# SEDIMENTARY DYKES, PIPES AND RELATED STRUCTURES IN THE MESOZOIC SEDIMENTS OF SOUTH-EASTERN ALEXANDER ISLAND

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ABSTRACT. Sedimentary dykes of sandstone, mudstone and conglomerate cut a thick (approximately 8 000 m), predominantly argillaceous marine succession of Upper Oxfordian–Kimmeridgian to Lower Albian age in south-eastern Alexander Island. The sedimentary trough, located within the seismically active circum-Pacific fold-mountain belt, was subjected to contemporaneous volcanicity and earthquake shocks which diminished the shear resistance of several sandstones. As a result, spectacular, large-scale, bifurcating, often sinuous and usually parallel-sided sandstone dykes were formed. These were injected with minimal disruption and deformation of the host rocks via an open and/or dilated joint system and several (?) synformational faults. The impetus was provided by earthquake shocks coupled with high pore pressures, hydrostatic pressure and probably some gas pressure.

The lateral offsetting of the dykes at slickensided and mineralized veins (and less commonly at bedding planes) is attributed to post-dyke transcurrent faulting, penecontemporaneous bedding-plane slip (which may have induced some of the jointing and effectively sealed off the sand as it was injected) and the infilling of a scalariform joint system. The vertical foreshortening of several dykes into *schuppen*-like segments is due to compression. Fossiliferous inclusions and dykes emerging from source beds indicate that the principal sandstone sheets were injected upwards, whereas the many apophyses were upwardly and downwardly injected. At least two phases of injection occurred at one locality. Sills are infrequently developed and only one dyke may have been extruded as a sand volcano. The unflexing of the more sinuous and vertically foreshortened dykes and other workers' experimental data suggest that some dykes were compacted by at least 20–30%. All of the sandstone dykes were subsequently cemented by calcite and subordinate authigenic prehnite and laumontite.

Of the small-scale injection structures, at least one of two mudstone dykes was emplaced upwards, whereas all the linguiform sandstone dykes and conglomeratic dykes were injected downwards. Most of the sandstone dykes, which are closely associated with micro-faulting, probably represent examples of intensive but locally restricted load deformation. The sandstone pipes were probably produced by jets or springs of water carrying sand in suspension.

The postulated environment of the Mesozoic trough and the occurrence in south-eastern Alexander Island (at least between Pluto and Venus Glaciers) of two distinct sub-parallel zones of slides and sandstone dykes can be matched in the Senonian San Antonio Formation of eastern Venezuela.

SEDIMENTARY dykes, mainly of sandstone, are common in south-eastern Alexander Island and they represent the most spectacular sedimentary structures in the area. They were discovered by V. E. Fuchs and R. J. Adie of the Falkland Islands Dependencies Survey during their geological reconnaissance journeys down George VI Sound in 1948–49 and 1949–50. However, the location and field observations of the dykes observed by Fuchs and Adie have not been published.

Between Ablation Point (lat. 70°48′S, long. 68°22′W) and Hyperion Nunataks (lat. 72°04′S, long. 68°54′W) and westward to the Milky Way (lat. 71°11′S, long. 68°55′W) (Fig. 1) there are large numbers of sandstone dykes (locally in swarms) and fewer sandstone pipes and mudstone and conglomeratic dykes. The sandstone dykes are represented by large-scale bifurcating sheet-like structures, small-scale linguiform dykes and narrow veinlets. Sandstone sills and plugs or chonoliths are less common.

The 52 large-scale sandstone dykes mapped by the author are well exposed, often easily accessible, either vertical or steeply dipping (70–80°) and usually plane-sided sheets. They strike north-north-east to south-south-west or east-north-east to west-south-west across often southerly or south-easterly dipping sedimentary rocks. Thirty-two of them are exposed at Mount Ariel (Figs 2a, b and 3), where many are traceable across the cliff face for over 305 m. One of these is 5.5 m wide, the thickest sedimentary dyke so far examined in the field. However, an even larger (?) sedimentary dyke has been observed in recent air photographs by M. R. A. Thomson on the east face of the hook at Belemnite Point (lat. 70°39′S, long. 68°32′W).

*Br. Antarct. Surv. Bull.*, No. 51, 1982, p. 1–42.

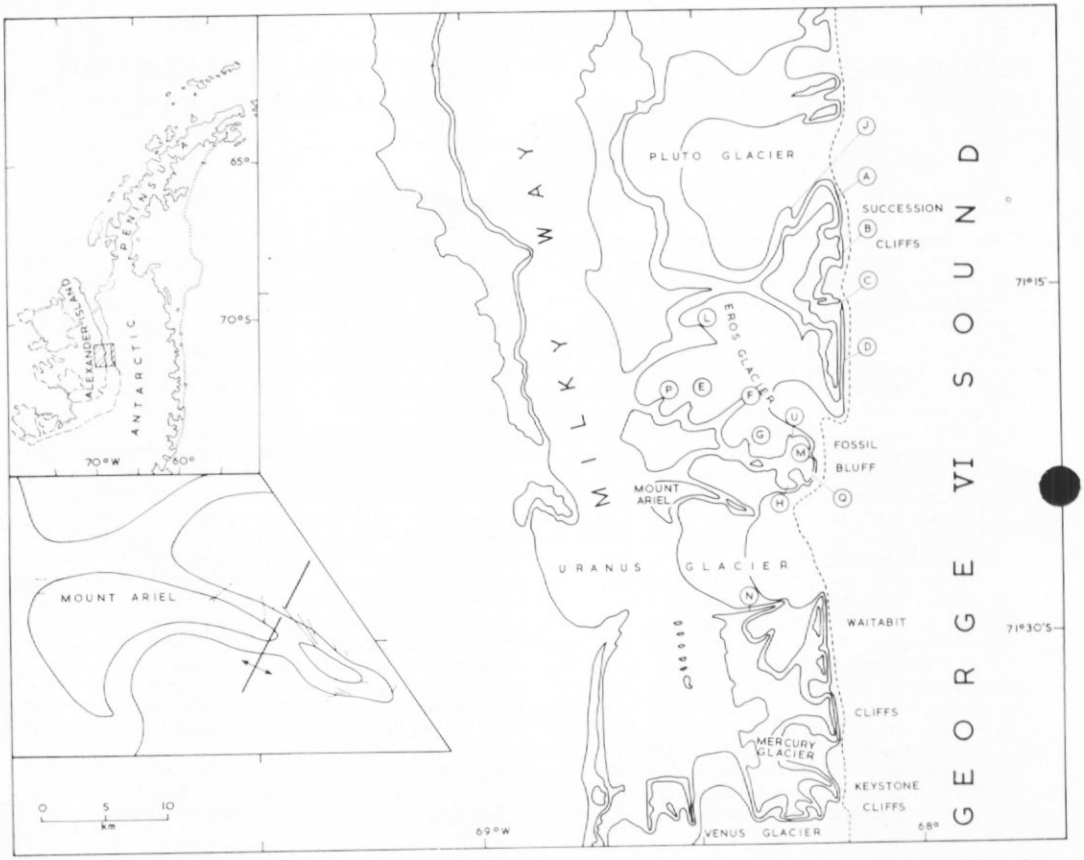


Fig. 1. Sketch map of the area between Succession Cliffs and Keystone Cliffs, showing the localities where sedimentary dykes and related phenomena were mapped, and the distribution of the large-scale sandstone dykes.

The large-scale dykes, which resemble igneous dykes (Zeil, 1958) or "fissure veins" in their general form, are difficult to map accurately because of their innumerable bifurcations and (?) synformational and post-dyke tectonism. However, the total extent of most of the dykes was measured using a 1.5 m Jacob's staff and Abney level, and the strike directions of the principal and secondary sandstone sheets were determined. The amount of horizontal offsetti[illegible] was also recorded. The more extensive structures are shown in Fig. 1. For cartographical and descriptive purposes, all of the dykes are regarded as single units injected during one phase even though some probably represent several injections which, by following the same general strike and occasionally intersecting one another, ultimately formed an extremely complex hybrid structure. To date, the most detailed work on these structures has been undertaken in the Fossil Bluff area, notably at Mount Ariel, Fossil Bluff and locality G.

### *Depositional environment*

The depositional environment of the Mesozoic sedimentary succession has been described or referred to elsewhere (e.g. Horne, 1968*a*, *b*, 1969*a*, *b*; Horne and Taylor, 1969; Horne and Thomson, 1972; Taylor and others, 1979). However, several factors related to the origins of the sedimentary dykes need to be emphasized here. The sedimentary environment was an unstable one conducive to the re-mobilization of sediment. The sedimentary trough, which

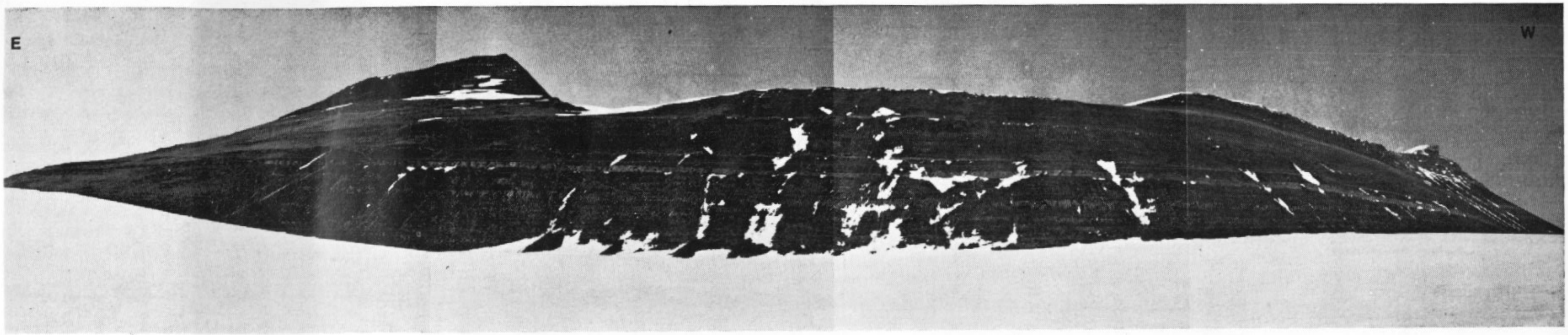
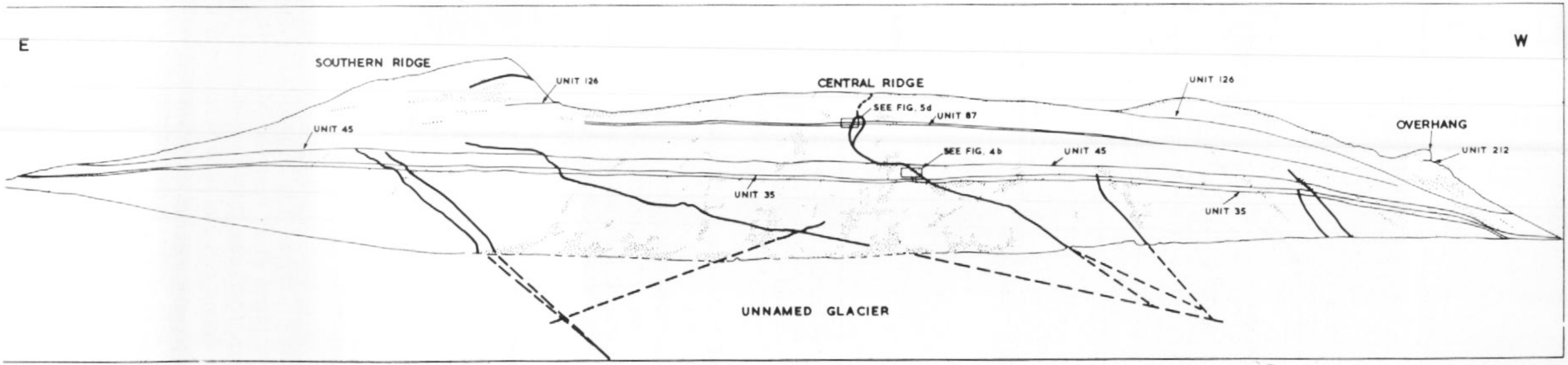


Fig. 2. a. The 7 km long northern scarp of Mount Ariel where 19 large-scale sandstone dykes were mapped. The anticlinal structure and thick-bedded units in the sequence can be seen. The succession here is 730 m thick.



b. An outline of Fig. 2a showing the distribution and extent of some of the large-scale dykes and the main thick-bedded units in the succession. The downward extent of the dykes towards possible common source beds is also indicated.

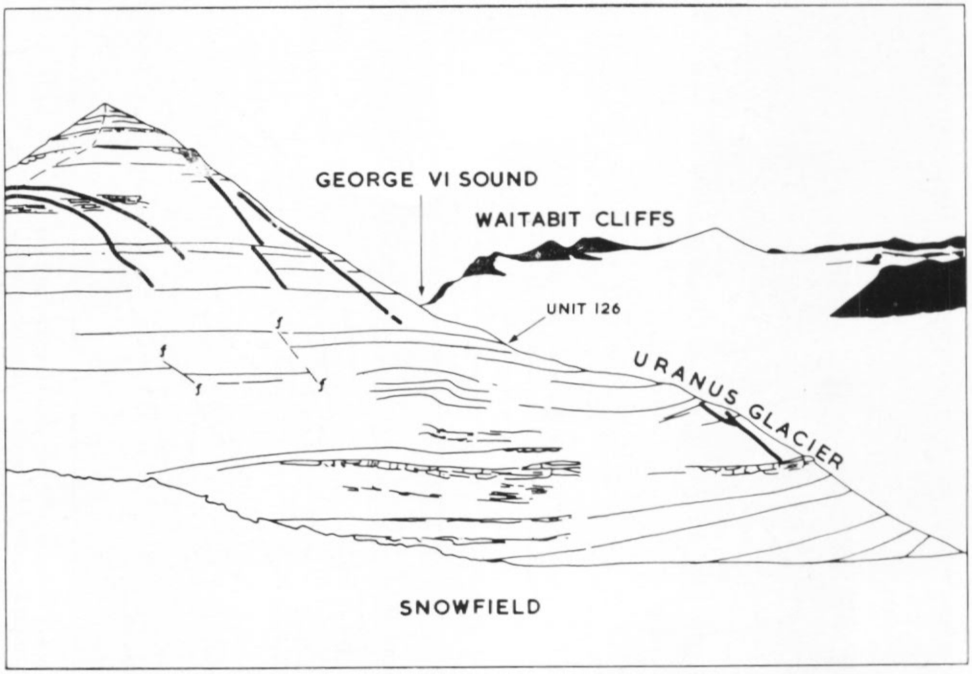


Fig. 3. The eastern ridge of Mount Ariel viewed from the west, showing five large-scale sandstone dykes, two of which are horizontally offset (up to 3 m) across a slickensided band. The occurrence of the bivalves *Aucellina* and/or *Inoceramus* in some of the inclusions within the uppermost four dykes indicates that they were probably injected from a source bed *above* unit 126 (p. 24).

was probably elongated north–south and parallel to the structural trend of the cordilleran axis (Horne, 1969*b*, p. 63), formed part of the seismically active circum-Pacific fold-mountain belt, in common with many other areas characterized by numerous sandstone dykes. On its eastern side, i.e. approximately parallel to the present eastern coastline of Alexander Island, the trough may have been bounded by an active arcuate thrust or series of thrusts (Horne, 1967, fig. 13c) representing one boundary of a compressed tectonic plate.* A high overall rate of sedimentation (Horne, 1968*b*, p. 80, 1969*b*; Taylor and others, 1979) of alternating competent and incompetent strata, coupled with concomitant movement of this "megathrust", probably increased both the gradient of the continental slope and the shearing stresses within the sediments.

Volcanicity occurred intermittently throughout the period of sedimentation as shown [illegible] the stratigraphical distribution of airborne pyroclastic material, i.e. disc-like vitric crystal blebs, devitrified lapilli and shard deposits (Horne, 1968*b*, *c*; Horne and Thomson, 1972; Taylor and others, 1979). Its intensity seems to have increased with time, notably in the Lower Albian. The volcanicity, presumably accompanied by earthquake shocks, probably caused many of the sandstones to become thixotropic, retarded lithification of the succession and may have been directly or indirectly responsible for some of the "soft-sediment" deformation structures. A later, possibly Middle or Upper Cretaceous pre-diagenetic volcanic and seismic phase in or near the Mesozoic sedimentary trough may have triggered off the slump-shear structures, mass-flow deposits (Horne, 1968*a*) and sedimentary dyke injection. Mass-flow diamictites and intraformational slump-shear structures occur at several localities

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* The thrust probably continues northward along the western coastline of the Antarctic Peninsula to the Scotia arc, the most active part of this megastructure at the present time. The convexity of the thrust towards the ocean is comparable with most other arcuate thrusts encircling the Pacific Ocean.

(Horne, 1968*a*, fig. 1) and at different stratigraphical levels in south-eastern Alexander Island. Several authors (e.g. Bailey and Weir, 1932; Fairbridge, 1946; Smith and Rast, 1958) have associated sandstone dykes with such an unstable environment.

The Upper Oxfordian–Kimmeridgian to Lower Albian succession cut by the dykes is approximately 8 000 m thick (Horne, 1969*b*, p. 1; Taylor and others, 1979). It is composed predominantly of mudstones and siltstones with interbedded sandstones, conglomerates and occasional pebbly mudstones. Differences in the porosity and permeability of these lithologies undoubtedly induced behavioural irregularities under stress, resulting in liquefaction, foundering and re-mobilization of water-saturated sand. Furthermore, many of the associated sedimentary structures (e.g. load casts, convolute bedding and small-scale slump faulting) suggest that lithification had not reached an irreversible stage prior to deformation. This retardation may have been due to an absence of primary cements in some of the sandstones, frequent seismicity and the rapid rate of sedimentation (Horne, 1968*b*, p. 80). Some of the water involved in re-mobilizing the sandstone may have been derived from the compaction and solidification of the argillaceous rocks. Their cohesiveness prior to injection is demonstrated by the linearity of the dyke walls, the apparent absence of a salband or re-worked zone, the angularity of most of the argillaceous inclusions in the dykes and the occurrence of brecciated mudstone beds within several convoluted sandstones.

