	3.36 ± 0.54
14	1681	4.25 ± 0.25	51.0 ± 0.25	3.89 ± 0.58
DF0b 12	1049	3.00 ± 0.25	42.0 ± 0.25	1.94 ± 0.45
13	1365	3.50 ± 0.25	46.0 ± 0.25	2.73 ± 0.52
14	1681	4.00 ± 0.25	49.0 ± 0.25	3.55 ± 0.57
15	1944	4.50 ± 0.25	52.0 ± 0.25	4.74 ± 0.62
16	2226	4.75 ± 0.25	52.5 ± 0.25	5.03 ± 0.63
17	2541	4.75 ± 0.25	54.5 ± 0.25	5.43 ± 0.65
DF0c 18	1392	4.50 ± 0.25	45.0 ± 0.25	2.76 ± 0.52
19	1708	4.75 ± 0.25	50.0 ± 0.25	3.64 ± 0.58
20	2023	5.00 ± 0.25	52.5 ± 0.25	4.75 ± 0.64
21	2339	5.25 ± 0.25	56.0 ± 0.25	4.91 ± 0.64
22	2654	5.00 ± 0.25	58.0 ± 0.25	5.00 ± 0.63
23	2970	4.75 ± 0.25	61.5 ± 0.25	5.56 ± 0.67
24	3285	4.25 ± 0.25	67.0 ± 0.25	6.57 ± 0.72

Note: Amplitude and diameter measurements determined from tracings of diametrical profiles of the top of the intrusion (one overburden layer above the upper contact of the intrusion). Volume estimates calculated from the profiles, assuming intrusions are circular in plan. Volume errors estimated by propagation of linear measurement errors (diameters of circular disc elements each 0.25 mm thick).

Most of the variation in the work done in deforming the cover strata is masked by the work done in deforming the magma as it flows up the conduit, except in the last stage.

The relationships between amplitude, diameter and volume show changes in slope corresponding to the transitions between growth stages. The amplitude–diameter (aspect) ratio (Fig. 9) increases subtly between the sill and bending stages (first three solid circles are still stage), and decreases at the onset of the kink stage. The intrusions grow in diameter throughout their formation (Figs. 9 and 10), but they undergo a decrease in amplitude (Figs. 9 and 11) during the kink stage, while the form changes from domed to flat-topped.

Upward bowing of the stratified cover above the intrusions involves not only bending strain but also elongation of the strata. In our models the geometry of the laccoliths implies a layer-parallel extension of approximately 4%, assuming that all the increase in layer length over the intrusions is accommodated by stretching, and none by displacement of the layer ends away from the edges of the model chambers. This assumption is difficult to verify, but is probably justified as the edges of the layered overburden were in all cases sealed together by melting them with a hot knife following assembly of the layered stack. We have not documented the distribution of this overall 4% extension (and corresponding 4% stratal thinning), but expect that it is concentrated as perhaps a 10% extension in the region of the peripheral monocline. Johnson & Pollard (1973) describe elongation and thinning of competent sandstone strata by displacement on cataclastic shear planes in the overburden where it is deflected upward above the periphery of Trachyte Mesa laccolith in the Henry Mountains.

Factors affecting the development of model laccoliths

We have investigated the influence of a number of parameters on the intrusion process. These include the strength of the overburden material, the total thickness of the overburden and the thickness of individual overburden strata, the nature of the interlayer contacts in the overburden, and the magmatic driving pressure. The models described above are used as a standard evolutionary series, against which the effects of alteration of these parameters, individually, can be compared. Our aim is simply to demonstrate the direction of influence of each of these parameters, rather than to derive quantitative expressions for their effects. Thus we have run only a limited number of models in this phase of the study.

