Fig. 9. Cross-section A-A through D.D.H.s S.E.13 and S.E.4 (After Travis et al., 1971)
Fig. 10. Cross-section B-B through the Golden Mile (After Travis et al., 1971).
of the structure in attempting to elucidate the genesis of the ore, the G.M.D. has been re-examined in some detail in this study.

The Nature of the Layering in the G.M.D. and its use in Stratigraphic and Structural Interpretation

Ten individual layers or units in the G.M.D. have been distinguished by Travis et al. (1971) on the basis of type, grain size, texture and amount of Fe and Ti oxides present (Table 4). Other distinctive mineralogical features are the prominent amphibole plates in units 2, 3 and 4 and the abundant granophyritic intergrowth of quartz and albite in unit 8. According to these authors, unit 2 is the most mafic unit and is characterized by a high Mg and Ni content; units 6, 7 and 8 have a high Fe and Ti content reflecting the abundance of oxides.

In order to check the validity of the layering in the G.M.D., part of the type hole, D.D.H. S.E.13 was relogged (Appendix 2); the layering was also checked in all other drill core studied (MC243, MCS2A and MC402 from the Mt. Charlotte area; K.E. 53, 54 and 55 from the Enterprise mine; 5022, 5027 and 5028 from the Chaffers mine; and sections of D.D.Hs S.E.10 and S.E.4 from the south end of the field).

It was found that even in the type hole, D.D.H. S.E.13, layering is not clearly defined; rocks conforming to the definitions of units 3 and 4 show rapid alternation, units 5 and 6 are indistinguishable, unit 7 which by definition, contains abundant fine-medium-grained subhedral ilmenite and magnetite, in places contains sharply defined coarse-grained patches of G.M.D. with prominent skeletal leucoxene (Fig. 11) and unit 9 contains patches of coarse-grained rock with long curved chloritic pseudomorphs, probably after pyroxenes (Fig. 12). In addition, unit 8 in D.D.H. S.E.13 is highly sheared, altered and intruded by albite-rich porphyry dykes(?) and its original nature can only be inferred. Overall however, the layering
Table 4

Mineralogical characteristics of the various units of the Golden Mile Dolerite

<table>
<thead>
<tr>
<th>Unit</th>
<th>Grain Size</th>
<th>Texture</th>
<th>Fe-Ti-Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Fine-grained</td>
<td>Variolitic</td>
<td>Skeletal leucoxene</td>
</tr>
<tr>
<td>9</td>
<td>Fine-grained to coarse-grained</td>
<td>&quot;Ophitic&quot;</td>
<td>Skeletal leucoxene</td>
</tr>
<tr>
<td>8</td>
<td>Medium-grained</td>
<td>Granophytic</td>
<td>Ilmenite</td>
</tr>
<tr>
<td>7</td>
<td>Fine- to medium-grained</td>
<td>&quot;Ophitic&quot;</td>
<td>Ilmenite-magnetite (abundant)</td>
</tr>
<tr>
<td>6</td>
<td>Medium-grained</td>
<td>&quot;Ophitic&quot;</td>
<td>Ilmenite-magnetite (abundant)</td>
</tr>
<tr>
<td>5</td>
<td>Medium-grained</td>
<td>&quot;Ophitic&quot;</td>
<td>Skeletal leucoxene (sparse)</td>
</tr>
<tr>
<td>4</td>
<td>Medium-grained</td>
<td>Intermediate between unit 5 and 3</td>
<td>Skeletal leucoxene (aggregated)</td>
</tr>
<tr>
<td>3</td>
<td>Medium-grained</td>
<td>Prominent amphibole laths</td>
<td>Skeletal leucoxene (sparse)</td>
</tr>
<tr>
<td>2</td>
<td>Coarse-grained</td>
<td>Amphibole plates</td>
<td>Skeletal leucoxene</td>
</tr>
<tr>
<td>1</td>
<td>Fine-grained</td>
<td>Variolitic</td>
<td>Skeletal leucoxene</td>
</tr>
</tbody>
</table>

After Bartram and McCall (1971) with additional information from Travis et al. (1971).
Fig. 11. Coarse-grained patch of G.M.D. (C) in fine-grained unit 7(F). The coarse-grained patch contains prominent skeletal leucoxene (L). The boundary between the coarse-grained and the fine-grained patches is marked by segregations of chlorite (c) and oxides (o) (5371/13).