### *Other occurrences of sandstone dykes*

Sandstone dykes, extensively reviewed by Newsom (1903), Shrock (1948) and Strauch (1966), are found in rocks ranging in age from Precambrian to Pleistocene. Although they usually cut sedimentary successions, they have been reported in both granitic (Vitanage, 1954) and volcanic rocks (Fackler, 1941). Most of the occurrences are in North America (e.g. Diller, 1889; Cross, 1894; Newsom, 1903; Lawler, 1923; Russell, 1927; Jenkins, 1930; Monroe, 1950; Vitanage, 1954; Peterson, 1966) and often associated with the Rocky Mountains, but over 10 000 sedimentary dykes occur in Japan (Hayashi, 1966). Other important areas are Venezuela (Hedberg, 1937, 1950; Laubscher, 1961), Chile (Decat and Pomeyrol, 1931; Cecioni, 1957; Zeil, 1958), Poland (Dzułynski and Radomski, 1956), Sicily (Colacicchi, 1958), Tunisia (Gottis, 1953), New Zealand (Waterhouse and Bradley, 1957; Gregory, 1969), southern France (Rutten and Schönberger, 1957) and northern Scotland (Bailey and Weir, 1932; Waterston, 1950).

In the Antarctic Peninsula, sandstone dykes have been reported from the (?) Carboniferous Trinity Peninsula Series at Hope Bay, north-eastern Graham Land (Hooper, 1955), in the sedimentary succession at Cape Legoupil (Halpern, 1965) and cutting a Lower–Middle Campanian sedimentary succession at Bibby Point and Ula Point, James Ross Island (Nelson, 1960, p. 10, pl. X, 1961, p. 12). In South Georgia, dykes composed mainly of a tuffaceous sandstone cut Cumberland Bay type sediments ((?) Mesozoic) at Right Whale Bay (Trendall, 1959, pl. Ic), Lighthouse Bay, Prince Olav Harbour (Skidmore, 1972, p. 19), the Bay of Isles (personal communication from R. A. S. Clayton) and north of Gold Harbour (personal communication from P. Stone). A sinuous sedimentary dyke on the north-west side of Hestersletten may also transgress Cumberland Bay type sediments (personal communication from P. Stone). Dykes cutting Sandebugten type sediments ((?) Palaeozoic) have been recorded on the south coast of Hound Bay. Sedimentary dykes have also been found on nearby Annenkov Island (personal communication from T. H. Pettigrew).

### *Classification of sedimentary dykes*

Sedimentary dykes are often referred to collectively as phenomena of "sedimentary volcanism" (Kugler, 1933) or diapirism. The sheet-like sedimentary or "clastic"* dykes of

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* The term "clastic" is considered to be too imprecise, and "intruclast" (Jenkins, 1930, p. 421) is an unnecessary and unacceptable term for sedimentary dykes.

the type described here are usually classified as "injection" or "intrusive" dykes (not "neptunian dykes" as stated by Potter and Pettijohn (1963, p. 162), who misrepresented Smith and Rast (1958, p. 234). The two terms are often used synonymously by authors but Hayashi (1966, p. 16) used the term "intrusive" to describe dykes containing large fragments and solfataric muds emplaced primarily because of igneous (volcanic) activity. By contrast, "injection clastic dikes" represented the injection, usually of a quicksand, into voids. This is essentially the sense used here.

According to Hayashi (1966), injection dykes can be further subdivided on the basis of the original shape of the fissure, their post-diagenetic shape or on their supposed genesis. As many sedimentary dykes in Alexander Island correspond to several of Hayashi's morphological types (e.g. any one dyke can be straight-walled, branching, ptygmatic and later deformed), his genetic classification is more applicable. However, even here, many of the criteria defining the sub-groups, i.e. intrusive, injection, infilling, squeezed-in and diagenetic, overlap one another. In another classification, Swarbrick (1968) has subdivided "intrusive" sediment structures into two major classes, i.e. "injection of plastic or hydroplastic sediment" and . . . "intrusion of liquid sediment". These are discussed on p. 21.

The term "sandstone pipe" is used here for those structures known or assumed to be cylindrical in shape. Although these are quite different morphologically from the sheet-like injection dykes, they are regarded as end members of a series of injection sediment structures (Swarbrick, 1968, p. 164).

## LARGE-SCALE SANDSTONE DYKES

Large-scale sandstone dykes cut the Mesozoic (Upper Oxfordian–Kimmeridgian to Lower Albian) succession at many localities in south-eastern Alexander Island (Fig. 1). Thirty-two of them are exposed at Mount Ariel, an arcuate outcrop approximately 7 km long which forms part of the northern margin of Uranus Glacier. Dykes crop out over much of the snow-free area, although they are best seen on the long northern scarp (Fig. 2a and b) where 19 were mapped.

The large-scale dykes strike north-north-east to south-south-west or east-north-east to west-south-west across southerly or south-easterly (Fig. 11c) dipping mudstones and fine- and medium-grained sandstones. They are all greater than 15 m in length and can often be traced (obliquely and/or perpendicularly) for distances up to 305 m before they die out in the succession or reach the cliff top (Fig. 2a and b). Normally, the principal sheets are 10–120 cm wide but exceptionally they can be as wide as 5.5 m. Often first exposed at the glacier edge, the dykes usually consist of two or more sub-parallel rectilinear sheets which may converge or divide several times, often upwards but occasionally laterally or downwards. The result is a complex structure which is generally vertical or sub-vertical but sometimes sill-like [illegible] nearly concordant. The geographical extent of most of the dykes was not determined as they are normally seen only in two dimensions.

Unlike most igneous dykes, which usually divide only when they are about to die out, the sandstone dykes are commonly branched and many of the apophyses (some of capillary fineness) interconnect the principal sheets. Several subsidiary branches parallel the main dyke sheets but others diverge (at 60–90°) towards the east-south-east, i.e. along one of two joint directions. These may represent separate injections. Abrupt increases in thickness occasionally coincide either with a change from a concordant to a discordant attitude or at the junction of a sill with the dyke.

Most of the sandstone dykes contain varying numbers of angular mudstone inclusions which are either scattered throughout the dyke or are locally concentrated. The largest are usually orientated whereas the smallest are usually unorientated. Some of them contain fossils (usually belemnite guards) which can be used to determine the direction of injection (p. 24).

### *Dyke walls*

The thickest sections of the large-scale sandstone dykes protrude as walls (Fig. 4a and b). Comparable dyke walls have been described, mainly from the Sacramento Valley of California (e.g. Diller, 1889, pl. 6, figs 2 and 4; pl. 7, fig. 1; pl. 8).

The dyke walls are usually smooth and planar but irregularities occasionally occur. Unilateral and bilateral asymmetrical stepping (Fig. 4c) characterizes three dykes at Mount Ariel. In each example, only a few centimetres of dyke wall are involved. Faint fractures trend upwards or downwards from the right-angled corner of each step. Dykes cutting the Numidian flysch of Tunisia are "striated" and similarly stepped (Gottis, 953, p. 1780, pl. XXIV, fig. 2), perhaps due to small-scale boudinage. In one dyke associated with the disturbed zone at Keystone Cliffs (Taylor and others, 1979), part of one wall (Fig. 4d) consists of a series of irregular straight-sided steps and well-rounded crenulations. In Alexander Island, the stepping probably represents the shape of the original fissure or irregularities in the rate of dilation.

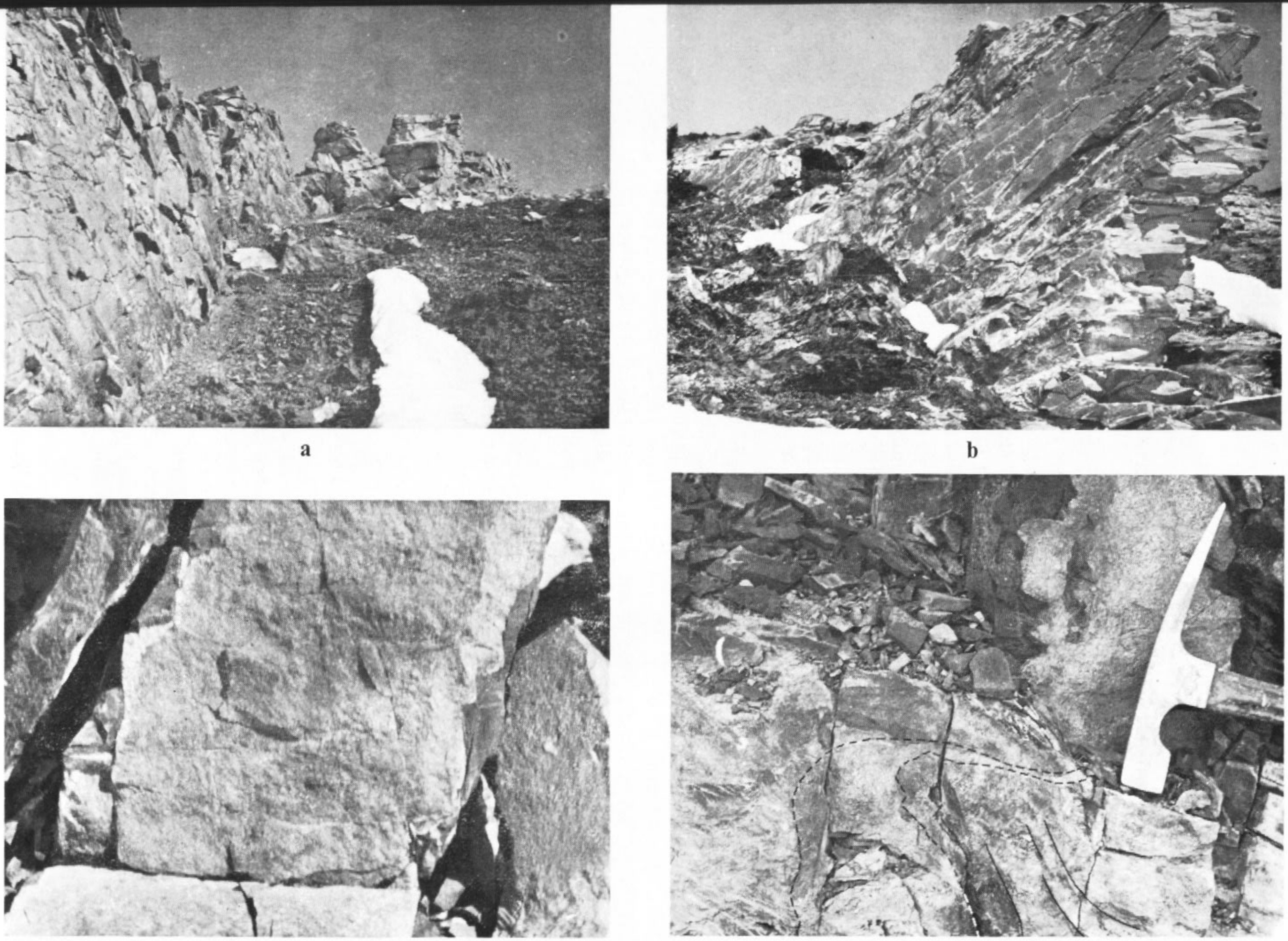
Fluting comprising asymmetrical ridges and grooves occurs along part of one dyke wall at Mount Ariel. The fluting, which is parallel to the dip of the wall, resembles that described by Lawler (1923, p. 163, fig. 2) and Peterson (1968, p. 186, fig. 11). The "layer-plane" structures of Peterson (1968, p. 185), which occur within the sandstone dyke, are rare and their origin is not known. However, an irregularity in the viscosity or velocity of the injected sand or in the subsequent deformation of the dyke is probably involved. The fluting also resembles a structure at Waitabit Cliffs which Horne (1967, p. 11, fig. 9a) called a pseudo-ripple mark. This was considered to represent "an extreme development of pressure trails". Both structures (and possibly the layer-plane structures of Peterson (1968)) may be related.

No evidence of scouring of the wall rock during injection was observed, i.e. a selvage or salband as described from eastern Venezuela (Laubscher, 1961, p. 303). Dykes sampled by the author in the Rio Querecual, eastern Venezuela, show a discontinuous dark band near the junction between the dykes and the fossiliferous (mainly foraminiferal) and strongly lineated host rocks. The band represents an enrichment of iron ore and does not contain any sedimentary stringers.

### *Attitude of the host rocks adjacent to the dykes*

The host rocks adjacent to several of the large-scale sandstone dykes and their apophyses are either unaffected or only slightly affected by the injected sandstone. This is shown by the simple cross-cutting relationship between the dykes and the laminated mudstones in the succession. Elsewhere, the host rocks are usually up-arched on both sides of the dyke but occasionally they are both up-arched and down-warped against the same dyke wall.

Although the distortion of sediments adjacent to sandstone dykes has been claimed to indicate the dykes' forceful injection and the direction of emplacement (e.g. Newsom, 1903, p. 233; Parker, 1933; Dzułynski and Radomski, 1956), these are often simulated effects. This is demonstrated in Alexander Island by the occurrence of up-arching and down-warping within 1 m along the same dyke wall (Fig. 7a) and by the up-arching of mineralized shear planes over parts of the outcrop where no dykes occur. These observations suggest that either differential compaction between the mudstones and the less compressible dyke sand has occurred or that the sediments, pushed aside by the injected dykes, subsequently moved back to abut against them—as suggested by dykes cutting the Cretaceous–Tertiary of south-eastern Wellington, New Zealand (Waterhouse and Bradley, 1957, p. 541, pl. 35, fig. 1).



a

b

c

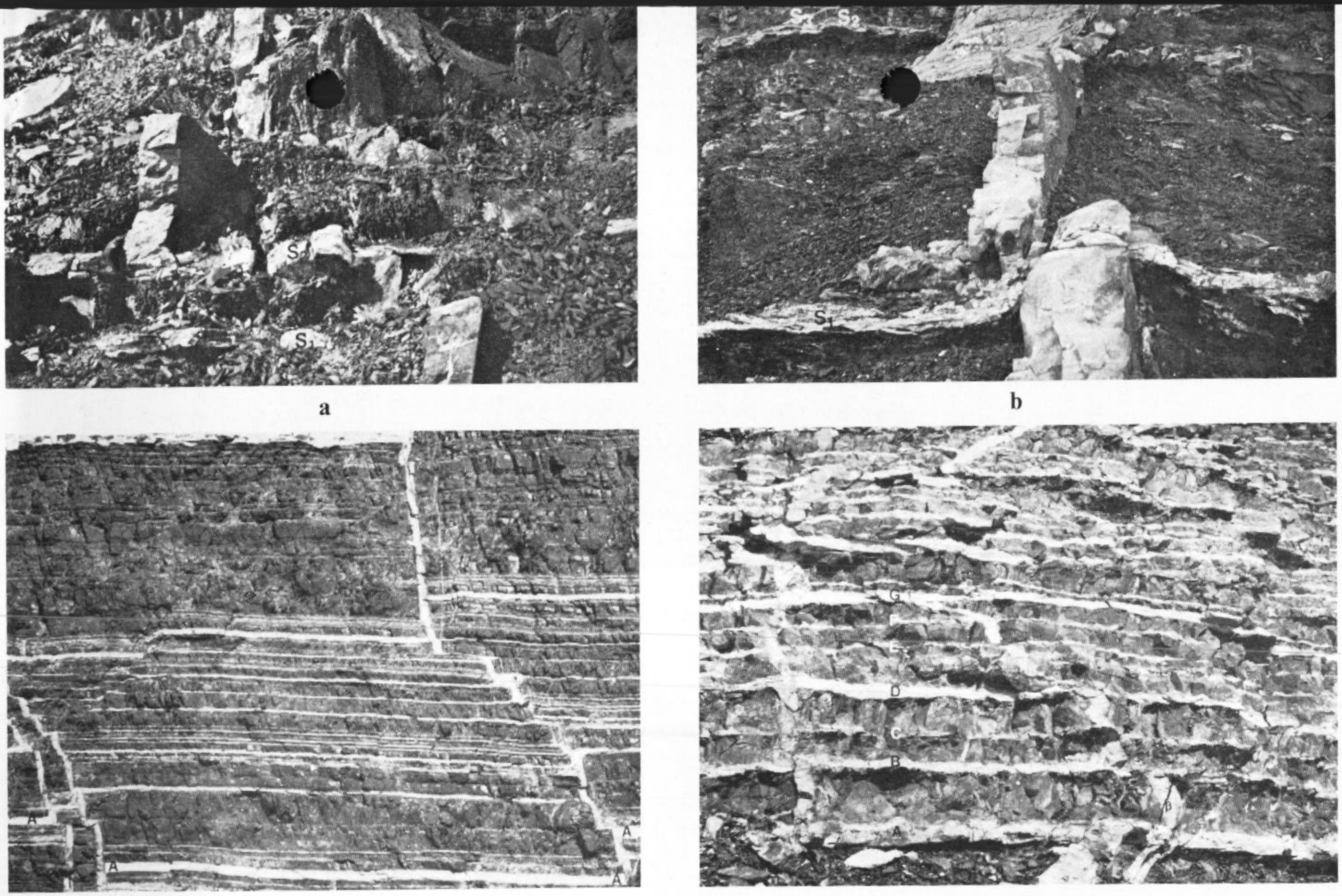
d

Fig. 4. a. Part of a dyke striking 232° across the northern scarp of Mount Ariel. The dyke here is 1.3 m wide and 2.3 m high (left foreground).

b. Part of a dyke striking 169° across the northern scarp of Mount Ariel. The dyke here is 0.74 m wide and 6.5 m high.

c. Part of a dyke exposed on the west-facing scarp of the eastern ridge at Mount Ariel showing bilateral and asymmetrical stepping. A distinct margin occurs along part of the right-hand side. The dyke is 15 cm wide.

d. Irregular straight-sided steps and well-rounded crenulations associated with a dyke in the disturbed zone at Keystone Cliffs. The passage (pecked lines) of the injected sandstone through a mainly ar[illegible]eous stratum and the up-warping of mudstone intercalations [illegible]e stratum are also indicated. Th[illegible]ead of the hammer is 18 cm long. (Photograph by M. R. A. [illegible]omson.)



a b

c d

Fig. 5. a. One branch of a large-scale sandstone dyke affected by horizontal offsetting at several sub-horizontal shear planes represented by slickensided bands of calcite and quartz. The 10 cm wide dyke is offset towards the east 48 cm at $S_1$ and 1.1 m at $S_2$ and $S_3$; northern scarp of Mount Ariel.

b. Two branches of a large-scale sandstone dyke transversed by three sub-horizontal shear planes ($S_1$, $S_2$ and $S_3$). At $S_1$ the 30 cm wide branch is reclined above the shear plane and thus simulates an offset attitude, whereas this and the other branch are unaffected by $S_2$ and $S_3$. The two branches coalesce at "x" and continue as one sheet; west-facing scarp of the eastern ridge at Mount Ariel.

c. An enlargement of part of Fig. 10a showing horizontal offsetting at several cream-coloured sandstones. Because the dykes were emplaced along two parallel fault planes, faulting preceded horizontal offsetting at locality D.

d. Anomalies in horizontal offsetting associated with two branches ($\alpha$ and $\beta$) of the *same* sandstone dyke cutting the lower 1.8 m of unit 87 at Mount Ariel. The relevant slickensided sandstone beds are lettered A–G and branch $\alpha$ is 6.5 cm thick.