Overburden strength. Models DF00a–d (Fig. 12) were constructed with geometry identical to that of the standard DF series, but with the overburden composed of W75/V25. DF00a and b were subjected to 2000 g through one extended run; they evolved through the same geometrical sequence as the DF series. Models DF00c and d were cycled and measured at a total of seven stages, as listed in Table 3. These data are plotted with open diamond symbols in Figs. 8–11 which also show the

Table 3. Results of DF00, DT and DL series models

Model No.	Time at 2000 g (s)	Amplitude (mm)	Diameter (mm)	Volume (cm^3)
DF00b	2115	4.25 ± 0.25	55.5 ± 0.25	6.72 ± 0.74
DF00c 1	316	2.75 ± 0.25	26.5 ± 0.25	0.69 ± 0.20
2	632	4.00 ± 0.25	38.0 ± 0.25	1.92 ± 0.44
3	948	4.50 ± 0.25	43.0 ± 0.25	2.86 ± 0.51
4	1263	5.00 ± 0.25	47.0 ± 0.25	3.87 ± 0.58
DF00d 5	1578	4.75 ± 0.25	51.0 ± 0.25	4.15 ± 0.58
6	1893	3.75 ± 0.25	55.0 ± 0.25	4.84 ± 0.63
7	2208	3.50 ± 0.25	58.5 ± 0.25	5.03 ± 0.64
DT3	7602	4.00 ± 0.25	48.0 ± 0.25	3.45 ± 0.52
DT4a	1301	3.25 ± 0.25	47.6 ± 0.25	3.55 ± 0.57
DT40a 1	38	2.25 ± 0.25	25.0 ± 0.25	0.60 ± 0.21
2	294	4.00 ± 0.25	35.5 ± 0.25	2.02 ± 0.44
3	609	4.00 ± 0.25	40.5 ± 0.25	3.00 ± 0.54
4	1346	3.50 ± 0.25	45.5 ± 0.25	4.68 ± 0.66
DT40b 2	294	4.00 ± 0.25	40.0 ± 0.25	2.51 ± 0.50
3	609	3.75 ± 0.25	48.5 ± 0.25	4.18 ± 0.59
4	1346	2.50 ± 0.25	56.5 ± 0.25	4.86 ± 0.66
DT5	18*	—	—	—
DT6	5963	3.75 ± 0.25	59.5 ± 0.25	7.52 ± 0.75
DT13†	2997	3.50 ± 0.25	42.5 ± 0.25	4.70 ± 0.61
DT14†	4219	3.25 ± 0.25	45.0 ± 0.25	3.40 ± 0.55
DT15†	4219	3.00 ± 0.25	42.5 ± 0.25	3.31 ± 0.51
DL4	465	3.00 ± 0.25	18.0 ± 0.25	—
DL5	450 s @ 2000 g and 600 s @ 3000 g			—

See note in Table 2 concerning measurement method and error estimates.

* DT5 models developed severe doming during acceleration to 2000 g and experiment was terminated after 18 s at speed.

† Measurements estimated from sectioned model rather than from traced profile.

equivalent data for the DF series. Several trends are evident: laccoliths with weaker overburden increase in volume more quickly (Fig. 8); weaker overburden undergoes localized failure to the cupola and then the kink stage sooner (that is, at a smaller diameter; see Fig. 9); and localized failure of weaker overburden proceeds more rapidly (as evidenced by the more rapid decrease in amplitude at the onset of the kink stage; see Figs. 9 and 11).

Thickness of overburden. A number of geologists (e.g. Gilbert 1877, Hunt 1953, Pollard 1968) have pointed out that laccoliths emplaced at greater depths tend to have larger diameters (and hence greater volumes). Gilbert's analysis, based on the analogy of the hydraulic press, predicts a linear dependence of the critical radius, at which the overburden can be raised, on the weight, and therefore the thickness, of the overburden. Pollard's analysis (Pollard 1968, Johnson 1970), based on plate-bending theory, predicts a similar linear relationship between radius and effective thickness of overburden, assuming that interlayer shear stresses in the overburden can be ignored.