Fig. 12. Chloritic pseudomorphs apparently after long curved clinopyroxenes in unit 9 of the G.M.D. (5740/13).
conforms with the definitions given by Travis et al: platey amphiboles were prominent in the lower units on each side of the Boulder Dyke and coarse-grained rocks with skeletal leucoxene, although not always with an "ophitic" texture, conform in general with the description of unit 9.

The layering also shows a fairly consistent distributional pattern. Zones 7, 8 and 9 are readily recognized in the Mt. Charlotte mine and deep drilling at the north end of the field (MCS2A). Although unit 8, the quartz-rich unit, is less well developed further south, it can still be recognized between units 7 and 9 in the Kalgoorlie Enterprise drilling and in the Golden Mile area (e.g. in D.D.H. 5028). As in the south end drilling, however, boundaries are not always distinct; in addition, both unit 7 and unit 8 in the Mt. Charlotte mine and D.D.H. MC402 contain patches of coarse-grained G.M.D. resembling unit 9 and unit 9 itself, in D.D.H.s MCS2A and 5027 has patches containing long curved chloritic pseudomorphs after pyroxenes similar to those in D.D.H. S.E. 13.

The patches in unit 9 containing long curved chloritic pseudomorphs after pyroxenes have a sharp but transitional boundary to finer grained unit 9 and bear a strong resemblance to the coarse-grained bands illustrated by Tomkeiff (1929) in the Whin sill and the pegmatitic schlieren described by Walker (1940) from the Palisade diabase. Walker interprets the schlieren as the crystalization products of a volatile rich residue. Lofgren and Donaldson (1975) have demonstrated that curved branching crystals in comb-layered rocks are the result of supercooling and it is possible that the long curved crystals in unit 9 have a similar origin.

The coarse-grained patches in unit 7 differ from those in unit 9 and the pegmatoidal schlieren described by Tomkeiff (1929) and Walker (1940) in having a sharp non-gradational boundary marked by a segregation of chlorite and oxides (Fig. 11). Whilst it is possible that these are late stage
crystallization products, another possibility is that these patches represent blocks of unit 9 G.M.D. caught up in the magma.

Although the presence of coarse-grained patches in units 7, 8 and 9 of the G.M.D. creates some problems in logging the units in drill core, their presence does not negate the overall concept of layering.

The chemistry of the different units on each side of the Boulder Dyke in D.D.H. S.E. 13 is given in Table 5 and Figure 13. It is interesting to note that the central units not only contain considerably more Fe and Ti than the other units of the G.M.D. but also more than typical Archaean tholeiites (Figs. 5 and 6). Some samples of units 2, 3 and 4 have komatiitic affinities whilst most unit 9 samples plot within the field of tholeiites given by Arndt et al. (1977).

The basal units of the G.M.D. are not as well defined on the eastern side of the Kalgoorlie Syncline (Boulder Dyke) as on the western side. The ultra-mafic unit 2 appears to be missing altogether and in its place is a siliceous K-rich rock containing abundant phenocrysts of biotite; this rock could represent either a later mafic intrusive or a highly altered phase of G.M.D. (the high Ni content of this rock suggests that it may have been originally more mafic but Ni tends to be erratic and could have been introduced). However unit 3 on the eastern side of the Boulder Dyke is moderately enriched in Mg and is probably equivalent to unit 3 on the western side. The Fe-rich central units are present on both sides of this structure and in each case show a marked differentiation trend with a drop in Mg content and a sharp increase in Fe and Ti followed by a drop in these elements in going from units 5 and 6 to unit 8. The rocks marked unit 9 on each side of the Boulder Dyke are petrologically and chemically identical. Thus in a broad sense, the layering is symmetrically repeated on each side of the Boulder Dyke, supporting the conclusions of Gustafson and Miller (1937) and Travis et al. (1971) that this structure is a syncline.
Table 5