In the Senonian of eastern Venezuela, differential compaction probably gave rise to the calcite fissures in the sandstone dykes. However, the deformation of the dykes and of the adjacent host rocks (Laubscher, 1961, figs 7 and 8) is attributed to sudden stoping (Laubscher, 1961, p. 320).

### *Horizontal offsetting*

Most of the large-scale sandstone dykes are horizontally offset. This phenomenon occurs at bedding planes (often coinciding with an indurated band of compacted vermicular structures (Taylor, 1967)), along slickensided sandstones within some of the thickest beds in the succession but most commonly at horizontal or sub-horizontal shear planes represented by slickensided veins of calcite and quartz (Fig. 5a). Many quartz prisms in the veins are elongated either parallel or slightly inclined to the bedding. The strike of the slickensides, although variable even along the same shear, is usually east-north-east to west-south-west (Fig. 12a and b), the relative movement (as shown by the occasional stepped slickensides) being towards the east-north-east. Immediately above any one dislocation, the dykes are almost invariably offset towards the east or east-north-east, the dislocations varying in magnitude from a few centimetres to several metres. Sedimentary dykes affected in this way have been described by many authors including Diller (1889), Anderson (1944, p. 256, fig. 4), Hedberg (1950, pl. 7, fig. 3), Monroe (1950), Dzułynski and Radomski (1956, figs 1 and 2), Hayashi (1966, fig. 5a–c) and Peterson (1966, fig. 4).

The horizontal offsetting may be attributed to one or more of the following:

i. Post-dyke tectonism (sometimes referred to more specifically as strike-slip faulting, bedding-plane slip, *Gleitbretter* or pinnate cleavage and sheeting. In pinnate cleavage and sheeting (Hills, 1963), the fault plane is either parallel to the cleavage in adjacent rocks and both become shearing surfaces under the same stress field, or the cleavage planes predetermine the direction of shear.
ii. Syn-formational tectonism caused by the sliding of one sedimentary mass over another. This mechanism, operating at several stratigraphical levels, would effectively "seal off" individual dykes from those injected above and below.
iii. The natural passage of the sand along joints and bedding planes, the sudden cessation and offsetting representing the farthest vertical extent of a particular joint and the subsequent lateral migration of the sand.
iv. Gases associated with volcanism.

Because the horizontal offsetting is usually complex and often seemingly anomalous, it is not always possible to determine precisely which of the aforementioned factors is involved at any one offset. The occurrence of several dykes or branches of dykes passing undisturbed through a shear plane (Figs 5b and 6) indicates a pre-dyke phase of transcurrent faulting which may have either initiated or dilated the joint system.

However, most of the stair-like horizontal offsetting is probably due to post-dyke bedding-plane slip at the slickensided mineral veins, which effectively disjointed sandstone dykes originally injected as single sheets or as a series of sub-parallel sheets. This is demonstrated by an ascending series of displaced segments of about the same width lying *en échelon* to one another and by the truncated junctions (Fig. 5a) between these faulted segments and the mineralized veins. In most examples, succeeding dyke segments are offset towards the east, i.e. in the same direction as the relative movement of the major thrusts in this area (Horne, 1967). However, dykes apparently offset towards the east *and* the west have been reported, notably at Mount Ariel. Some drag shear towards the east is also shown by some of the thinner disrupted dyke segments.

Elsewhere, the drag folding of thick dyke branches and the thrust faulting of thinner dyke

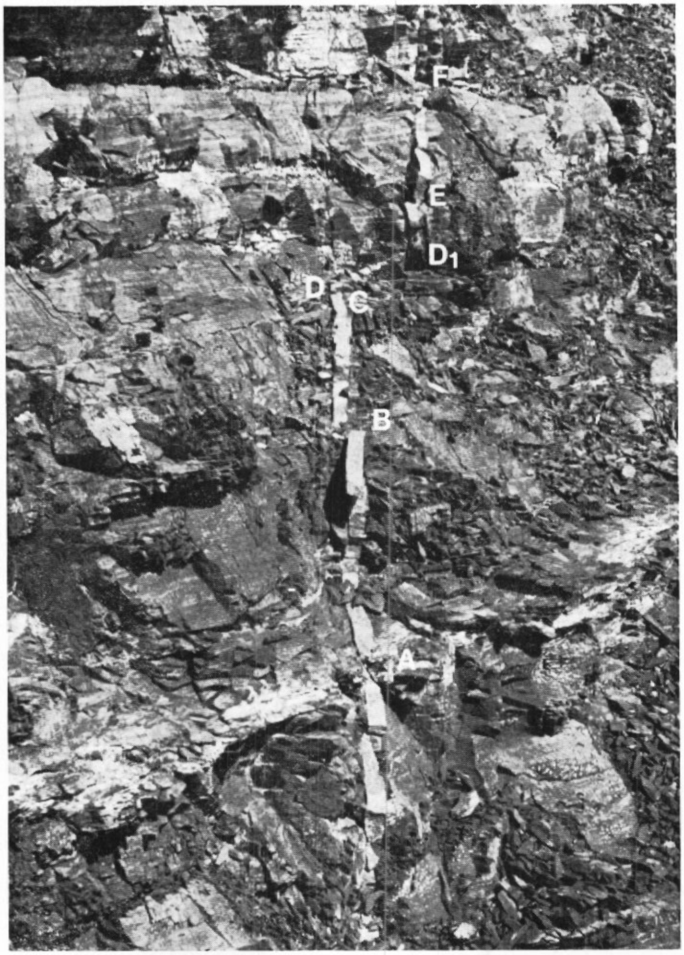


Fig. 6. Part of a sandstone dyke on the northern flank of Mount Ariel striking 206° and cutting a mainly argillaceous sequence. The dyke, 2 cm wide at A, cuts directly through A (a slickensided layer), is offset towards the east at B, cuts through C (a bedding plane), takes on a sill-like attitude ($D–D_1$) for 13 cm, is offset towards the west at E and then cuts through another bedding plane at F (upper bedding plane of unit 133).

branches at the same shear plane and differences (up to 50%) in displacement between adjacent offsets are probably due to disparities in frictional drag caused by differences in thickness or in strike. The latter were not always apparent in the field. At Mount Ariel, two intersected dykes (p. 20) are offset by different amounts at the same shear plane. The invariably greater displacements associated with the earlier dyke suggest that shearing probably accompanied both injections, the second shearing phase reinforcing the earlier one.

A much more difficult and somewhat anomalous example of horizontal offsetting is demonstrated by a dyke cutting the lower 1.8 m of unit 87 at Mount Ariel. This unit consists of 5.5 m of grey-black mudstones and cream-coloured and slickensided sandstones (Fig. 5d, A–G). The slickensides are all orientated east-north-east to west-south-west. Immediately beneath unit 87, the dyke comprises three bifurcating branches all of which abut against the lowest sandstone (A). The course of the westerly branch through the stratum is difficult to follow and the middle branch terminates at sandstone A. However, the easterly branch with its two 6 cm thick bifurcations is more readily examined in the field. The behavioural differences between the two bifurcations are well shown in Fig. 5d. Branch $\alpha$ to the left of Fig. 5d cuts sandstone A and then forms a right-angled flexure within sandstone B before continuing obliquely upwards through sandstones C, D and E. At sandstone F, branch $\alpha$ is offset towards the west before passing through sandstone G. The curvilinear branch $\beta$ tapers upwards and is offset towards the east at all but one (F) of the slickensided sandstones. The coalescence of the two branches produces a dyke twice as thick; this cuts obliquely across the upper part of unit 87 and adopts a sill-like attitude before emerging into more argillaceous rocks where it again increases to a thickness of 43 cm.

As the two branches bifurcate from the same dyke sheet and then appear to converge and coalesce, it is probable that they were injected contemporaneously. It is also easier to regard the anomalies as due to syn-formational tectonism (when the sediments were unlithified and more prone to disharmonic disturbance) rather than to post-dyke bedding-plane slip.

The offsetting of dykes at or almost coinciding with bedding planes apparently unaffected by bedding-plane slip, the apparent offsetting of dykes in opposing directions and the stair-like patterns produced elsewhere show that occasionally the sand was injected via a scalariform arrangement of joints. Most of the sand occupied the vertical joints but sometimes a sudden cessation in the flow trapped some of it along the bedding planes as sills.

In the south-eastern Transvaal, a sandstone dyke cutting a Karroo dolerite sill (van Biljon and Smitter, 1956, pl. XIX, fig. 1) may have owed its horizontally offset appearance to gravity filtration via joint planes, syntexis or to volcanism, the zig-zag fissures occupied by the dyke having been "drilled from below by pent-up gases, either in one operation or several" (Plumstead, 1956, p. 142). Plumstead suggested that the fissures were kept open or re-opened by escaping gases or by intermittent explosions. This somewhat bizarre mechanism is unlikely to have occurred in south-eastern Alexander Island.

### *Vertical offsetting*

Several large-scale sandstone dykes in south-eastern Alexander Island, notably two at Succession Cliffs (locality A) and Mount Ariel, are vertically offset and foreshortened by:

i. Overlapping of one segment against another without any apparent distortion.
ii. Coupling of two dyke segments by a Z- or S-shaped flexure.
iii. Complete separation of two or more parts of the same dyke.

At Mount Ariel, a perpendicular and somewhat inaccessible dyke (Fig. 7a) cuts a finely banded and mainly argillaceous succession. The dyke consists of several segments (all offset towards the west), which are either detached (Fig. 7a, lower left) or connected by Z-shaped flexures. In another dyke inclined at 40° to the bedding (Fig. 7b) the *schuppen*-like fault slices, which are often tapered at one or both ends, overlap one another by up to 50%. Assuming that the dyke was originally a single linear sheet, an extrapolation of the fault slices suggests that it has been foreshortened by at least 30%. At Succession Cliffs, a similarly foreshortened dyke (Fig. 7c) has been sheared along the bisectrix (the axis of maximum compression) between a set of steeply dipping shear joints striking at 180° and 236°, respectively. Slickensides parallel to the dip of a dyke's walls are common either within the dyke or at the contact with the host rocks. However, they are not restricted to dykes which have been obviously vertically offset.

Vertical offsetting of this type probably represents either the distortion of a planar sheet or of a dyke originally injected in a stair-like fashion, many of the connecting sills being destroyed or flexed. Comparable examples (Anderson, 1944, figs 3 and 4; Eisbacher, 1970, fig. 5c) have been attributed to small-scale lateral [*sic*] faulting (Newsom, 1903, p. 232, fig. 2), reverse faulting (Venter, 1956, fig. 1), the wedging or stoping effects produced by an advancing

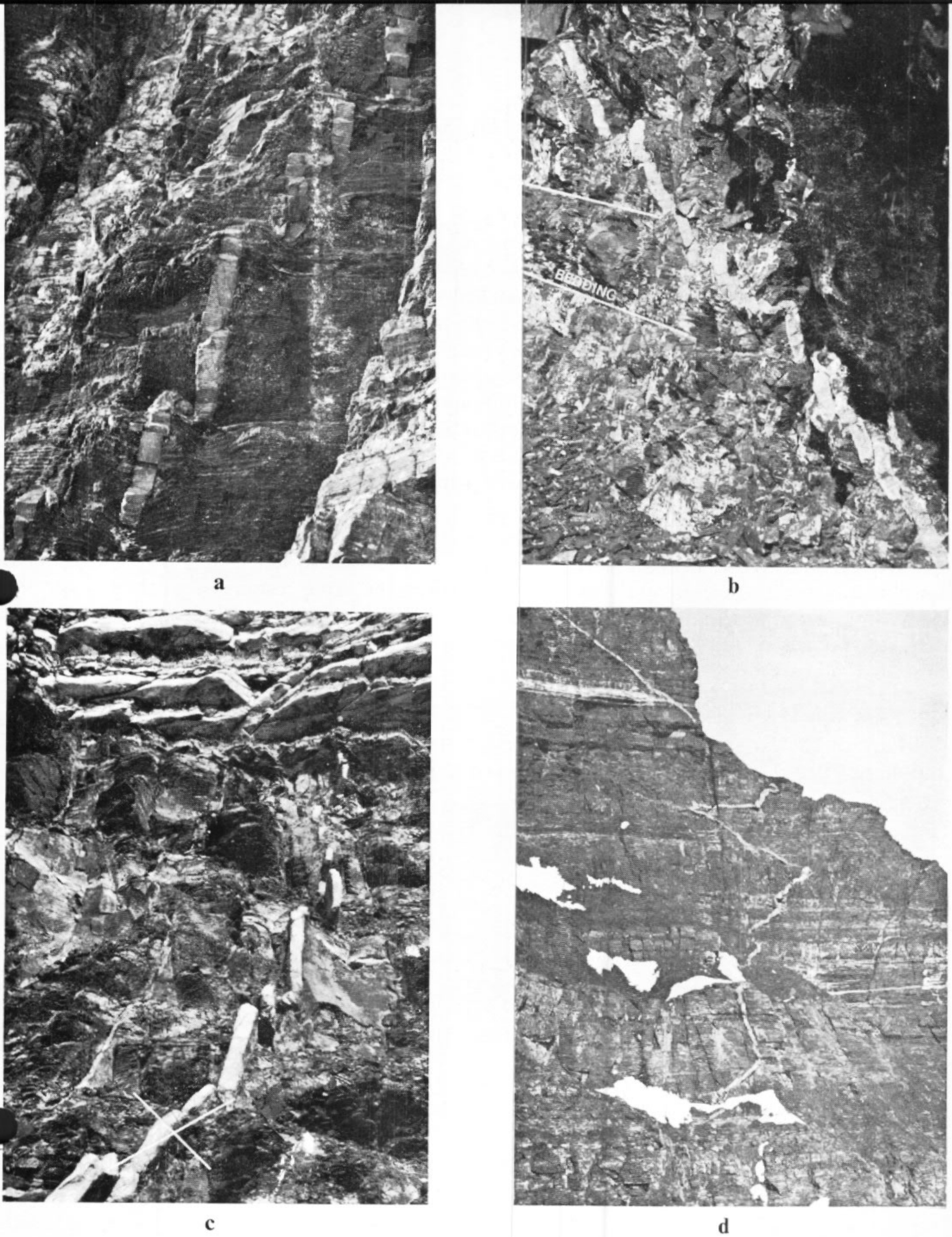


Fig. 7. a. Part of a large-scale sandstone dyke on the northern scarp of Mount Ariel showing vertical offsetting, shear buckling and distortion of the host rocks. All phenomena are probably due to post-dyke tectonism. The dyke is 10 cm wide.

b. Part of large-scale dyke showing considerable foreshortening due to compression and resultant shearing and buckling. The *schuppen*-like fault slices overlap one another by up to 50%. The 2 cm thick dyke is inclined at 40° to the bedding which strikes at 94°; eastern ridge at Mount Ariel.

c. A foreshortened sandstone dyke 6.5 cm wide sheared along the bisectrix between a set of steeply dipping shear joints striking at 180° and 236°, respectively. The mainly are naceousbed (upper part of photograph) is 2.4 m thick; Succession Cliffs, locality B.

d. Beneath the summit of Mount Ariel, this somewhat inaccessible sandstone dyke changes direction at least 16 times to form S- or V-shaped flexures and occasional peneconcordant sections. The course of the dyke, which cuts at least 61 m of succession, was probably joint-controlled.

quicksand (Laubscher, 1961, p. 314, fig. 24) and "further minor slump movements, or movements associated with later settling and compactional processes" (Gregory, 1969, fig. 21, p. 279). In the Looe area of Cornwall, sandstone and igneous dykes in a mainly argillaceous sequence are similarly offset due to cleavage, the transposed sandstone segments lying either parallel or oblique to the cleavage planes in the argillites (Lane, 1966, figs 5 and 6). Comparable mullions in the same area have been thrust.

Vertical foreshortening resulting in an imbricate effect was produced experimentally by vertically compressing by 20–30% quartz-veined Nelligen phyllites encased in constraining jackets (Paterson and Weiss, 1968). These authors found that when the quartz veins were relatively thicker than the kink folds in the phyllite (and parallel or at an angle to the foliation) the veins developed an independent number of reverse or thrust faults inclined at approximately 30° to the compression (Paterson and Weiss, 1968, p. 800), thus producing a vertical *en échelon* effect. When more compression was applied, the veins were further shortened due to the development of *schuppen*-like fault slices until an imbricate effect similar to that in Fig. 7b and c was induced.

Paterson and Weiss also observed that there were behavioural differences between two parallel quartz veins of unequal thickness affected by the same compression, the thicker ve being imbricated whereas the thinner vein was folded. Similar anomalies were found in the sandstone dykes of south-eastern Alexander Island.

*Sinuosity*

Many of the large-scale sandstone dykes in south-eastern Alexander Island are sinuous, the sinuosities varying in amplitude between different dykes and between different parts

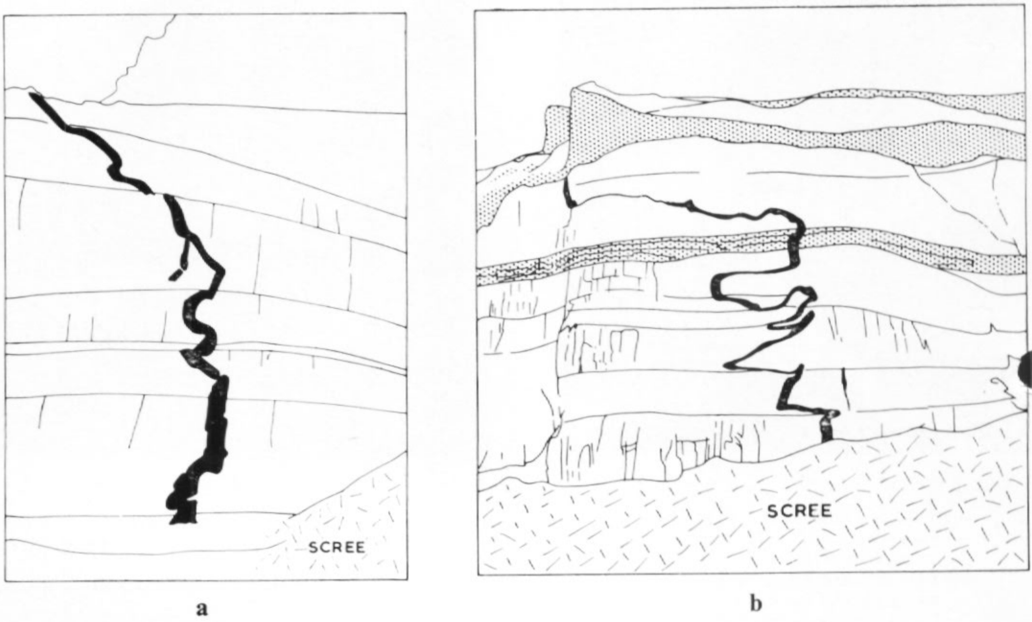


Fig. 8. a. A relationship between the bedding and the sinuosity of a sandstone dyke, northern scarp of Mount Ariel. At its base, where the argillaceous rocks are up-warped and down-warped, the dyke is 83 cm wide.

b. A relationship between the stratification and the sinuosity of a large-scale dyke; Succession Cliffs (locality A). There are 14 changes of direction (some at 90°), many approximately coinciding with the bedding planes. Three thick-bedded sandstones in the succession are shown stippled.

of the same structure. Some of the large-scale sinuosity appears to be related either to the bedding planes or to the occurrence of thick-bedded (>100 cm) units in the succession, whereas the small-scale flexures are usually more haphazard. In the field, no obvious relationships were found between the degree of sinuosity and differences in the attitude of the various dykes.