A series of four models designated DT4 was constructed with properties identical to the standard DF series, but with the overburden only 5 mm thick, simulating a 1000 m prototype cover (that is, just half that of the standard series). Two models subjected to a continuous run evolved through a sequence of forms (illustrated in

Fig. 13) similar to the standard series. The other two models were cycled and measured at several stages, as shown in Table 3 and with asterisk symbols in Figs. 8–11. The effects of a thinner overburden (shallower depth of emplacement) at the same magmatic driving pressure are as follows: the rate of intrusion is significantly greater (Fig. 8); the onset of localized failure (the geometric evolution to the cupola and the kink stages) occurs much earlier (i.e. at smaller diameter and volume; Figs. 9 and 11); and the decrease in aspect ratio associated with the development of the flat-topped kink form is much more dramatic (Fig. 9). With a smaller thickness, the overburden sequence has a lower weight per unit area and a lower resistance to bending. Its deformation dissipates energy at a lower rate, which allows more rapid magmatic intrusion; further, it can be raised in the gravity field and deformed to the kink form at a smaller intrusion size.

Minimum depth of laccolith intrusion. As was pointed out above, laccoliths are rarely seen to have intruded at depths shallower than about 1000 m; this is presumably because magma pressure is sufficient to deflect overburden that is thinner than this value to the point of brittle failure at a relatively small intrusion diameter, and the magma can then escape to the surface rather than continuing its lateral intrusion. Models DT5a and b (Fig. 14) were constructed with 2.5 mm of overburden (equivalent to a prototype depth of 500 m) to test this relationship. In model DT5a the overburden was thinly laminated as in the DF series, whereas the overburden of DT5b consisted of a single thick layer. Both models developed steep-sided, laccolith-shaped intrusions which increased rapidly in amplitude to a maximum of about 7.5 mm; vertical fractures propagated radially from the dome crests; silicone putty flowed upward through the fractures and extruded onto the free surface of the models. Upon dissection, model DT5a was found to have a circumferential fracture in the lowest overburden layer, situated at the periphery of the intrusion, although only partially surrounding it. These models support the observation that small laccoliths form at shallow depths, but suggest that laccolithic intrusions may not be preserved above a certain depth because the magma can rupture thinner overburden and so escape to the surface. The observed fracture patterns are identical to those predicted by Pollard (1968) on the basis of computed stress distribution in the overburden: upward-gaping radial fractures above the crest and downward-gaping circumferential fractures at the periphery.

Thickness of overburden strata. Model DT15 was constructed to investigate the effect of increased lamination thickness in the overburden stack. It was similar to models of the standard DF series except that its 10-mm overburden consisted of five layers of W95/V05, each 2 mm thick (that is, four times as thick as the lamination in the standard series). This stack has an effective thickness (Pollard & Johnson 1973) greater by a factor of 2.52 than that of the DF series, and hence an elastic bending resistance greater by a factor of 16 (again assuming negligible interlayer friction). This model should therefore more strongly resist upward deflection of the cover; the sill stage should persist to larger diameter, and onset of the cupola and kink stages should be suppressed as well.

The model was subjected to 2000 **g** for a total of 4200 s, by which time the intrusion had achieved only the bending stage. In profile (Fig. 15) the cover strata exhibited a smooth, sinusoidal shape and no tendency towards localized kinking or flattening of the roof was apparent. Intrusion of the model magma proceeded at a rate only one-third of that typical of the standard DF series (compare with DF0a13 (Table 2) which has a comparable volume), the greater effective rigidity of the cover hindering the intrusion process.