<table>
<thead>
<tr>
<th>Sample</th>
<th>FeO (%)</th>
<th>SiO₂ (%)</th>
<th>Al₂O₃ (%)</th>
<th>TiO₂ (%)</th>
<th>CaO (%)</th>
<th>MgO (%)</th>
<th>Na₂O (%)</th>
<th>K₂O (%)</th>
<th>CO₂ (%)</th>
<th>S (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N2</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N3</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N4</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N5</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N6</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N7</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N8</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N9</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N10</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N11</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N12</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N13</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N14</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N15</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N16</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N17</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N18</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N19</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N20</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Notes:
- CO₂ values are calculated by the method of Riley (1988).
- All other CO₂ determinations by the method of Riley (1988).
- CO₂ samples are from the same site.
- CO₂ values are corrected to 100%.

34.
Fig. 13. Variation in geochemistry of the G.M.D. across the Kalgoorlie Syncline, D.D.H. S.E.13.
The cause of the layering remains uncertain. In character, the layering differs from the phase and cryptic layering found in the Williamstown Dolerite and other layered sills in the Eastern Goldfields (Williams and Hallberg, 1973). Travis \textit{et al.} (1971) conclude that the layering is due to differentiation and that the Fe-rich central units which do not conform to an \textit{in situ} differentiation trend were introduced into a pre-existing dolerite sill consisting of units 1 to 5 and 9 and 10. The absence of a chilled margin at the top of unit 5 is the reason given for including units 9 and 10 with the initial magma pulse by these authors. An alternative explanation of the layering is that units 1-4 and 9-10 represent part of a thick flow and that units 6, 7 and 8 are a late differentiate intruded into the volcanic pile. Another possibility is that the G.M.D. represents two or more flows.

\textbf{Extrusive vs Intrusive Features of the G.M.D.}

One of the most important things to be considered is the form of the G.M.D. and its relationship to the other units in the Kalgoorlie succession. By mapping the black slates between the Paringa Basalt and the G.M.D., Gustafson and Miller (1937) demonstrated that the G.M.D. (referred to as the "Younger Greenstone") occupies the same stratigraphic horizon everywhere and that the G.M.D. was folded with the Paringa Basalt (referred to as "Older Greenstones"). On the basis of this evidence, together with the homogeneous nature of the G.M.D., the apparent chilled margin against the overlying slates in the Lake View South mine and the lack of volcanic flow textures, Gustafson and Miller suggested that the G.M.D. is a sill or laccolith intruded between the Paringa Basalt and the Black Flag Beds when these were essentially flat lying. Whilst these authors state that the G.M.D. "is obviously a moderately shallow seated intrusive" they go on to say that "the senior author has mapped lava flows of almost identical texture, appearance
and composition in the Hollinger Mine, Canada" (Gustafson and Miller, 1937, p.103). These authors also recognise the possibility that the sediments of the B.F.B. may have been deposited unconformably upon the G.M.D. (p.104). In fact, most early writers including Larcombe (1911), Feldtmann (1916) and Stillwell (1929) indicate that there is no conclusive evidence that the G.M.D. is intrusive rather than extrusive. The only evidence of a possible transgressive relationship is given by Stillwell in the discussion of the paper by Gustafson and Miller (1937). Stillwell cites a personal communication from K.J. Finucane "that at the 180' level of the Imperial mine, the east limb of an anticlinal fold in the slates is truncated by the Younger Greenstone (G.M.D.) without any sign of a fault". However, as Gustafson pointed out, discordances in structure can also occur when strong competent rocks are folded with weak incompetent rocks.

The evidence used to support an intrusive origin for the G.M.D. appears to be dominantly textural. Apart from units 1, 7 and 10, the G.M.D. is coarse grained and as pointed out by Travis and Woodall (1975), it bears no similarity to the underlying fine grained Paringa Basalt. The pillowed nature of the Paringa Basalt suggests that it was extruded under water. It is conceivable that if a flow or series of flows as thick as the Golden Mile Dolerite were extruded sub-areally, then the rate of cooling would be slow enough to enable coarse grained textures to develop.