Large-scale flexures (folds or elbows of some authors) characterize several large-scale sandstone dykes, notably at Succession Cliffs (locality A) and Mount Ariel (Fig. 8a). Along the northern scarp at locality A, a prominent dyke (Fig. 8b) at least 91.5 m in extent appears above a thick covering of scree. There are 14 changes of direction (some at 90°), many approximately coinciding with the bedding planes. The thickest parts of the dyke are vertical, whereas the peneconcordant sections are much thinner. Below the summit of Mount Ariel, a somewhat inaccessible dyke (Fig. 7d) cutting at least 61 m of sediments changes direction at least 16 times to form S- or V-shaped flexures and, at one point, the dyke is peneconcordant for approximately 4 m along a bedding plane.

The effects of thick-bedded strata on the course of sandstone dykes are best demonstrated at Mount Ariel. One such bed is unit 35 (Fig. 2b), a 7.3 m thick topographical marker unit of intercalated cream sandstones and dark mudstones. Of the six dykes which cut unit 35, one of them abruptly adopts a diagonal course for 30.5 m and is peneconcordant for part of its length. Two other dykes are characterized by a large-scale flexure and by an appreciable attenuation which is restored when the dykes emerge above the upper bedding plane. The pitch of the flexures is in the same sense (towards the east) in both dykes. The trends of the other three dykes cutting unit 35 were obscured by snow and debris.

Several dykes (including two common to unit 35) are similarly affected crossing unit 45 (Fig. 2b), a 3.4 m thick bed of mainly cream-coloured sandstones and subordinate siltstones which forms a small cliff across the northern scarp of Mount Ariel. Two dykes adopt a sill-like attitude, one of them being almost concordant for 19.8 m, whereas another two dykes become strongly sinuous. One of these thickens appreciably on emerging from the stratum.

Elsewhere in the succession, the sinuosity is more haphazard and often somewhat anomalous. For example, one branch of a dyke might be strongly sinuous whereas a parallel branch similar in thickness and cutting the same strata is perfectly straight.

The sinuosity exhibited by the large-scale dykes probably represents a combination of three factors:

i. The natural dispersion of sand via an open or dilated joint system or through stoping.
ii. Compaction of an essentially rectilinear structure.
iii. Re-folding.

Because the large-scale flexures are "enclosed" by essentially undisturbed sediments, they probably represent the natural dispersion of a high-pressure sand. The peneconcordant sections of many of these sinuous dykes exclude the possibility of infilling of open fissures and points to the dilation of a joint system and/or stoping. As the argillaceous part of the succession was firm and cohesive prior to injection (p. 28), any subsequent distortion of the flexures probably represents the effects of post-dyke settling of the sedimentary trough and/or some drag shear. Similarly, in the Senonian of eastern Venezuela, original sinuous fissures (representing "fluid loops") may have been modified by secondary compactional effects coupled with a resultant drag and shear phase (Laubscher, 1961, p. 290). Conversely, in the Oligocene–Miocene flysch of Sicily, a similar style of flexuring in sandstone dykes (Colacicchi, 1958, figs 3, 4, 6 and 7) was attributed by Colacicchi (1958, p. 916) to subsequent "orogenic" movements because the dykes were thought to have been originally almost rectilinear.

In Tunisia, some flexures probably represent compactional effects, whereas several small-scale sinuosities reflect the shape of the original fissure. Where these are wide compared

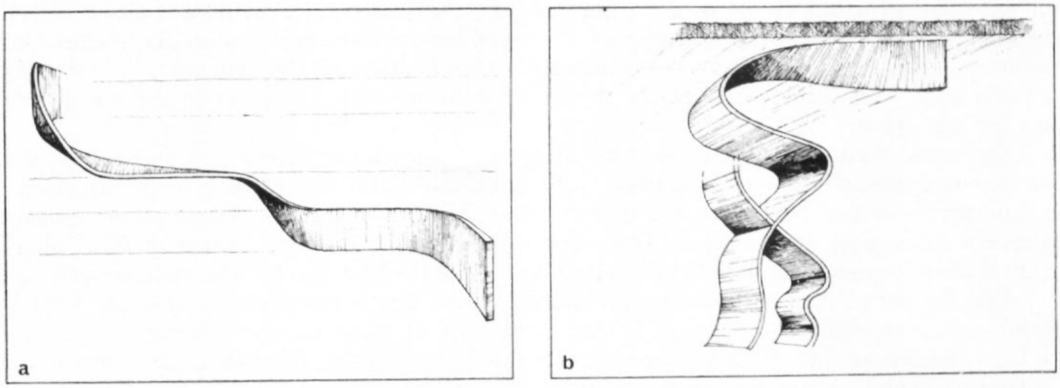


Fig. 9. a. Diagrammatic view (not to scale) of one of several large-scale sandstone dykes cutting unit 35 at Mount Ariel. The dyke, 70 cm thick, cuts diagonally across the stratum for approximately 30 m, adopting a sill-like attitude for a short distance before becoming discordant again. Large numbers of angular inclusions (some containing belemnite guards) were found in this part of the dyke.
b. Diagrammatic view (not to scale) of two sinuous bifurcations (each 1.5 cm thick) of a large-sca[illegible] sandstone dyke beneath an indurated layer (cross hatched). The main branch "follows" the layer along the strike for several metres while maintaining a vertical attitude and it was not observed to transgress the layer.

with the bed they cut, they acted as pillars and opposed any compaction (Gottis, 1953). In the sandstone dykes cutting the Eocene of Poland, many of the "folds" may be due to compaction as the most intense flexuring coincides with the more perpendicular dykes. However, even here, some of the sinuosity probably represents original sinuous fissures (Dzułynski and Radomski, 1956, p. 261).

Experiments using actual sediments to determine the origin of certain forms of soft-sediment deformation suggest that rounded flexures of primary origin were probably formed when the injected sand was still water-saturated, whereas the more angular flexures were produced when less water was present (Rettger, 1935, p. 286).

The flexures and sill-like attitudes invariably adopted by dykes cutting the relatively undisturbed thick-bedded strata at Mount Ariel suggest that these units may have been difficult to negotiate more directly. This is particularly well shown by a dyke cutting unit 35. Initially, the dyke is parallel to the bedding while still discordant (Fig. 9a) but then it becomes a sill for 30.5 m before reverting to a discordant attitude. Similarly, a branch of a large-scale dyke (Fig. 9b), which becomes sinuous beneath an indurated layer, follows the layer along the strike while maintaining a vertical attitude. Immediately after penetrating the upper bedding planes of these thick-bedded strata, most dykes revert to a strongly discorda[illegible] attitude and suddenly thicken, probably in response to their entry into more negotiable sediments.

An abrupt change of strike coupled with a pronounced thinning of a dyke is shown on a much smaller scale at Keystone Cliffs. Where this 15 cm thick dyke (Fig. 4d) cuts through a sandstone bed, it becomes sill-like and the overlying segment of the dyke is effectively offset. Above and below the sandstone, the dyke is approximately the *same* thickness.

Whereas much of the sinuosity appears to be primary in origin, some of the flexures are undoubtedly due to transverse drag shear. For example, where thin and thick dykes cut the same horizontal shear plane, the former is usually laterally offset, whereas the latter is either unaffected or drag folded across the shear plane. Disharmonic drag shear is also demonstrated by two equidimensional branches of the same dyke (with different strikes) cutting the thick-bedded strata at Mount Ariel. One branch is latterly offset at each of the slickensided sandstone interbeds, whereas the other is strongly folded. The attenuation and sill-like attitude of those dykes crossing unit 35 at Mount Ariel also resemble the effects of inhomogeneous shearing of competent beds or of tectonic thinning on transverse shears (Kaitaro, 1952, p. 68, fig. 1c). These effects contradict the comment that "contorted" dykes represented those injected "early prior to compaction" (Pettijohn and others, 1972, p. 127).

### *Dykes emplaced along fault planes*

Dykes emplaced along fault planes are relatively common in south-eastern Alexander Island, notably at localities D, L and Fossil Bluff. Approximately half-way up the cliff at locality D, on the north side of one of several deep gullies, there are three sub-vertical, straight-sided and uniformly thick dykes striking at 161–165°. The dykes, which are not easily accessible, have been emplaced vertically at least 61 m along a high-angled reverse fault and a narrow graben comprising two parallel high-angled normal faults (Fig. 10a). The largest and more elongated inclusions are aligned parallel to the dyke walls. As the parallel faults comprising the graben show a relative displacement of less than 1 m, compared with a downthrow of 3.5 m for the prism between them, the faulting and emplacement of sand probably occurred simultaneously, the prism falling as the hanging walls were extended. The graben is offset in the foreground of Fig. 10a and continued downwards to form an even more complex scalariform structure comprising four sub-parallel sandstone sheets. Down-faulted sandstone beds form "the rungs of the ladder".

All three large-scale dykes are offset several centimetres eastward across at least ten thin-bedded (1.3 cm) and flag-bedded (3–10 cm) sandstones, whereas the ladder-like structure is displaced approximately 1.8 m in the same direction. Smaller dykes, some curvilinear, parallel the major structures. Evidently, faulting preceded horizontal offsetting here.

The uppermost parts of the dykes at the right of Fig. 10a enclose several elliptical concretions. These may have been derived from an underlying concretionary sandstone which appears to have been the source horizon for several subsidiary sandstone injections. One of the dykes forming the graben also appears to enclose several concretions but these are difficult to distinguish from other inclusions.

The dykes in this gully side may extend 2 km farther south where a sandstone dyke swarm strikes in the same general direction. These linear dykes, which are vertical or steeply inclined, were emplaced along several normal faults (Fig. 10b). One dyke, partly exposed in side view (Fig. 11b), shows several large, rafted siltstone blocks which could only have been transported by a dense suspension under considerable pressure. The frequent orientation of these blocks parallel to the walls and the general absence of rounding suggests a laminar flow with little abrasion during injection. Unfortunately, the dyke in Fig. 11b was not readily accessible and the siltstone blocks were not examined for fossils. A similar high concentration of coarse fragmental material has been reported for a clastic plug in New Mexico (Parker, 1933, p. 48, fig. 6). In both instances, the specific gravity of the host rocks may not have been much greater than that of the injected sands so that in the main, the large fragments were in suspension. In the dyke, the blocks could not have been transported far without impinging against the confining walls and fragmenting.

Two sandstone dykes, probably emplaced along fault planes, are exposed at locality L near the headwall of Eros Glacier. One of them, which is somewhat inaccessible, strikes at 230° and cuts a basal cliff consisting of interbedded cream arkosic sandstones and thin and flaggy siltstones. The dyke appears to have been emplaced via several small-scale parallel faults arranged *en échelon* to one another. A second dyke emplaced along a fault and cutting a more conspicuous palisade-like cliff near the summit of locality L was not examined in detail.

At Fossil Bluff, at least one dyke (exposed on the south side of the small glacier immediately behind the scientific station) was emplaced along a fault having a downthrow of 1.5 m to the

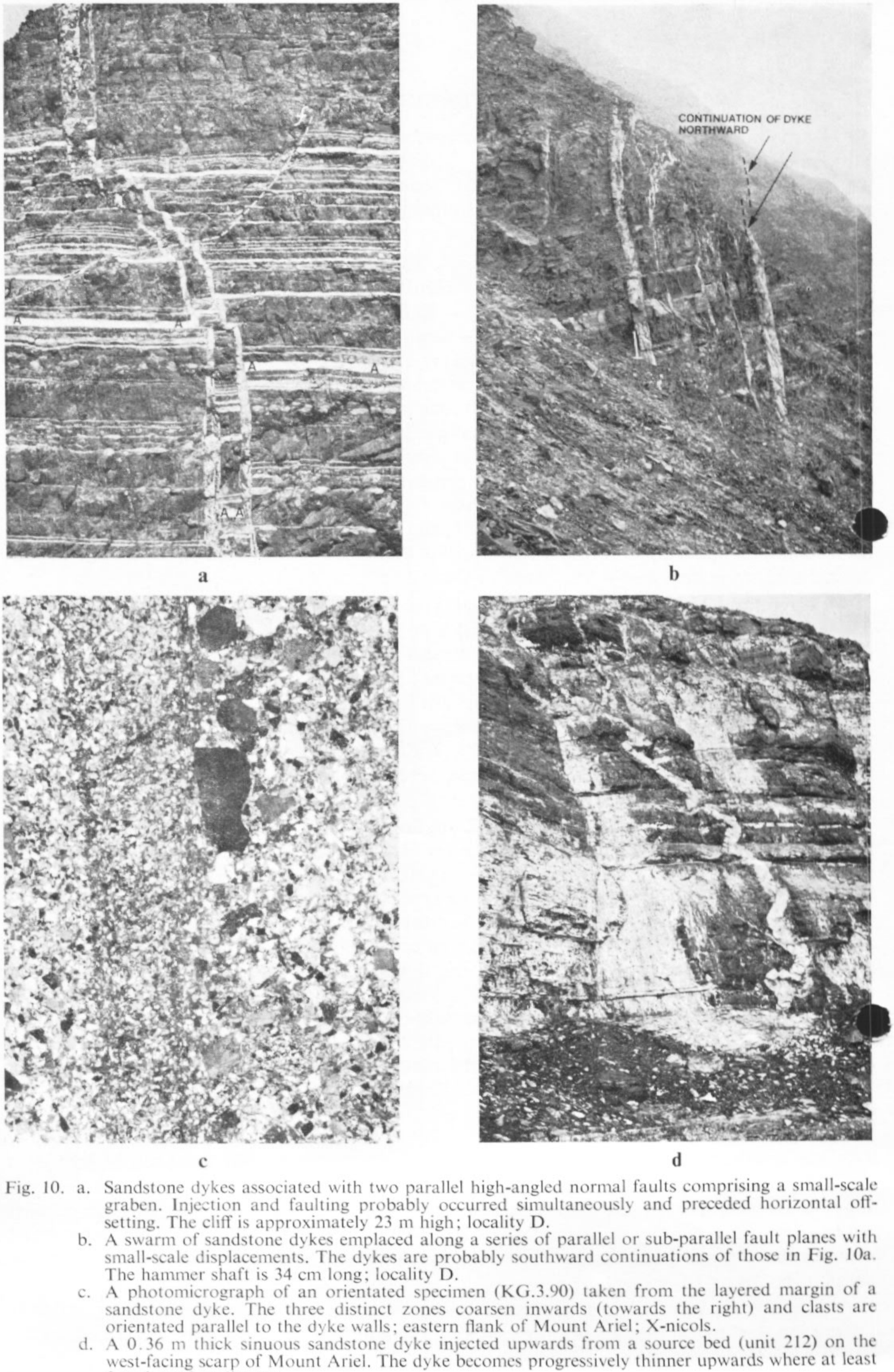


Fig. 10. a. Sandstone dykes associated with two parallel high-angled normal faults comprising a small-scale graben. Injection and faulting probably occurred simultaneously and preceded horizontal off-setting. The cliff is approximately 23 m high; locality D.

b. A swarm of sandstone dykes emplaced along a series of parallel or sub-parallel fault planes with small-scale displacements. The dykes are probably southward continuations of those in Fig. 10a. The hammer shaft is 34 cm long; locality D.

c. A photomicrograph of an orientated specimen (KG.3.90) taken from the layered margin of a sandstone dyke. The three distinct zones coarsen inwards (towards the right) and clasts are orientated parallel to the dyke walls; eastern flank of Mount Ariel; X-nicols.

d. A 0.36 m thick sinuous sandstone dyke injected upwards from a source bed (unit 212) on the west-facing scarp of Mount Ariel. The dyke becomes progressively thinner upwards where at least four branches diverge.