Interlayer properties. In the mathematical analyses of Pollard (1968) and Pollard & Johnson (1973) the laminated overburden is treated as having freely-sliding interfaces. This character favours deflection of the overburden into a smoothly curved form; beyond elastic bending the strata should fail over the periphery of the intrusion where bending strain and differential stress are greatest. Pollard's photoelastic models confirm the theoretically predicted stress maximum. A massive, single-layer overburden should also deflect into a smoothly curved form, although its much greater bending resistance would favour wider, lower-amplitude laccoliths and slower rates of intrusion. The extended mathematical analysis by Koch *et al.* (1981) incorporated layer interfaces with non-zero shear strength. This modification yields a prediction of a second episode of localized failure, due to a maximum in the layer-parallel shear stress above the flanks of the intrusion, leading to flattening of the strata above the intrusion and formation of a monoclinal flexure around the periphery. The nature of the overburden layer interfaces thus exerts significant control on the form and evolution of laccoliths.

The models of the standard DF series had unbonded contacts between the W95/V05 overburden layers. These contacts have virtually no cohesion at 1 **g**, but have some (unknown) resistance to shear when loaded at 2000 **g**. The models first developed continuously curved forms, then localized bends at the periphery of the intrusions, and finally, monoclinal flexures bounding flat roofs. This sequence of forms is consistent with the theoretical predictions, and suggests that the layer interfaces do not slide freely. The relatively rapid development of localized kinks suggests that the interfaces have a fairly well-defined yield strength and behave in a plastic manner.

We performed several experiments (models DT13 and 14, Table 3) in which the interlayer properties were varied. In model DT13 the wax strata were coated with thin layers of vaseline prior to assembly of the overburden stack, and in model DT14 they were rubbed with graphite powder before assembly. These two materials affected the evolution of the laccoliths quite differently, and their behaviour can be deduced qualitatively from their effects. The overburden in model DT13 (Fig. 16a) developed a very sharply defined, steeply dipping monoclinal flexure at the periphery of the laccolith; in model DT14 (Fig. 16b) the sinusoidal form was maintained throughout the experiment, and no localized failure occurred. This suggests that vaseline imparts an even more sharply defined yield strength and plastic behaviour to the multilayer than those of the simple interfaces. Graphite, in contrast, apparently suppresses the plastic behaviour of the interfaces, either by bonding the layers together or by reducing the interface strength to a negligible value. The slow rate of intrusion in model DT14, which required some 4219 seconds at 2000 **g** to attain the form illustrated in Fig. 16b, favours the former interpretation. Graphite apparently bonds the W95/V05 wax layers together to such an extent that the overburden stack behaves in a manner approaching that of a single thick layer without planes of easy slip. Thus the cover of the intrusion maintains the sinusoidal form rather than transforming to the kinked shape. This model evolved to a form and at a rate almost identical to those of model DT15 (see above); thus the effective thicknesses and bending resistances of the thin-layered overburden with graphite-bonded interfaces (DT14) and the thick-layered, unbonded overburden (DT15) are very similar.

Magmatic driving pressure. The standard DF series of models, which had a 20-mm layer of Plasticine to pressurize the silicone putty magma reservoir, developed a magmatic driving pressure (Johnson & Pollard 1973; see above) of 2.23×10^5 Pa at 2000 **g**. If the model ratios specified in Table 1 are applied, this model magmatic driving pressure scales to 53.2 MPa, which is close to the maximum 70 MPa estimated for the Henry Mountains (Johnson & Pollard 1973). In order to quantify the effect of magmatic driving pressure, model DT3 was constructed with its layer of Plasticine reduced in thickness to 10 mm, thus generating a magmatic driving pressure of 1.12×10^5 Pa at 2000 **g**. This model was run under the same conditions as the DF series until peripheral failure and a slight degree of flattening was observed. The final form is listed in Table 3. This form, which required some 7600 s at 2000 **g**, is comparable to those of models DF0a-13, DF0b-14 and DF0c-19, which evolved in 1365, 1618 and 1708 s, respectively (see Table 2). Thus a halving of the driving pressure resulted in roughly a five-fold reduction in the rate of intrusion, reflecting the non-linear rheologic behaviour of the wax overburden and particularly of the silicone putty 'magma'.