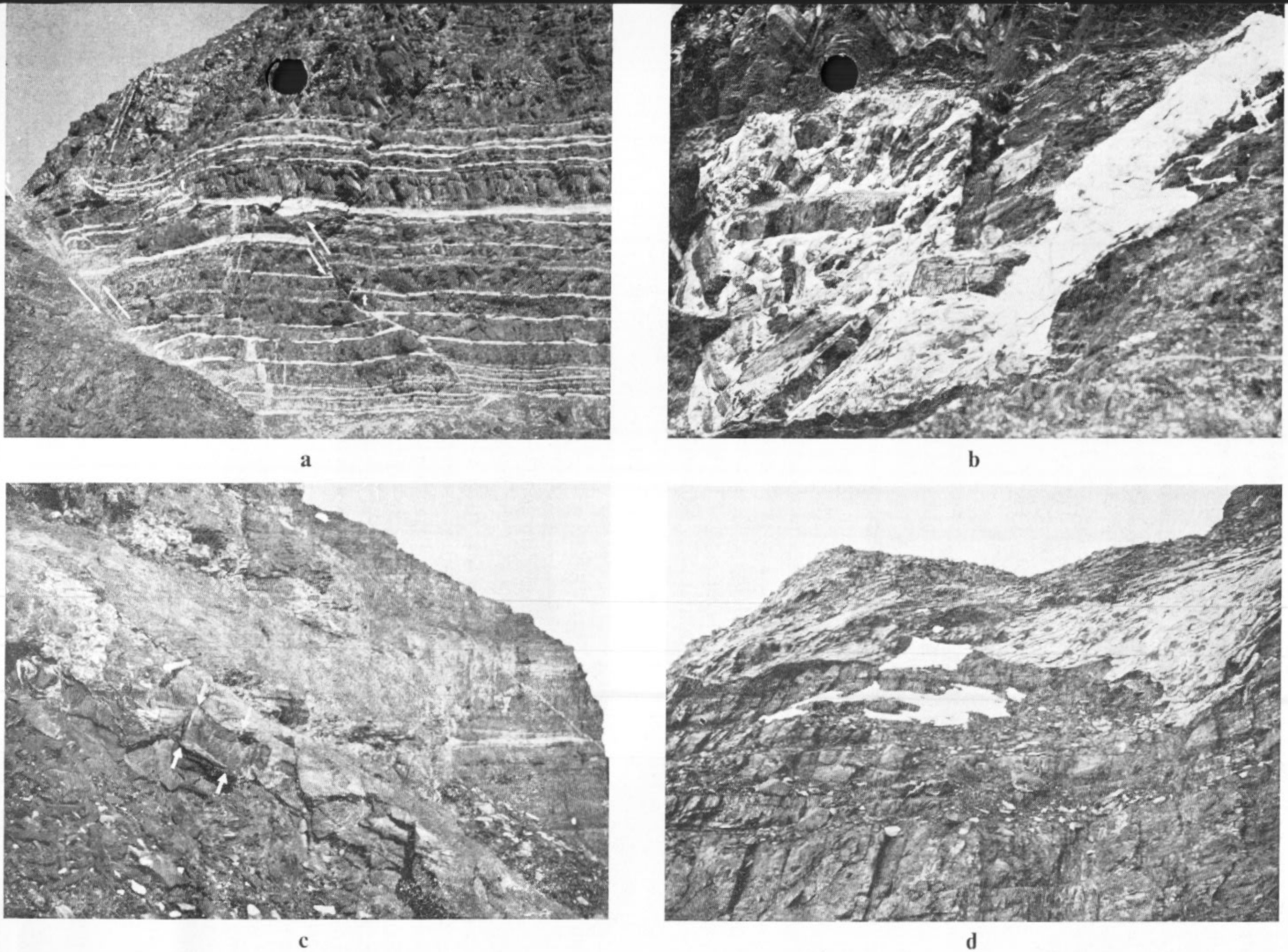


Fig. 11. a. Sub-parallel sandstone dykes disrupted by one major west to east thrust plane and several subsidiary thrusts; locality D.

b. Oblique view, looking upwards, of a sandstone dyke exposed in an almost vertical cliff at locality D. The large rafted blocks (some over 1 m in length) probably had a specific gravity approximately equivalent to that of the injected sand.

c. A sandstone dyke approximately perpendicular to the strike of the sedimentary succession and containing an inverted (at arrows) argillaceous block characterized by flaser bedding. The dyke, which may be laterally continuous with another exposed nearby (at right), may either have been emplaced along one or more faults or injected downwards. The hammer shaft is 34 cm long; Mount Ariel.

d. A discordant chonolith-like body approximately 15.2 m thick at the western end of Mount Ariel. Studded with "cannon-ball" concretions, the injected material probably originated via feeders from unit 212.

south-west. The dyke, which strikes at 157° and is traceable vertically for 244 m, comprises two parallel sheets which ultimately converge. Near the cliff top, the dyke is offset towards the east across two slickensided mineral veins before protruding as a high wall veined by calcite and quartz.

On the opposite side of the glacier, two other major sandstone dykes striking parallel to three high-angled normal faults were observed. Although these dykes were not examined in the field, it seems possible that they were emplaced along fault planes and that one or both of them is laterally equivalent to the dyke described above. At least one sandstone dyke at locality J was also emplaced along a fault.

### *Intersecting large-scale dykes*

So far only two occurrences of large-scale dykes intersecting one another have been recorded. Near the axial fold plane on Mount Ariel and close to the glacier margin, two dykes striking at 146° and 269°, respectively, form a broad "X" low down on the scarp, the westerly dyke being the later of the two. The junctions are straight and sharp and neither dyke is offset. The acute angle of intersection (57°) is in broad agreement with that normally associated with intersecting shear fractures bisected by the axis of maximum compression (Smith, 1952, p. 890). Therefore, the two dykes probably represent shear fracture dykes. The axis of maximum compressive stress indicated by the two dykes is in agreement with the inferred regional compression derived from an analysis of joints measured by Horne (1967, fig. 10). Below the intersection, where the two dykes are disrupted by the same horizontal shear bands, the direction of relative displacement is comparable, although there are considerable differences in movement along the same shear (p. 10). Higher up on the scarp east of the central ridge, two other dykes striking 245° and 208° intersect, the westerly dyke being the later of the two. The acute bisectrix of these is much less (37°) and the theoretical axis of maximum compression is at variance with the other cross-cutting dykes.

In the Panoche Hills, California, "primary and secondary" sandstone dykes intersecting at 60–80° have been described by Smyers and Peterson (1971, p. 3205). Their junctions appear to be normal but, because of the weathering of the host rock (the Moreno Shale) and the gypsum-cemented dykes, it is not known whether there was more than one phase of injection. However, it is suggested (personal communication from G. L. Peterson) that the dykes were injected contemporaneously and filled V-shaped fractures.

In the Senonian San Antonio Formation of eastern Venezuela, intersecting dykes are common (Hedberg, 1937, p. 1993), an observation confirmed by the author, who observed numerous examples on Cerro San Antonio and Cero San Andrés. The junctions of some of these appeared to be normal. Intersections were not described by Laubscher (1961) in his otherwise comprehensive account of these remarkable structures.

Only a few instances are known where dykes (notably of an igneous origin) obliquely intersecting one another are not offset (Goodspeed, 1940). In Washington State, USA, Goodspeed suggested that the absence of offsetting between an aplite and an earlier porphyritic dyke "may be explained by lateral movement along the walls of the fissure in such direction and amount as exactly to annul the offset produced by widening of the fissure as the dike filled it". However, Goodspeed emphasized that his interpretation would not necessarily explain all other occurrences, and Billings (1925) attributed a similar phenomenon in a diabase dyke at Medford, Massachusetts, to sudden stoping rather than dilation.

### (?) *Downwardly injected dyke*

One dyke (Fig. 11c) which cannot be grouped with any other on the northern scarp of Mount Ariel is exposed several hundred metres below the summit. The dyke, approximately perpendicular to the strike, abuts against the sediments at an acute angle. One wall is linear whereas the other is irregular. At one point, a large block of sedimentary rock, which was probably derived from a bed immediately above the dyke, is sandwiched between two parallel sandstone sheets. The block, characterized by flaser bedding, has been inverted. The dyke, which may be laterally continuous with another exposed nearby, may either have been emplaced along one or more faults or injected downwards.

### *Internal structures*

The large-scale dykes are composed of a grey-coloured calcareous sandstone that normally weathers to a pale yellow. The rock is outwardly similar to other sandstones in the succession but it contains numerous angular mudstone fragments which, exceptionally, are several metres long.

The dyke rock is usually structureless but occasionally there are laminations which are normally confined to one side of the dyke and of limited vertical extent. In one example, the laminae are convoluted and extend diagonally from one wall towards the other. The laminae, which are usually parallel or sub-parallel to the walls and have sharp and well-defined contacts, may represent the inversion of original bedding, multiple injection or, more probably, the concentration of grain-sizes due to laminar flow. A similar form of vertical banding has been recorded from sandstone dykes in California (Diller, 1889, p. 425; Peterson, 1968) and eastern Washington (Jenkins, 1925). The sporadic distribution of the laminae suggests that periodically there may have been variations in the velocity and viscosity of the injected sand which otherwise possessed a higher water content and a significantly lower viscosity (Peterson, 1968, p. 189).

The best example of layering occurs in a dyke (Fig. 10c) exposed on the extreme eastern flank of Mount Ariel. Laminae, partly accentuated by differential weathering and erosion, extend over a distance of 0.35 m along one wall. The layering is divisible into three distinct zones, i.e. an outer fine-grained zone (16 mm), a median zone (2–4 mm) and an inner coarse zone (30 cm) (Fig. 10c). Thin sections of orientated specimens collected from this laminated part of the dyke show that the larger grains and rock fragments are elongated vertically and that in the median zone, which is the finer-grained of the three, the two dark bands defining the outer and inner contacts are composed of numerous orientated and partly chloritized biotite flakes. The vertical orientations of the clasts suggest that the sediment was injected. The three zones, which are well cemented by calcite, are mineralogically similar to one another. At locality C, one sill was horizontally laminated.

Occasionally, somewhat haphazard vertical gradations occur. For example, at Succession Cliffs (locality B), a dyke (Fig. 7c) composed of a yellow-weathering sandstone passes upwards through a 2.4 m thick unit of cream-coloured sandstones and subordinate thin mudstones and siltstones. At the junction with the unit, the dyke becomes almost completely argillaceous and remains so until it emerges from the bed when it is more obviously arenaceous again. At the eastern end of Mount Ariel, a dyke passes upwards from a medium-grained sandstone with inclusions (extending for 10.7 m) to a finer-grained laminated sandstone without inclusions. These somewhat abrupt lithological changes may represent an incomplete differentiation of a "liquid sediment" as described by Swarbrick (1968, p. 166), the mobilized sedimentary mass tending to become finer-grained with increasing distance from the source bed. However, visual evidence and somewhat inadequate sampling suggest that most of the large-scale dykes represent the other major class in Swarbrick's (1968, p. 165) classification of intrusive sediment structures, i.e. "the injection of plastic or hydroplastic sediment". In these structures, the injected material is thought to be more cohesive and the water component, which is partly fixed by absorption, cannot leave the sediment without an increase in pressure.

Vertical gradations on a smaller scale range from patches of relatively coarse sand containing abundant mudstone fragments (randomly located) to a fine sand without fragments. The occurrence of concentrations of the coarser-grained fraction in the central parts of several dykes may be indicative of liquefaction. Experiments and theoretical studies have demonstrated that in laminar flow the solid particles separate from the walls and tend to segregate towards the centre of the injected sheet (Bhattacharji and Smith, 1964). Furthermore, the rate of this segregation increases with increased velocity or shear gradient. Similar forms of internal sorting have been reported by Pettijohn and Potter (1964, pl. 113B), Hayashi (1966, p. 16), Young (1968, p. 140, pl. 2, fig. 2) and Eisbacher (1970, p. 220, fig. 5a). To date, no horizontal stratification similar to that observed in some dykes near Santa Cruz, California (Newsom, 1903) has been recorded.

### *Petrology*

All of the dykes sampled consist of a calcareous arkose with quartz, plagioclase and alkali feldspar slightly in excess of rock granules, biotite (partly chloritized), muscovite and such heavy minerals as iron ore, sphene, zircon, epidote, apatite and allanite. The kink bands and bend gliding (Hills, 1963, p. 117) in several of the biotite flakes probably occurred prior t[illegible] injection.

Many of the quartz grains are large, angular, fresh or slightly strained and with moderate to large numbers of small inclusions which are often arranged linearly. Stringers in the orthoclase and microcline crystals may be due either to the exsolution of albite or to the infilling of strain cracks by quartz. Most of the feldspar grains are also angular and show few indications of abrasion, although many are altered to sericite or calcite. The twin lamellae in some are sheared and deformed. However, as this deformation is confined to isolated grains, it probably preceded injection of the dykes.

In the larger of two dykes at locality H, the cement is mainly detrital matrix probably composed of chlorite and clay minerals (KG.2.29) but elsewhere in Alexander Island the cement is principally calcite with subordinate prehnite (KG.3.90a and b, 92a and b). Exceptionally, dykes such as those (e.g. KG.17.44) sampled by R. R. Horne at locality C are cemented mainly by prehnite and laumontite. The calcite, which has etched many of the crystal grains or has formed veins between fragments of the same crystal, shows a good rhombohedral cleavage where it occurs in large patches. Minute quartz fragments in amongst large areas of calcite probably represent "ghosts" of larger grains that have almost been completely replaced.

The general angularity of the grains and absence of shear planes in the few dykes sampled suggest that the sand was not materially deformed when injected. However, at Waitabit Cliffs, M. R. A. Thomson collected two specimens, one from a dyke and the other from wha[illegible] was possibly the source bed, which suggest that the dyke sand was strongly abraded, probably through solution. Both rocks are light green in colour, a significant feature in this part of the succession where there are few similarly coloured sandstones.

In thin section, the stratified fine-grained arkose (KG.104.3) consists of relatively large angular quartz and feldspar crystals (the latter partly epidotized), perthitic microcline, patches of calcite, rock fragments, fibrous zeolite, biotite, sphene, zircon and epidote. The dyke rock (KG.104.4) is coarser-grained (medium to coarse sandstone), individual crystals are more rounded and the plagioclase more sericitized. Prehnite occurs in the matrix and with calcite in parallel veins 0.4 mm thick. These represent solution planes of lime and alumina resulting from a form of low-grade load metamorphism. As in some of the New Zealand greywackes, calcite appears to be replacing prehnite (Coombs, 1960).

The differences in texture and petrology suggest that either the two specimens are unrelated or the dyke sand has been intensively re-worked. Because of the close spatial relationships, it is unlikely that the dyke sand was mechanically abraded but solution may have occurred even over such a short distance.

Several dyke sands appear patchy because of differences in the relative proportion of calcite to the other constituents and to the other cements. This is particularly well shown by a yellowish white friable sandstone (KG.17.44) collected by R. R. Horne from a dyke at locality C. The darker areas are cemented mainly by calcite which has replaced many crystal grains but prehnite and laumontite are also present.

In the lighter areas, it is impossible to distinguish between foci of prehnite and laumontite in the hand specimen. The prehnite is either crystalline or in turbid and irregular patches but no veins branch from these as elsewhere in the succession. Laumontite is proportionately more abundant and represents much of the rock's cement. At least some alumina was derived from the plagioclase which is partly or completely laumontitized and commonly, partly etched plagioclase crystals are margined by laumontite.

The authigenic prehnite and laumontite probably resulted from the diagenetic alteration of a succession rich in tuffaceous material. In the Mesozoic of New Zealand, these minerals characterize two metamorphic facies, the quartz-prehnite stage of the prehnite-pumpellyite metagreywacke facies (Coombs, 1960, p. 342) and the laumontite stage of the zeolite facies (Coombs and others, 1959). According to Coombs and others (1959), these two facies represent distinct depth zones of load metamorphism but this concept seems inapplicable to other areas of regional low-grade load metamorphism within the circum-Pacific fold-mountain belt such as Oregon and Alexander Island. In Oregon, correlation between the authigenic silicates and depth of burial is not always possible and the initial rock composition is considered to have influenced the formation of particular metamorphic facies minerals (Brown and Thayer, 1963, p. 424). Dickinson (1962), working in the same area on a stratigraphically younger sequence, arrived at a similar conclusion. In Alexander Island, there is as yet no obvious correlation between the authigenic silicates and their stratigraphical distribution (Horne, 1968*c*), and often both prehnite and laumontite occur together in the same rock.

### *Source of the dyke sand*

Unfortunately, most of the large-scale dykes are first exposed at the glacier edge. In the absence of other evidence (usually palaeontological), their direction of injection can either be inferred or is not known. However, data from other dykes suggest that most if not all of the large-scale structures were injected upwards.

To date, the only large-scale dyke observed emerging from its source bed occurs on the west-facing scarp at Mount Ariel. Here, a sandstone dyke, 0.36 m thick near its base, was injected upwards (Fig. 10d) through at least 15.2 m of sediments from unit 212, a 2.4 m thick cream-coloured calcareous arkose containing numerous "cannon-ball" concretions. The dykes were not observed *cutting* either the cement-stone concretions, as in eastern Venezuela (Laubscher, 1961), or the cannon-ball concretions. The dyke, characterized by open and closed flexures, becomes progressively thinner upwards where at least four branches diverge. The dyke was not traced above the cliff top shown in Fig. 10d.

On the same scarp, at least one other dyke and a discordant chonolith-like body probably originated from the same source bed. The dyke, 5.5 m wide and the thickest so far examined in the field, rises as a perpendicular column against regularly stratified mudstones and siltstones. The dyke contains numerous "cannon-ball" concretions which were probably derived from the underlying arkosic sandstone.

Close by and probably originating via several "feeders" is a discordant chonolith-like body approximately 15.2 m thick which covers the underlying beds like a facing of roughly laid sand (Fig. 11d). Cannon-ball concretions and angular siltstone fragments are so abundant that the dyke sand resembles a sedimentary breccia similar to those found elsewhere in the succession. The structure, which resembles a sedimentary chonolith in the Upper Cretaceous of south-eastern Alberta (Williams, 1927, pl. III, fig. 2), may have been a sand volcano considerably larger and probably more complex than those, for example, in the Carboniferous of County Clare, Ireland (Gill and Kuen, 1958).

Elsewhere at Mount Ariel, the relative positions of other source beds and the direction of emplacement can be determined by the fossils which the dykes or their mudstone inclusions contain. For example, at one stratum (unit 126) in the succession (Figs 2b and 3), there is a relatively abrupt faunal change between a sequence composed predominantly of belemnite guards and an overlying one of bivalves (mainly *Aucellina* and *Inoceramus*). It is therefore reasonable to assume that dykes cutting this stratum and containing belemnite guards were injected upwards from a source bed below this stratum. This direction can often be deduced from other evidence, notably upward thinning. Conversely, dykes containing *Aucellina* and *Inoceramus* were injected upwards from a source bed above this stratum. On the northern scarp of Mount Ariel, the extrapolation (Fig. 2b) of the principal strike directions of three large-scale dykes suggests that they may radiate from a common source situated approximately 100 m below the present ice level. Two other dykes on the same scarp may also have originated from a common source bed. Elsewhere at this locality, four other sandstone dykes of smaller dimensions were injected upwards from known source beds.

Most of the apophyses of the large-scale sandstone dykes taper upwards and were probably injected in that direction (Gutierrez, 1966, p. 31), whereas those tapering downwards were probably injected from above like most of the small-scale dykes found elsewhere in the succession (p. 28). These observations seem to confirm Newsom's (1903, p. 268) comment that injection from below is the commonest direction of emplacement.

The choice of source bed is not obvious. Great thickness was probably not important because no dykes are associated with any of the thick-bedded sandstones. Although unit 212 at Mount Ariel (the source of at least three large-scale dykes) was probably more than 2.4 m (its present thickness), it is doubtful whether it was ever as thick as several other sandstones at the same locality. Unless the choice was entirely fortuitous, i.e. an accident of geographical or stratigraphical position, the granular composition of the sandstone, i.e. its shape, sorting and packing, must have been important. Some of the multi-branched dykes may have had several sources.

Many dykes terminate abruptly within the sedimentary succession (notably at Mount Ariel), presumably because of a change in pressure and a reduction in volume of the dyke sand which gradually became expended. If the injected material was a high-pressure gas sand (p. 28), the gradual escape of gas would cause the sand concentrate to slow down by its own inner friction and solidify. Alternatively, only a slight reduction in water content would induce solidification (Mead, 1925). When the flow of sand finally ceased, the dykes were presumably held up by the sedimentary blocks on either side which subsequently subsided to compensate for a loss of material from below. The quantity of injected sediment cannot easily be calculated because the dykes are incompletely exposed but it probably amounted to several thousand cubic metres. However, the amount of subsidence may have been relatively insignificant as shown by the Goose Creek oilfield. Here, subsidence represented only one-fifth the estimated volume of oil, gas, water and sand extruded on to the surface (Pratt and Johnson, 1926, p. 589).

Because many dykes terminate abruptly, it is doubtful whether any reached the surface as sand volcanoes except for the chonolith-like structure at Mount Ariel (see above).

### *The relationship between the tectonics of south-eastern Alexander Island and the large-scale sandstone dykes*

There is undoubtedly a close correlation between the general structure (Horne, 1967; Taylor and others, 1974) and the strike directions (Fig. 12a) and branching patterns of the sandstone dykes. Dykes related to joints or gash veins occur at Mount Ariel, Waitabit Cliffs and localities A, B and G, whereas dykes associated with faulting are found at Fossil Bluff and localities D and L.

At Mount Ariel, the dykes are arranged almost centripetally (Fig. 1) about a symmetrical fold dipping at 9°. Because sheared competent and incompetent beds on a fold are normally displaced towards the fold axis, the almost invariable easterly offsetting of the sedimentary dykes cutting *both* limbs suggests that injection preceded folding at this locality. There is no obvious relationship at Mount Ariel between several small-scale faults and the dykes which were emplaced along one or other of two principal joint directions. Although the author made only a few measurements in this area (at localities F, G and U), they agree with the overall regional analyses of Horne (1967, fig. 10), who demonstrated a conjugate set of steeply dipping shear joints approximately at right-angles to each other. The two examples of intersecting dykes are consistent with this view and the axis of maximum compressive stress derived from one example agrees with the inferred west-north-west to east-south-east regional compression suggested by Horne (1967). The slickenside orientations (Fig. 12b and c) both in the succession and in the sandstone dykes approximately bisect the angle between the axis of maximum compressive stress (north-north-east to south-south-west and not east-north-east to west-south-west as reported by Horne) and the direction of inferred regional compression. The few stepped slickensides recorded face towards the east, the direction of the offsetting and of the movement of the principal thrusts in this area. Slickensides on the dyke walls are usually orientated parallel to the dip of the dyke.

At Succession Cliffs (locality A), the strike of all but one of the dykes is approximately parallel to that of several normal and reverse faults and to the general strike of numerous sigmoidal gash veins which are particularly prevalent in this area. The north–south strike of the veins is almost parallel to the theoretical axis of compression derived from the joint analyses (Horne, 1967, p. 13, fig. 10a and b) and indicative of east to west or, more probably, west to east shear.

At present, no genetic relationship has yet been proved between the so-called "lubrication zones" (Horne, 1967, p. 3) or disturbed zones and the origin of the large-scale sandstone dykes. Disturbed zones and sandstone dykes occur in close juxtaposition at Fossil Bluff, Ablation Point, Waitabit Cliffs, Keystone Cliffs (Fig. 1) and Hyperion Nunataks (p. 30). One of the best examples is exposed on the east-facing scarp south of the scientific station at Fossil Bluff, where a dyke cuts a disturbed zone and seems to commence either a few metres

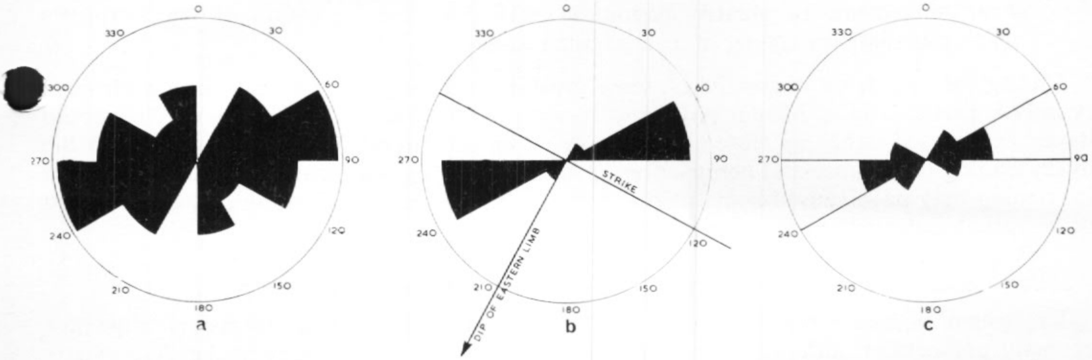


Fig. 12. a. Orientations of large-scale sandstone dykes at Mount Ariel based on the main and secondary branches; 90 observations.
b. Orientations of slickensides at Mount Ariel; 216 observations.
c. Orientations of slickensides (excluding vertical slickensides) within the large-scale sandstone dykes at Mount Ariel; 126 observations.

below or within the zone. The precise relationship (if any) between the two features is obscured by scree but the dyke's straight-sided walls and cross-cutting relationships suggest that it post-dates the disturbed zone. Almost homologous examples perhaps occur in New Zealand, where dykes post-date the "initial great surge of movement in the slump sheet" (Gregory, 1969, p. 278) but they may have been emplaced as the sheet came to rest.

Concerning the disturbed zone at Fossil Bluff, Horne (1967, p. 4) stated that "The mobile state of these sandstone [*sic*] beds during and after thrusting is shown by the fact that they have been injected in the form of dykes into the overlying undisturbed strata". This ambiguous statement suggested to Grikurov (1971, p. 36) that some sandstone dykes originated in the disturbed zones; this has not been proved so far as the large-scale structures are concerned.

On the north-east face of the hook at Ablation Point, a more argillaceous sedimentary dyke is exposed within a disturbed zone at least 350 m thick. Unfortunately, this dyke has not been examined in detail. At Keystone Cliffs and Hyperion Nunataks, several dykes are associated with disturbed zones but their precise relationships are obscured by poor exposure and/or scree.

The emplacement of dykes along fault planes suggests either penecontemporaneous faulting and injection or the dilation and subsequent filling of a pre-existing fault system. The shearing of a sandstone dyke swarm towards the east at locality D (Fig. 11a) by a major high-angled thrust and several subsidiary thrusts indicates that here injections of sandstone preceded west to east thrusting.

The almost invariable offsetting of many dykes towards the east probably resulted from a prevailing stress field in this direction. Subsequent tectonism related directly or indirectly to this stress are given below approximately in order of occurrence:

i. Formation of joints, either in a stress field involving tension or in a two-phase field, one compressive in which conjugate shear joints were developed and a later period of tension when tension joints were formed and the shear joints opened up. Some if not all of the small-scale faulting may have taken place at this time.
ii. A period of horizontal shear movements and the formation of mineralized and slickensided veins.
iii. Injection of sand from depth into an open or dilated joint system and into syn-formational fault planes. Occasionally, some wall rock was plucked off and incorporated into the slurry. Syn-formational horizontal shear movements may have fissured the succession and effectively sealed off the sand as it was injected.
iv. Post-dyke tectonism involving further bedding-plane slip together with folding and shear movements of greater magnitude leading to the formation of major thrusts which post-date the dykes, at least at one locality.

During the formation of the dykes, some crustal shortening in a vertical sense must have occurred, particularly at Mount Ariel and locality D where dykes are common. This could have been caused either by tectonic shrinkage or by the lateral secretion of water into the dykes leading to collapse and compaction of the surrounding sediments. Some of this crustal shortening may have caused some of the vertical and horizontal offsetting and either flexed or accentuated flexures in the sandstone dykes.

### *Possible mechanisms involved in the injection of the large-scale sandstone dykes*

The origin of many sandstone-dyke systems (excluding neptunian forms) is often not properly understood, although two energy sources are normally suggested, i.e. hydrostatic pressure and gas pressure. Whichever is invoked, the injection of any mass involves an expenditure of energy. The wall rocks often have to be separated (usually by dilation), the internal cohesion of the injected material overcome and an impetus is necessary to maintain the flow (Harms, 1965). Theories advocating hydrostatic pressure imply that the dyke sand was injected because of external pressures, whereas those based on gas pressure suggest that the source beds expanded *internally*, the material being injected in response to a local fall in external pressure such as that resulting from the fracturing of the host rocks. The close association of sedimentary and igneous dykes in several collieries in South Africa suggested to Plumstead (1956) that they may have been generated by the same energy source.

### *Hydrostatic pressure, earthquake shocks and associated phenomena*

Many authors have discussed the origin of sandstone dykes in terms of hydrostatic pressure and earthquake shocks, the latter momentarily liquefying a water-saturated sand and injecting it as a quicksand under considerable hydrostatic pressure (the hydrostatic pressure of sea-water is 20 atmospheres at a water depth of 200 m, i.e. upper edge of the continental shelf) along fissures opened up by the earthquake. Earthquake fissuring has been described (Venter, 1956, p. 147) as "The most common way in which sandstone dykes are formed . . .". Sedimentary dykes formed during an earthquake have been confirmed by eye-witness accounts (e.g. Diller, 1889, p. 435; Hansen and others, 1966) of earthquake fissures injecting and even extruding (Reimnitz and Marshall, 1965, figs 7 and 8) considerable quantities of water-mixed sand. Much of the excess water produced on such occasions probably represents the release of interstitial water (under considerable hydrostatic pressure) due to horizontal dilation, compaction and momentary liquefaction of the sediments. The initial supersaturation of several sandstones may be due to the expulsion of water from the mudstones during the "dewatering stage" (Hedberg, 1936, p. 272) and from the "soft-sediment" deformation of parts of the succession. Based on the "curvature" of sedimentary dykes, Diller (1889) attempted to determine in the Sacramento Valley the epicentre of the "fossil" earthquake(s) which he thought was to the south-east of the area described. This procedure has not been adopted in south-eastern Alexander Island.

In the Alexander Island area during the Mesozoic, the fissuring and injection of sandstone dykes may have been caused directly by earthquakes or indirectly by several associated phenomena such as interstratal sliding and slumping. It is obvious from the numerous horizontal and sub-horizontal shear planes (or strike-slip thrust planes) and their relationships with the large-scale sandstone dykes that both pre- and post-dyke interstratal sliding occurred. It is also possible, but more difficult to prove, that some interstratal sliding actually induced the sandstone injections by initiating a grid of fissures (caused principally by frictional drag) and effectively tapping a series of sandstone source beds. If this sliding took place concurrently at several stratigraphical levels, the upwelling sand filling the fissures would be sealed off by the sandwich effect (or distributive slicing) of the moving sedimentary blocks. A natural association between decomposing muds, sliding and sedimentary injection has been proposed (Laubscher, 1961, p. 309).

Fissures formed by inter- or intrastratal sliding (Anderson, 1944) and concurrently filled by injected sandstone have been described from New Zealand (Waterhouse and Bradley, 1957) and eastern Venezuela (Laubscher, 1961, p. 308). Some of the sliding (and injection) may have been caused by the extraordinary fluid pressures which occur both in geosynclinal areas and in areas of tectonic compression, as in south-eastern Alexander Island. These fluid pressures may exceed the limit of flotation of the overburden and result in the sliding of the sedimentary succession under the influence of its own weight (Laubscher, 1961, p. 308).

In Peru, sandstone dykes cutting rocks of Tertiary age appear to be genetically related to spectacular slip planes developed in strata deposited on a steeply dipping sea floor. The gliding was caused by slight movements along a normal "geofault" near the coast and by a decrease in grain pressure (Baldry, 1938; Brown, 1938). There are divergent views as to whether the gravity slides took place during deposition or when some of the sediments may have become lithified.

Earthquakes may also have induced fissuring and injection of sandstone by triggering off the intraformational slump-shear structures and mass-flow deposits (Horne, 1968*a*). Like the glide planes in Peru, these may have moved westward in Alexander Island due to movements along a megafault demarcating the western margin of George VI Sound. The frictional drag of these disturbed intraformational units, at several stratigraphical levels, may have resulted in some horizontal or sub-horizontal shearing and the development of joints and synformational faults. However, their influence on the origin of the sandstone dykes of Alexander Island is difficult to assess because of their sporadic occurrence in the area discussed here, notably at Mount Ariel where any such units must underlie the exposed rock. Similarly, whereas the large-scale gravity sliding in south-eastern Alexander Island (represented by most if not all of the "disturbed zones") may have induced fissuring and the injection of sandstone dykes, the precise relationship here between slumping and sandstone dykes is far from clear. However, in Poland, such a relationship may exist (Dzułynski and Radomski, 1956) even though the dykes, which are small-scale structures, vary in strike and are randomly orientated relative to the principal slump directions. In New Zealand (Waterhouse and Bradley, 1957), sandstone dykes and sills were injected contemporaneously and/or penecontemporaneously with slump folding, the fissuring and injection being concomitant. Elsewhere in New Zealand (Gregory, 1969, p. 276), sandstone dykes are also "associated intimately with slumped strata".

Small eustatic movements accompanying contemporaneous uplift within the sedimentary trough may also have resulted in fissuring. In Tunisia, open cracks formed in this way at the end of a period of clay or shale sedimentation were subsequently filled with sand (Gottis, 1953).

Thus, fissures with little or no vertical displacement could have arisen through one or more agencies or a combination of them. Whether all of the fissures were dilated by the dykes is open to dispute but most of the available evidence favours a dilated joint system.

Following the initial explosive stage, the injected sandstone probably passed through several fluidization phases as in eastern Venezuela (Laubscher, 1961). These phases, which were not observed in the field, may be detected when more detailed sampling is carried out. The almost complete absence of inclusions throughout many sections of the dykes suggests either stoping, or, more probably, the infilling of an open or dilated conjugate joint system; hence the absence of any apparent erosion of the dyke walls and of a selvage or salband between the dykes and the host rocks. Because the peneconcordance of many dyke sections excludes sedimentation into *open* cracks and joints, high-pressure injection into a dilated joint system probably took place. The overall "smoothness" of the dyke walls suggests that fissuring and injection occurred concomitantly.

The sandstones probably remained in a water-saturated and "quick" or mobile state for an abnormally long period after their deposition (Horne, 1968*b*, p. 80), partly because of frequent seismic shocks resulting from tectogenesis in the hinterland. The vertical elongation of the crystal grains and of larger mudstone inclusions, the perpendicular laminae within the dykes and the negligible amount of erosion of the wall rock indicate that most of the sand concentrate "flowed" essentially parallel to the dip of the walls. The maximum angle of erosion in such a concentrate would be about 20°. The energy necessary to maintain the internal cohesion and laminar flow was probably a combination of hydrostatic and gas pressure so that the sand concentrate behaved essentially like a high-pressure gas sand. Although muddy sediments at depth are said to revert "to a liquid form by thixotropic phenomena" and tend "to flow under the influence of excess hydrostatic pressure" (Swarbrick, 1968, p. 163), the angularity of the rafted mudstone fragments and the planar walls of the dykes suggest that at least the argillites were firm and cohesive before the sand was emplaced, i.e. at a relatively late diagenetic stage as in eastern Venezuela. However, contrary to the observations in Venezuela, there is no evidence in south-eastern Alexander Island that the dyke sand re-worked some of the host rock into a clayey mush and then re-introduced it into the solidifying and partly cohesive sand (Laubscher, 1961, p. 302).

Some of the sandstone dykes, notably those at localities D, L and Fossil Bluff, may owe their origin directly or indirectly to faulting, a "necessary pre-requisite to sedimentary vulcanism of any conspicuous magnitude" (Kugler, 1933, p. 746). The faults (with comparatively small throws) may have been either dilated by the sandstone dykes or developed concomitantly with them. In the latter case, the faults may have "tapped" several suitable source beds and then acted as conduits for the sand slurry. This may have occurred at locality D where the horizontal offsetting clearly post-dates the high-angled faults and their associated sandstone dykes (Fig. 11a). In the Huronian of Ontario, sandstone injections were also triggered by contemporaneous faulting (Eisbacher, 1970, p. 224).

Sandstone dykes directly associated with faulting if not actually emplaced along fault planes are known, mainly from Colorado (Vitanage, 1954; Harms, 1965) and California (Peterson, 1966). In the Cretaceous Budden Canyon Formation of north-west Sacramento Valley, California, approximately 150 dykes occupy tension gashes probably developed penecontemporaneously and in response to strike-slip faulting in the underlying competent basement complex rocks (Peterson, 1966). In the southern Front Range of Colorado, more than 200 sandstone dykes are concentrated within a mile, and strike approximately parallel to several reverse faults (Harms, 1965).

### *Gas pressure*

Another possible mechanism for the injection of sandstone dykes is gas pressure. This may have been generated by bacteria (in small quantities), as a result of the heat output which presumably accompanied the compression of the sediments or the gas may have occurred in larger reservoirs located throughout the succession. This important energy source has been overlooked or discounted by most authors apart from Jenkins (1930) and Kugler (1933), but Laubscher (1961) has stressed its importance in discussing the origin of the sandstone dykes of eastern Venezuela and in analysing the mass movement of sedimentary material as a whole.

Unfortunately, Laubscher's explanation for the origin of the Venezuelan dykes is of limited application here. Although some of the concretions in south-eastern Alexander Island emit a petroliferous odour and there is a similarity in lithology and sedimentology between the succession and, for example, the oil-bearing Lower Albian shales of the Magdalena Valley of Colombia (particularly in the abundance of calcareous concretions), no oil or gas reservoirs have so far been found in Alexander Island. However, the considerable extent of many of the large-scale dykes, coupled with the fineness of some of their bifurcations, suggests that the injected sand possessed a low viscosity perhaps comparable with that calculated (200 centipoise) for the dykes cutting the San Antonio Formation, i.e. equivalent to machine oil or 200 times that of water at atmospheric pressure and 20° C (Laubscher, 1961, p. 313). This low viscosity may have been due to hydrocarbons migrating from the fine-grained decomposing cohesive muds and shales to the coarser-grained sandstones, which in turn became filled with methane and water.

An abnormally high percentage of organic matter in this succession is indicated by an abundant benthos (Taylor and others, 1979), numerous trace fossils (mainly feeding burrows) of lithophagic organisms (Taylor, 1967) and by large numbers of plants and plant fragments. Such organic-rich sedimentary rocks constitute excellent sources for gas and petroleum (Russell, 1960, p. 171). Proof that gas pressure can provide the necessary chemical and mechanical energy to inject thick sheets of sand is demonstrated in Venezuela (Laubscher, 1961) and Trinidad. In several oilfields in Trinidad, sandstone dykes 6.1 m thick and 30.5–61 m in vertical extent were probably injected via "epi-anticlinal" faults under gas or oil pressure (Kugler, 1933).