Pollard & Johnson's (1973) mathematical analysis of the deflection of laccolith overburden predicts direct proportionality between aspect ratio and magmatic driving pressure for laccoliths of a given diameter, assuming a uniform magmatic driving pressure beneath an elastic overburden. Our models are at variance with this relationship, as DT3 has a similar diameter and amplitude to DF0a-13, DF0b-14 and DF0c-19 in spite of its lower driving pressure. This is not surprising, because the silicone putty magma has a rheologic character approaching that of a Bingham fluid (Dixon & Summers 1986), so it does not exert a uniform pressure on the base of the overburden (Johnson & Pollard 1973). Furthermore, the overburden has deformed well beyond its elastic limit in these models.

In our experiments the magmatic driving pressure apparently affects primarily the rate of magmatic intrusion and has little effect on the form of the intrusion or its evolution. The flow properties of our model magma remain constant throughout the intrusion process. In natural laccoliths, if lower driving pressure produces a similar reduction in the intrusion rate, then cooling of the magma during intrusion would likely cause modification of the laccolith's form as magma strength and flow properties change. Ultimately the intrusion process might be arrested at an earlier stage. Some possible effects of magmatic cooling and crystallization during laccolith intrusion have been discussed by Johnson & Pollard (1973).

Resistance to lateral spreading of the magma. Some natural laccoliths are far from circular in plan (Hunt 1953, Johnson & Pollard 1973). Pollard & Johnson (1973) discuss the concept that an elliptical plan may result from azimuthal anisotropy of the bending resistance of the overburden strata, but point out that the anisotropy would have to be inexplicably large to account for the observed ellipticities (axial ratios up to 9:1 are described by Hunt 1953). They also propose that the shape of the feeder conduit, circular or tabular, would have a strong influence on the shape of the intrusion. In our experiments the model laccoliths, fed by circular pipes and intruded into azimuthally isotropic overburden, were in all cases within 10% of circular in plan. Furthermore, the shape of the intrusions is apparently insensitive to the rectangular shape of the models. Indeed, the model laccoliths maintained circular outlines even when the perimeter of the intrusion approached the margin of the model (see Figs. 6 and 7). A few of our models developed local shape irregularities; these were inevitably due to local changes in the level of the intrusion within the overburden stack. For example, where the level of intrusion stepped locally downwards below the lowest wax layer (Fig. 17; see also Fig. 12), lateral spreading was hindered by the locally increased weight and bending resistance of the thicker overburden. We have not run any models with tabular, dyke-like feeder conduits.

Several of our models incorporated variations in primary character that led to other intrusion effects. Model DL4, for example, had overburden composed of W65/V35 in layers 1.0 mm thick, with the lowest layer bonded to the Plasticine substrate by gentle heating during assembly of the model. The laccolith that formed in this model (Fig. 18a) had a much higher aspect ratio than those of the standard series, as a result of the greater resistance to lateral penetration of the magma beneath the cover, and the lower overburden strength. This structure resembles Gilbert's (1877) original concept of the laccolith but lacks similarity to accurately mapped natural laccoliths (e.g. Hunt 1953) which tend to have much lower aspect ratios. In some of our other models with weak overburden the silicone putty spread laterally by crumpling the cover strata rather than by penetrating along layer interfaces. This behaviour is similar to the mechanism of intrusion of sills and some laccoliths, advancing with blunt terminations into weak host rocks, discussed by Johnson & Pollard (1973) and Pollard & Johnson (1973).

In some models the silicone putty magma did not remain confined to one stratigraphic level during intrusion. Figure 18(b) illustrates a compound intrusion comprising a laccolith underlain by a more laterally extensive sill. This model structure resembles the relationships between interfering laccoliths and sills in the Henry Mountains as interpreted by Hunt (1953).