Undoubtedly, the large-scale injection of sedimentary material in Alexander Island was facilitated by the sedimentary environment both during sedimentation and prior to lithification. In many respects, the proposed tectonic environments of the Mesozoic troughs of Alexander Island and eastern Venezuela are similar. Both were affected by volcanicity and earthquake shocks, and bounded (less convincingly in Alexander Island) on at least one side by a megathrust (or series of thrusts) which may have been active at the time of injection. Movement along this megathrust probably increased both the gradient of the continental slope and the shearing stresses on the underlying sediments. In Alexander Island, as in Venezuela, there may have been two zones between the postulated continental slope and the edge of the shelf, i.e. a zone of slides defining the margin of the shelf (Horne, 1969*b*, fig. 1) and an inner zone of dykes.

In eastern Venezuela (Laubscher, 1961), the zones of mass-flow deposits and sedimentary dykes were probably genetically related, the frictional drag of the intrastratal slides inducing the fissuring. However, in Alexander Island, particularly between Waitabit Cliffs and Succession Cliffs, the few mass-flow deposits reported so far in this area suggest that they may have been of minor importance in producing fissures.

It is therefore concluded that the large-scale sandstone dykes of south-eastern Alexander Island, like those described from other parts of the world, owe their origin to several inte[illegible]dependent factors operative both during the deposition of the sedimentary succession and prior to its complete lithification. Of these, probably the most important were earthquake shocks, which fissured and laterally compacted the succession, released interstratal water under high pressure, made several of the sandstones thixotropic and provided some of the energy to maintain the internal cohesion and laminar flow of the "quicksand". Volumes of gas derived from decaying organisms and from the heat which presumably accompanied the compression of the sediments may have been equally important.

Prior to at least some of the horizontal offsetting, folding and major thrusting, the sand was injected in at least two phases via open and/or dilated tension and shear joints, and syn-formational faults. Some of the jointing and horizontal offsetting may have been caused by penecontemporaneous bedding-plane slip, which effectively sealed off the sand as it was injected.

## SMALL-SCALE LINGUIFORM DYKES AND NARROW VEINLETS

Much smaller sandstone dykes also occur, notably at Hyperion Nunataks, Mount Ariel (Fig. 13) and localities G, L and N. At the western end of Hyperion Nunataks, several sandstone dykes (Fig. 14a) 10–20 cm wide and often dipping at approximately 45°, were injected downwards from a 1–2 m thick zone of sediments apparently deformed by gravitational sliding. Some of the sliding may represent the compactional effects of a thick-bedded conglomerate which forms the summit at this locality. Several of the dykes a[illegible] curvilinear and sills are developed. The sliding may have caused the re-mobilization of the sediment and concomitant fissuring and injection of sandstone. One dyke may have been emplaced along a thrust.

At Mount Ariel, small linguiform dykes 1.5 cm deep and closely associated with high-angled micro-faults (Fig. 13) are confined to one lip and one stratum within a 2.3 m thick lens of laminated cream sandstones and interbedded siltstones. Occasionally, two or more dykes in the same plane probably represent the arrested development of a much larger structure. Various stages from slight distortion of the laminations in the upper part of the host sandstone to their eventual collapse lower down in the stratum can be seen. The direction of injection is indicated by the down-warping of laminations adjacent to the dykes. The contacts are represented by dark boundary lines or slurried zones defined by down-warped laminae. The dykes and associated micro-faulting probably formed through differences in competency between the sandstone lens and the surrounding siltstones and shales. This micro-faulting

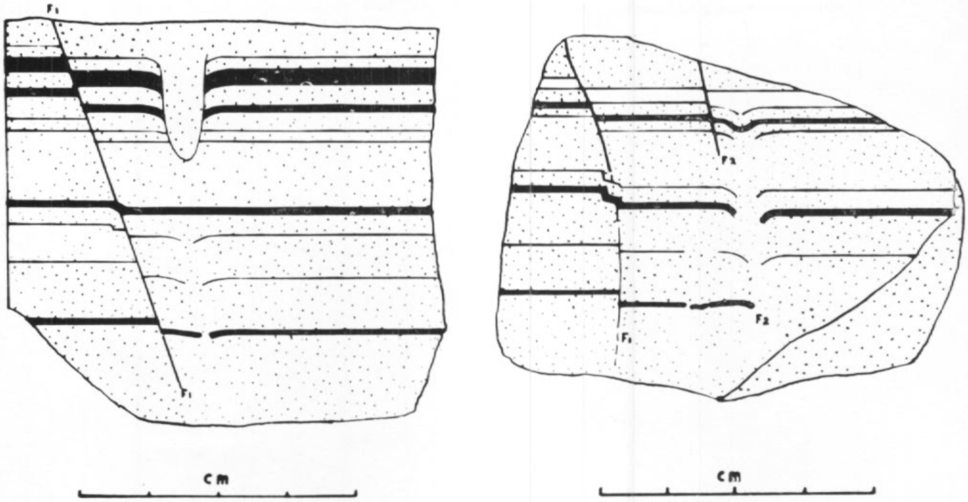


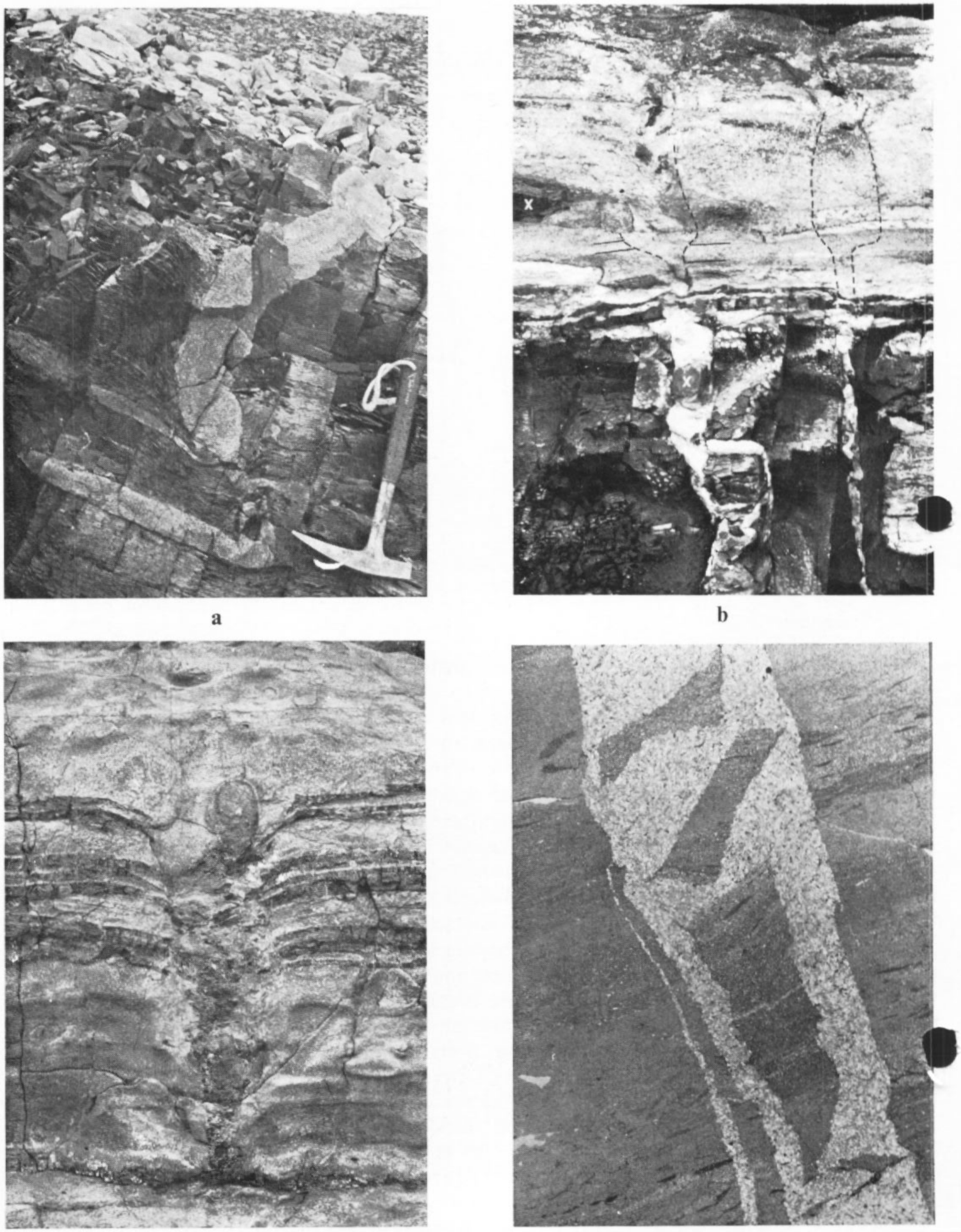
Fig. 13. Small linguiform dykes closely associated with high-angled micro-faults in a 2.3 m thick lens of laminated cream sandstones and interbedded siltstones at Mount Ariel. The occurrence of two or more dykes in the same plane probably represents the arrested development of much larger structures.

resembles that in the Dakota Sandstone and probably took place when the sediments were unconsolidated (Rettger, 1935, p. 291).

A relatively large number of small dykes also occur in the lower part of the succession at locality G. At least 12 are associated with three sandstones, four dykes interconnecting two of the sandstones. Several dykes also lie in the same plane, indicating a vertically more extensive line of weakness. The dykes, up to 6.5 cm wide and 15–50.5 cm long, are usually perpendicular to the bedding although several are sinuous. They commence near the top of the source bed, where the upper bedding plane may be down-warped, and are traceable through the stratum either because the dyke has a distinct margin or because the interbedded siltstones have been bent downwards by the re-mobilized sandstone (Fig. 14b). Many siltstones cut by the dykes are brecciated. Where dykes intersect laminations in the sandstone, junctions are usually sharp. On penetrating the underlying siltstones, the dykes are more conspicuous and irregular in form. They become sinuous and may branch several times, sometimes to form sills, and small blocks of host rock are occasionally completely enclosed by dyke sand (Fig. 14b). All of the dykes narrow downwards and one occupies the plane of a small normal fault and associated miniature step faulting. Some fragments within the dykes have moved downwards 18 cm. Because whole source beds are involved, the dyke sand was injected some time *after* these were deposited. Similar dykes occur at Succession Cliffs (locality A) in a bed immediately underlying the lower of three thick-bedded sandstones, in a russet-coloured sandstone at the base of the sequence and also at locality B. A comparable sandstone dyke (on a somewhat larger scale) has been described from North Island, New Zealand (Gregory, 1969, fig. 22), as an example of "intense but locally restricted load deformation".

At locality A, a number of mainly rectilinear and downwardly injected dykes interconnect several sandstones and siltstones comprising unit 24. At least one sill is developed. One dyke trending obliquely downwards joins a flag-bedded sandstone to a "flow roll" or pseudo-nodule. At locality N, small-scale sandstone dykes occur at several horizons including the basal sandstone cliff where they were emplaced downwards.

Within the lower few metres of the basal sandstone cliff at locality L two tongue-shaped dykes occur. Both are close together and cut through three flag-bedded siltstones. One is



a

b

c

d

Fig. 14. a. 10–20 cm wide small-scale sandstone dykes and associated sills injected downwards from a 1–2 m thick zone of sediments apparently deformed by gravitational sliding. The hammer head is 18 cm long; Hyperion Nunataks. (Photograph by M. R. A. Thomson.)

b. Two downwardly injected sandstone dykes showing the down-warping and disruption of intercalated siltstones in the 13 cm thick sandstone source bed. Because the whole bed is involved, injection occurred some time *after* this stratum was deposited; locality G.

c. A small-scale lingual sandstone dyke in the basal few metres of the lower sandstone cliff at locality L. Siltstone intercalations have been down-warped and brecciated. The dyke is 0.8 m thick.

d. Thin section perpendicular to the bedding, showing a small-scale tabular sandstone dyke (KG.10.9) (with inclusions) emplaced along a fault plane; Succession Cliffs (locality A); ordinary light.

0.36 m deep and scarcely extends below the lower siltstone, whereas the other is 0.64 m deep and forms a narrow V-shaped fissure filled with detritus derived from the brecciated siltstones (Fig. 14c). An undisturbed bedding plane in the sandstone overlying this second dyke suggests that the sand was injected only from the lower part of the bed. The three siltstones are bent downwards on both sides of the dykes, emphasizing the direction of emplacement. Because the long axes of the fragments lie perpendicular to the length of the dykes, turbulence was minimal and the detritus probably floated in a sandy mush.

Another small-scale dyke emplaced along a high-angled normal fault was found in a loose block (KG.10.9) at Succession Cliffs (locality A). The dyke, 7 cm high, 5–9 mm wide and at least 3 cm long, is rectilinear and composed of a cream sandstone which encloses several angular siltstone fragments, the largest elongated parallel to the dip of the walls which are perpendicular to the bedding. The dyke is unbranched apart from a stringer on one side of the main sheet (Fig. 14d).

In a thin section cut perpendicular to the strike, the dyke sand consists mainly of quartz, feldspar, altered biotite, muscovite and heavy minerals (zircon, sphene, allanite, epidote); many grains, especially those nearest the margins or confined within narrow veins, lie parallel [illegible] the walls. Much of the matrix is prehnitized and many grains show partial to complete replacement by prehnite. The siltstone surrounding the dyke also contains prehnite but in much smaller amounts. The prehnite forms large turbid aggregates, although occasionally sheaves show a bow-tie structure. In another dyke (KG.19.31) the matrix is mainly of calcite with minor amounts of prehnite. Narrow calcite veins branching from larger aggregates are perpendicular and some cut turbid patches of prehnite. Near the dyke margins, the long axes of many biotite flakes lie parallel to the dip of the walls. Some biotite is spongy with diffuse margins, whereas other flakes form stringers between the crystal boundaries and may be authigenic.

At Fossil Bluff several structures probably representing small-scale sandstone dykes occur within a complex "lubrication" or disturbed zone where many beds have been rotated and "balled up". Some structures are linear and are comparable with the sandstone dykes described from other parts of this area, but others resemble boomerangs. These may represent disconnected drag-folded segments of former sandstones.

## SANDSTONE PIPES

Cylindrical bodies of sandstone resembling sandstone pipes or "sandstone-plugged pipes" occur at Succession Cliffs (localities A and B) and localities Q, P and E. At locality A, a sandstone pipe 10 cm high and 14 mm in diameter occurs in a flag-bedded sandstone which forms part of an interbedded series of siltstones and cream sandstones (unit 28). Convolute [illegible]mination, brecciated siltstone fragments and small-scale linear dykes characterize these sandstones.

The pipe swells above several constrictions and is accentuated from the surrounding sandstone (Fig. 15a). In horizontal section (Fig. 15b), the pipe rock is composed of a calcareous sandstone and several poorly defined concentric mudstone bands contain Foraminifera. These bands, which are sheared and comprise an outer margin and an excentric core, are probably rich in finely divided iron oxides. Similar colour banding in pipes in the Potsdam Sandstone has been attributed to solution of iron-oxide films from crystal grains (Hawley and Hart, 1934, p. 1031).

The main cement apart from mudstone is calcite, which occurs in relatively large patches and partly pseudomorphs many crystal grains, particularly the more unstable hornblende. The surrounding sediment is also cemented by calcite. Crystal grains are fairly angular and the plagioclase is laumontitized. In perpendicular sections, discrete crystals within the mudstone are orientated parallel to the walls of the pipe.

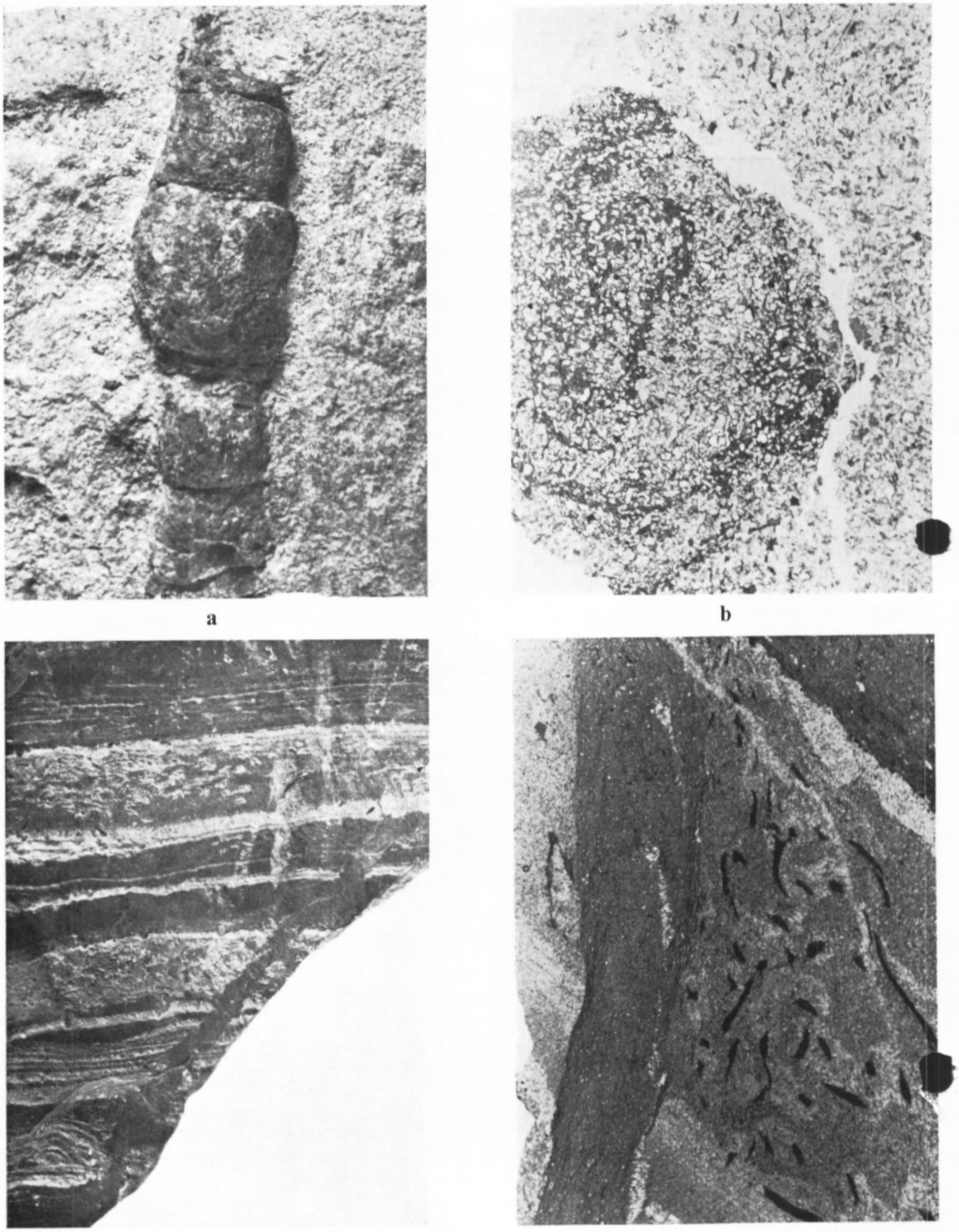


Fig. 15. a. Sandstone pipe (KG.10.75) 10 cm high and 1.5 cm in diameter in a stratum at Succession Cliffs (locality A). The pipe is interrupted by several constrictions.

b. Thin section cut in the horizontal plane through specimen KG.10.75, showing several concentric mudstone bands and an excentric core. The colour bands are rich in finely divided iron oxides; ordinary light.

c. A 3 m wide and upwardly injected mudstone dyke (KG.6.22) cutting obliquely across the stratification from its source bed. The lenticular appearance of two bands is due to trace fossils called vermicular structures; Waitabit Cliffs.

d. Thin section cut normal to the stratification and showing the relationship between the mudstone dyke and the host rock. The dyke rock is characterized by numerous fine discontinuous "shear" planes and by more obvious shears which are convex upwards, i.e. in the direction of injection. The aureole effect of the vermicular structures is also clearly seen; ordinary light.

At locality B, several pipes were found in a 4.5 m thick sandstone underlying a prominent 38.5 m high cliff studded with cannon-ball concretions. The sandstone is finely banded, convolutely laminated, cross bedded and micro-faulted. The pipes, which are closely spaced, are 4 cm high and up to 2 cm in diameter. The down-warping of laminations at the junction with the pipes indicates their direction of emplacement. Some pipes contain siltstone bands which have either been inverted and elongated parallel to the walls or bent to form a "U", thus emphasizing the overall shape of the pipe. A transverse section (KG.10.47) shows a concentric arrangement of grains surrounding a central core of siltstone.

Two sandstone pipes occur at locality Q within a hemi-pyramidal sandstone cliff laterally equivalent to the lowest thick-bedded sandstone at locality M. These pipes (KG.1.865 and 866) are 2 cm in diameter and 14 cm long, and dip at 45°. Their junction with the surrounding sediments is sharp and defined above and below by dark argillaceous bands rich in biotite and iron ore. The pipe rock, a cream arkosic sandstone, is identical in colour and composition with an overlying thin-bedded sandstone from which the pipes were clearly derived.

In thin section, the pipe rock is composed mainly of a laumontite cement which has partly replaced the plagioclase feldspar, the more prismatic laumontite showing two cleavages (010; 110). Within this cement, there are grains of quartz, feldspar, sphene, biotite, zircon, epidote, fibrous zeolite (probably detrital) and allanite. Many of the biotites are studded with numerous small, unidentifiable non-opaque grains which are sub-rounded, cubic or hexagonal in shape. Although they are the same colour as the biotite, their relief is generally higher and some pigment may have been derived from the biotite. The origin of the grains is not known, although they may represent a form of recrystallization. Similar hexagonal grains associated with a "bleached" biotite occur in another dyke rock (KG.3.92). At locality E, a sandstone pipe 1 cm in diameter occurs within a bed of siltstone and interbedded fine-grained, laminated arkosic sandstone.

Most of the sandstone pipes are in the lowest rocks at locality P where dark siltstones and cross-laminated sandstones are overlain by a 15.2 m thick pebbly mudstone containing boulders 43 cm in diameter. The pipes, which are simple discordant cylinders of sandstone, are inclined at 20–30° to the bedding and are orientated west-north-west. Tabular sandstone dykes, intruded downwards, occur in the same strata. The pipes are circular in cross-section and up to 12 mm in diameter but none is completely exposed. In sections perpendicular to the bedding, the pipes are discontinuous but this may be because the rock face they cut is itself irregular. Several pipes are characterized by crescentic laminations which are convex upwards.

Several smaller sandstone pipes 8 mm in diameter containing siltstone fragments occur in a loose block at Succession Cliffs (locality A). The pipes dip at 35° to the bedding and the junctions are sharp and relatively straight. In a thin section cut parallel to the length of the pipe, filaments of iron pyrites are inclined at 45° to the walls. The rock is cemented by prehnite.

Structures usually called sandstone pipes have been described from rocks of different ages, some of the best known being those in the Permian (?) of Colorado (Gabelman, 1955), the Upper Cambrian Potsdam Sandstone of Ontario (Hawley and Hart, 1934), the lower Old Red Sandstone of Shropshire (Allen, 1961) and the Jurassic of New Mexico (Schlee, 1963). Many are large, those of New Mexico ranging from a few metres to several hundred metres high and from 5 cm to 45.5 m wide.

Several origins for these sandstone pipes have been proposed, although movement of ground water as water jets or springs is a common basis for most interpretations. In Ontario, the pipes were probably formed by gently flowing springs, the flow of water being sufficient to create quick-sand zones and to destroy the original bedding but not powerful enough to re-sort many of the grains (Hawley and Hart, 1934, p. 1032). The structures were therefore formed *in situ*. The pipes of Colorado were probably formed in a similar way, although the occurrence of inclusions and the abrupt cessation of laminations against the pipe margins suggest that the water jets eroded the sediments (Gabelman, 1955). In Shropshire, the sandstone pipes were thought to represent the plugging of tubular ducts eroded by jets of water, the water originating either from settling slumps or from underground reservoirs (Allen, 1961, p. 334). Foundering of partly consolidated sand above the necks of springs may have produced the sandstone pipes in the Laguna area of New Mexico. These are located near synclinal axes and may have formed during a period of gentle folding (Schlee, 1963, p. 122). Deformation, including earth tremors, may have triggered off the water jets.

The sandstone pipes of Alexander Island, especially those at locality P, are smaller but closely comparable with the "sandstone-plugged pipes with lateral structures" described by Allen (1961, p. 328) and may have originated in much the same way. The water and liquefied sand were probably forced through the sediments (cf. Swarbrick, 1968, p. 164) from an underlying reservoir or from ground water either under hydrostatic pressure or, in the case of locality P, following settling of the overlying pebbly mudstone. The preferred orientation of the pipes may indicate the relative movement of this deposit—towards the west-north-west. The open ducts were filled with upwelling sand only when the settling velocity of the suspended detritus exceeded the velocity of the water jet. The laminations within the pipes resemble menisci associated with *Zoophycos* burrows at the same locality (Taylor, 1967, fig. 7g) but in this context their preferred orientation is problematical. Allen (1961) rejected an organic origin for the Dittonian structures principally because of their large size and absence of skeletal remains. In neptunian [*sic*] dykes in a bore hole at Rashiehill, Stirlingshire (Anderson, 1963, pl. VIII, fig. 4), the crescentic laminae were thought to have been formed by rising jets of water which carried up mud from an underlying source bed.

## SANDSTONE (?) PLUGS

Two unusual small-scale bodies resembling sandstone plugs occur at different stratigraphical levels at locality G. The first of these is a lingual structure 3 cm high and 20 cm long, probably representing either an abrupt upwelling of sand in the vicinity of a joint or a sudden response to some obstruction in the free flow of the "liquidized" sand. The (?) source bed becomes thinner near the base of the plug and the surrounding laminated mudstones are up-warped on either side. A similar dome-like structure 1.8 m wide and overlain by up-warped sediments abruptly terminates a normally bedded sandstone. A narrow sill near the rounded top follows the bedding northward for approximately 27 m before being obscured by debris. In Trinidad, sandstone "dykes" occasionally follow the bedding planes or form irregular bodies (Kugler, 1933) which may be comparable with those at locality G.

At Keystone Cliffs, a 10 cm wide convexi-concave sandstone lens containing mudstone inclusions is associated with a sub-horizontal sill. A branch occurs to one side of it.

## MUDSTONE DYKES

Although most sedimentary dykes are composed of sandstone, siltstone and mudstone have occasionally been injected either upwards or downwards (e.g. Swarbrick, 1968, fig. 2a and b). In Trinidad, numerous mudstone dykes, sills and volcanoes have been recorded, the dykes having been emplaced via shatter belts or parallel to cross faults (Kugler, 1933, p. 749), and many have salbands. In Alexander Island, there are two mudstone dykes, one at Waitabit Cliffs and the other at Succession Cliffs (locality A). Neither is *in situ*.

The dyke at Waitabit Cliffs was found in a loose block (KG.6.22) composed of alternating layers of mudstone (with vermicular markings (Taylor, 1967, p. 24)) and thinner calcareous bands (Fig. 15c). The dyke, 3 mm wide, trends diagonally upwards for 7 cm after emerging from its source bed, a dark mudstone layer overlain by a convolutely laminated bed. Junctions between the dyke and the surrounding sediments are sharp and relatively straight (Fig. 15d). At least one calcareous band is micro-faulted and characterized by "laminar corrugations".

Much of the micro-folding is adjacent to the dyke and the fold axes are acute to the walls. These plications were probably formed when the dyke was injected, the calcareous band being shortened by an amount equal to the dyke's thickness. Where the dyke terminates abruptly beneath a calcareous band, a small cylindrical branch occurs which is horizontally banded and slightly bulbous near the top.

Near its source, the dyke consists of numerous parallel shear planes which are particularly dense near the walls but higher up these are curved and form fairly sharp "folds". The dyke is composed of a light brown calcareous mudstone in which larger grains, mainly of quartz and calcite, are dispersed. These appear to be unsheared. Stringers of more calcareous sandstone have been squeezed through the mudstone from one of the lower sandstone bands and arranged *en échelon* to one another (Fig. 15d). The dyke is crossed by a narrow vein which may represent a worm burrow.

A second mudstone dyke was found at Succession Cliffs in a rock (KG.10.10) of alternating mudstone and tuffaceous sandstone bands. The dyke or pipe, 0.5–3 mm wide and at least 2 cm high, is an irregular mudstone fissure surrounded by a sheath of sandstone in which the long axes of many grains lie parallel to the dip of the walls. All but one intercalated mudstone band stop abruptly at the sandstone sheath which is cut by a mudstone sill at one point. Some grains from the surrounding greywacke such as quartz, fresh zoned labradorite, hornblende (partly pseudomorphed by calcite) and biotite occur as discrete patches within the dyke.

## CONGLOMERATE DYKES

At locality J, strongly folded siltstones overlain by 70 m of conglomerate, all probably Berriasian in age, have been thrust against rocks of Albian age (Taylor and others, 1979). From the base of the conglomerate, at least four conglomeratic dykes trend obliquely downwards into the argillaceous sediments. The walls are linear and converge downwards. Two of the dykes, striking 102° and 88° respectively, are the same width (6 cm). Approximately 15.0 m beneath the conglomerate, at least another two dykes resembling conglomeratic lenses occur. These enclose angular siltstone blocks 18 cm long and several smaller dykes branch from them. No imbrication of the clasts in any of the dykes was observed.

The contact between the massive conglomerate and the underlying argillites is defined by a calcite- and quartz-veined slickensided layer comprising partly sheared lingual load casts. The dykes and load casts probably formed through differences in competency between the two lithofacies and by horizontal gliding which fractured the siltstone. The fissures were filled in from above and, as the conglomerate settled in response to a loss of material, there was probably a fall in pressure which effectively terminated the injections.

Although gravel-filled fissures are common, the forceful emplacement of conglomerate [illegible] conglomeratic dykes is a relatively rare occurrence. Nevertheless, several of these particular conglomeratic dykes are known, notably in the Espanola Formation (Huronian) of Ontario (Eisbacher, 1970), within a post-Triassic dolerite sill in Connecticut (Walton and O'Sullivan, 1950), in the Seymour Canal Formation (late Jurassic–early Cretaceous) of Admiralty Island, Alaska (Loney, 1964), and in the Cerro Toro Formation (Upper Cretaceous) of Chile (Zeil, 1958, p. 441; Scott, 1966).

At New Haven, Connecticut, a branched conglomeratic dyke composed mainly of granitic and metamorphic phenoclasts was injected upwards through a fissure in a dolerite sill. The dyke was probably injected due to a sudden fall in pressure caused by fracturing within the sill while it was still hot, the corresponding rise in water-vapour pressure filling pore spaces in the conglomerate. The conglomerate therefore expanded internally during emplacement and the mobilized material flowed as a suspension due to the high-pressure fluid in the pore spaces (Walton and O'Sullivan, 1950). The dyke, which extends vertically 9.2 m, has sharp contacts with the dolerite and narrows upwards.

In Alaska, sandstone and conglomeratic dykes were injected into slaty argillaceous sediments and thin-bedded greywackes. The ordinary bedded conglomerates and greywackes, which occur in lenses, were probably deposited as submarine slides which fissured the fine-grained sediment. These fissures were filled with material transported by the slides (Loney, 1964, p. 92).

In the area of Cerro Toro and Lago Toro, "sind Hunderte dieser Gänge, die aus psephitischem und psammitischem Material aufgebaut sind . . ." (Zeil, 1958, p. 441). The conglomeratic dykes, probably originating from the Lago Sofía Conglomerate, were attributed to considerable seismic activity which opened up fissures in the sediments. One of these dykes, which was injected upwards 91.5 m, was reported to be 13.7 m thick in places, structureless and composed of 35–95% clasts. Scott (1966, p. 95) suggested that it was probably formed by intraformational "post-burial flow".

Near the same locality, several neptunian dykes were probably formed by torrential floods opening up fissures in the underlying sediments. These were subsequently filled with pebbles transported by glacial solifluction (Cecioni, 1957, p. 132).

## CONCLUSIONS

The Upper Oxfordian–Kimmeridgian to Lower Albian succession of eastern Alexander Island was deposited in a trough located within the seismically active circum-Pacific fold-mountain belt. This trough was subjected to contemporaneous and probably post-depositional volcanicity and earthquake shocks, which together retarded lithification, made several of the sandstones thixotrophic and locally re-mobilized sediment at several stratigraphical levels to form mass-flow diamictites and intraformational slump-shear structures. Because of this instability, and directly or indirectly due to the earthquakes, parts of the succession were fissured and large numbers of sedimentary (mainly sandstone) dykes were injected.

Of these, the most spectacular and commonest are usually parallel-sided, multiramous and often sinuous large-scale sandstone dykes which often protrude as high walls. These were injected with minimal disruption and deformation of the host rocks via an open and/or dilated joint system (including a conjugate set of steeply dipping shear joints) and several (?) syn-formational faults. The occurrence of sills further implies high-pressure injection into a *dilated* joint system. The impetus was probably provided by a combination of factors including earthquake shocks, high pore pressure, hydrostatic pressure and gas pressure, and by interstratal sliding and slumping. Sliding and slumping at several stratigraphical levels in the succession may have initiated a grid of fissures, tapped a series of sandstone source beds and effectively sealed off the upwelling sand at various horizons by the sandwich effect of moving sedimentary blocks. Fossiliferous inclusions and dykes emerging from source beds indicate that the principal sandstone sheets were injected upwards, sometimes apparently from the same stratum. At least two phases of injection occurred at Mount Ariel and [illegible] locality D injection preceded major west to east thrust/reverse faulting. Most of the dykes terminate in the succession.

The overall "smoothness" of the dyke walls and the angularity of the inclusions suggest that fissuring and injection occurred simultaneously and that the fissures were formed in a mainly argillaceous succession that was cohesive. Sporadic laminations usually parallel to the dyke walls and concentrations of the coarse-grained fraction in the central parts of several dykes indicate liquefaction and laminar flow. Differential compaction was mainly responsible for distorting the host rocks adjacent to the dykes.

The horizontal offsetting of the dykes at slickensided and mineralized shear planes, and less commonly at bedding planes, is attributed to post-dyke transcurrent faulting, penecontemporaneous bedding-plane slip and the infilling of a scalariform joint system. At Mount Ariel, horizontal offsetting preceded folding. Compaction vertically foreshortened several dykes by at least 20–30% into *schuppen*-like segments and modified original sinuous fissures.

The initiation of many of the large-scale flexures coincides either with the bedding planes or with the thick-bedded units in the succession. The smaller-scale sinuosity is more haphazard and often somewhat anomalous but some of it is attributed to disharmonic drag shear.

At locality D, faulting preceded horizontal offsetting and, both here and elsewhere in Alexander Island, faulting and injection of sandstone may have occurred concomitantly. In one of two examples of intersecting shear-fracture dykes at Mount Ariel, the axis of maximum compressive stress indicated by the dykes is in agreement with the inferred regional compression derived from the joint analyses. In both examples, the westerly trending dyke cuts the south-south-easterly trending dyke. At present, no genetic relationship has yet been proved between the "lubrication" or disturbed zones and the origin of the large-scale sandstone dykes. However, at Fossil Bluff, the straight-sidedness of a dyke cutting a disturbed zone suggests that injection post-dated the zone. All of the sandstone dykes were subsequently cemented by calcite and subordinate prehnite and laumontite.

Equally numerous but often easily overlooked are small-scale sedimentary "injection" phenomena, notably linguiform sandstone dykes, sandstone pipes, sandstone (?) plugs, mudstone dykes and conglomeratic dykes. At Hyperion Nunataks, several sandstone dykes were injected downwards from a zone of sediments apparently deformed by gravitational sliding, whereas in a lens at Mount Ariel, smaller linguiform structures are closely associated with high-angled micro-faults. Intercalated mudstones and siltstones indicate that all of the small-scale sandstone dykes were injected downwards, probably due to intensive but locally restricted load deformation. All of the straight-sided conglomeratic dykes at locality J were formed by west to east shearing of the overlying 70 m thick conglomerate and were "injected" downwards, whereas at least one of two mudstone dykes was emplaced upwards. Several of the sandstone pipes, which are usually inclined to the bedding, were probably produced directly by jets or springs of water carrying sand in suspension, or indirectly by foundering of partly consolidated sand above the necks of springs. The origin and inclination of those at locality P are probably related to the deposition of an overlying pebbly mudstone.

The postulated environment of the Mesozoic trough in Alexander Island and the occurrence of two distinct and virtually sub-parallel zones of slides and sandstone dykes (at least in the area between Pluto and Venus Glaciers) can be matched in the San Antonio Formation (Senonian) of eastern Venezuela.

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