DISCUSSION: COMPARISON OF THE MODELS AND NATURAL LACCOLITHS

The model laccoliths developed into four geometric forms, the sill, 'bending laccolith', 'cupola' and 'kink laccolith' forms. Natural examples of each of these forms can be found. In nature, brittle failure and uplift of the cover strata relative to the surroundings, by displacement on a steeply dipping peripheral fault, gives rise to the forms termed sphenolith and bysmalith. It has been recognized from the beginning of the laccolith concept (Gilbert 1877) that laccoliths (*sensu lato*) evolve from sills. Pollard (1968) and Pollard & Johnson (1973) predicted localized failure of the overburden above the periphery of the intrusion on theoretical grounds, thus implying the evolution from bending to cupola stage. Pollard (1972) and Koch *et al.* (1981), in an extension of the elastic mathematical model that incorporated a finite yield strength along the overburden bedding planes, predicted a secondary localized failure of the overburden that would give rise to a flat-topped intrusion bounded by a circular monocline. This secondary failure marks the evolution from cupola to kink form. Our models provide experimental documentation of this evolutionary sequence; the logical further evolution to the sphenolith and bysmalith forms is not achieved due to the ductility of the analogue materials employed.

Careful study of the cover strata of flat-topped laccoliths, at localities just inside the inner flexure at the top of the peripheral monocline, may yield evidence of radial propagation of the lower flexure and monocline as the intrusion grew in diameter: strata at such points should have been bent and then unbent during radial passage of the hinge. On the other hand, if the kink form grew directly from the sill form without passing through the intermediate stages, such localities might be expected to bear little evidence of internal deformation.

Although the model laccoliths resemble natural laccoliths in form and aspect ratio, they grew to larger sizes than are typical of natural laccoliths, given the assumed model ratio of length (Table 1). Several factors favour the larger size. First, we employed a model geometry and acceleration that produced a magmatic driving pressure which scales close to the maximum value estimated for the Henry Mountains laccoliths by Johnson & Pollard (1973). As they discussed, the driving pressure could have been significantly lower in nature. Second, the model overburden is somewhat too soft. The wax of the model overburden undergoes more elastic strain prior to onset of permanent strain, and more permanent ductile strain before initiation of brittle deformation, than the rocks of the prototype overburden. Third, the viscosity and strength of the model magma do not increase due to cooling during intrusion (see below). In spite of these deviations from strict dynamic similitude, we believe that the models give a realistic record of the sequence of forms through which natural laccoliths evolve during their intrusion.

The time required for intrusion of laccoliths is not certain, but most estimates tend towards rapid intrusion (Hurlbut & Griggs 1939, Hunt 1953). Price (1975) pointed out that a laccolith-sized body of magma would cool through half of its initial temperature differential with respect to the country rock in roughly 100 years, and the time of intrusion cannot exceed this. Price also noted that surface uplifts recorded in volcanic areas may indicate that laccolithic bodies may form in as little as one year. Pollard & Johnson (1973) conclude that intrusion of Black Mesa, a Henry Mountains laccolith that measures about 1.7 km in diameter and 200 m in thickness, could have occurred in less than several weeks time, given their estimates of magma viscosity, driving pressure and overburden strength.

The laccoliths in our models grew in times (Tables 2 and 3) that scale, given the model ratios listed in Table 1, to between one and a few tens of years, an agreement that may be fortuitous in view of the uncertainty in estimates of magma viscosity upon which our chosen model ratio for time was based. Furthermore, as we argue above, the diameter of the feeder conduit probably exerts a significant control on the rate of intrusion. We did not investigate the effect of size or shape of the conduit (the pipe was circular and 3 mm in diameter in all experiments). Virtually nothing is known about the shape or size of the feeder conduits of natural laccoliths. We would expect a correlation between the final size of laccoliths and the rate of magma injection in cases where the time of injection is not much less than the time of cooling (i.e. laccoliths with small feeders and/or low magmatic driving pressures). These circumstances allow competition between magma supply and chilling. Laccoliths can be arrested at various stages of growth because of different magma supply rates, due to conduit shapes and sizes, even if intrusions are forming at same depth (where cooling rates should be uniform), and with the same initial magmatic driving pressure.

CONCLUSIONS

In scaled analogue experiments we have produced model laccoliths whose overburden evolves through a series of geometric forms that resemble those exhibited by natural laccoliths, and those predicted on the basis of the theoretical bending behaviour of a stack of plates with finite interlayer shear strength. Fluid intruding a stack of plates from beneath first insinuates itself between layers and spreads laterally as a sill. Once a critical area is penetrated, the pressurized fluid begins to raise the overburden and bend it into a continuously curved form which we name the 'bending laccolith'. Subsequently, localized failure of the overburden occurs at the tip of the intrusion, and the overburden assumes the form of a smooth dome surrounded by a sharp hinge, the 'cupola' form. Finally, the rounded dome collapses to a flat-topped form surrounded by a monoclinal flexure. This 'kink laccolith' form develops when the interlayer shear strength of the overburden stack is locally exceeded by the layer-parallel shear stress above the flanks of the intrusion. Natural laccoliths can evolve further to the sphenolith and bysmalith forms if the bounding monoclinal flexure fails in a brittle fashion and the roof of the intrusion is lifted by displacement on a steeply dipping bounding fault. This behaviour is not observed in the models because the material used as an analogue for the overburden strata does not exhibit brittle behaviour in the experiments.

By varying appropriate design parameters we have investigated the role of factors such as overburden strength and total thickness, overburden layer thickness and interface properties, and magmatic driving pressure on the formation and evolution of laccoliths. Our models suggest the following relationships. (a) Increased overburden strength delays the onset of localized failure that marks the cupola and kink stages; these occur at larger diameter and volume. Increased strength also reduces the amplitude and aspect ratio of the intrusion at a given volume. (b) Increased overburden thickness delays onset of cupola and kink stages until the intrusion has attained a larger volume. It also reduces the amplitude and aspect ratio at a given volume. (c) Increased thickness of overburden layers suppresses localized failure of the overburden, thereby prolonging the bending form to larger intrusion size. (d) Overburden interfaces with sharply defined yield strengths and plastic or frictional behaviour promote the second episode of localized failure that results in formation of the monoclinal flexure. Overburden interfaces that are effectively bonded suppress localized failure and prolong the sinusoidal form. (e) Magmatic driving pressure affects the rate of intrusion, which is also influenced by the flow properties of the fluid and is probably very sensitive to the form of the feeder conduit through which the magma enters the intrusion. Driving pressure does not appear to influence the evolution of form of the intrusion.

Our model laccoliths formed in times that scale to prototype times on the order of one to a few tens of years, given the assumed model ratios. While these times are similar to published estimates for intrusion of natural laccoliths, the correspondence may be fortuitous in view of the uncertainty of estimates of the viscosity and strength of natural magmas. It is likely that the variation of final form exhibited by neighbouring laccoliths is a result of competition between intrusion of the magma, controlled by driving pressure and conduit geometry, and chilling of magma in the laccolithic bodies.

Acknowledgements—The study reported here is an outgrowth of part of the M.Sc. thesis research project of D.G.S. (Simpson 1980), which was conducted under the supervision of J.M.D. J. M. Summers provided technical assistance and advice, including the suggestion that thin, uniform paraffin layers could be prepared by floating molten wax on hot water and allowing the bath to cool. Christopher Peck assisted with preparation of photographs.

The Experimental Tectonics Laboratory at Queen's University has been funded by Operating and Equipment grants from the Natural Sciences and Engineering Research Council of Canada, and research grants from Queen's University's Advisory Research Committee, to J.M.D. During his graduate study, D.G.S. received financial support from Queen's University in the form of a McLaughlin Scholarship, a Queen's Graduate Award, and an E. L. Bruce Scholarship. This financial support is gratefully acknowledged.

We thank David D. Pollard and D. Hutton for their constructive reviews of the manuscript.

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