Far more critical in the question of the genesis of the G.M.D. are the observations made by Tomich (1974,1975,1976) in the Golden Mile area of tuffaceous features, amygdules, possible pillow structures, interbedded slates and volcanic breccia within the G.M.D. Whilst some of the features described by Tomich may be of doubtful origin, others have been observed by the author in the south end drilling and prove beyond all doubt that the G.M.D. is at least in part, extrusive.
Perhaps the most significant contribution made by Tomich (1976) is his illustration of pyroclastic features including large fresh twinned albite crystals and embayed quartz crystals in a fine-grained matrix in the G.M.D. from the South Kalgurli mine. Numerous examples of tuffaceous G.M.D. are present in the south end drilling. In specimen 1939/4, D.D.H. S.E.4 (Figs. 9 and 14) the pyroclastic nature of the G.M.D. is clearly visible in weathered drill core due to oxidation of the iron in the matrix surrounding the dolerite fragments (Fig. 15A). On the freshly sawn surface, the matrix appears light grey and thin section studies indicate that it consists predominantly of carbonates with minor quartz and sericite. On the basis of their textures, the G.M.D. fragments come from units 9 and 10; the fragments vary considerably in grain size from very fine-grained to medium-grained with respect to leucoxene (Fig. 15B) and hence the rock could not represent a tectonic breccia. The inclusion of fragments from the upper part of unit 9 and unit 10 in this pyroclastic suggests that the drill hole has just grazed the top of the G.M.D. at this locality. Further down this hole, another pyroclastic was encountered in the G.M.D. near its contact with the B.F.B. At its base (2491/4, Figs. 9 and 14), this pyroclastic is quite coarse-grained with fragments up to 25 cm across (Fig. 15C) but becomes finer grained as the contact with the B.F.B. is approached; some of this finer grained material is illustrated in Figure 15D. As the fragments in these samples are predominantly G.M.D., it is probable that these pyroclastics represent an explosive end phase to the extrusion of the G.M.D. However, the volcanic breccias overlying the G.M.D. in D.D.H.s. S.E.10 (Fig. 16) and S.E.7 (Fig. 17) contain fragments of felsic volcanics and chert in addition to G.M.D. (Figs. 18A and B), indicating that in these localities, the volcanic breccias were either formed or reworked during early felsic volcanism of the Black Flag Beds. The presence of G.M.D. fragments in these
Fig. 14. Simplified log of D.D.H. S.E.4 (Based on detailed log in Appendix 2).
Fig. 15. Pyroclastic features of the G.M.D.

A. Weathered drill core showing lighter-coloured G.M.D. fragments (G) in dark, iron-stained, fine-grained groundmass (1939/4).

B. Sawn surface of above sample. Note variation in grainsize of the leucoxene (white specks) in the G.M.D. fragments; fragments of units 9 (G9) and 10 (G10) are represented (see sketch).

C. Large fragments of unit 9 G.M.D. (G) in tuffaceous matrix (T) (2491/4).

D. Smaller fragments of G.M.D. in tuffaceous matrix. Units 9 (G9) and 10 (G10) are present (2494/4).
Fig. 16. Cross-section through D.D.H.s S.E. 9 and S.E.10 (After W.M.C. Ltd. Plan No. 201-328).
Fig. 17. Cross-section through D.D.H.s S.E.7, S.E.11 and S.E.12 (After W.M.C. Ltd. plan).
Fig. 18. Reworked volcanic breccias containing G.M.D. fragments at the base of the B.F.B.

A. G.M.D. (G), chert (C) and possible pumice fragment (P) in reworked volcanic breccia (3558/7).

B. G.M.D. (G), felsic volcanic (F) and possible pumice fragments (P) in reworked breccia (3874/7).
volcanic breccias clearly demonstrates that the G.M.D. preceded the Black Flag Beds and could not have been intruded into them.

Further evidence of the relative age of the G.M.D. and Black Flag Beds can be observed in specimens 2501/4, 2510/4 and 2546/4 (Figs. 9 and 14) where fragments of G.M.D. ranging from pebble to boulder size are enclosed in the black shales (Figs. 19A, B and C). The presence of tuffaceous matter around some of the G.M.D. fragments suggests that these basal conglomerates formed by reworking of the underlying pyroclastics and indicate that a period of erosion separated the formation of the G.M.D. and the Black Flag Beds.

In addition to the coarse-grained pyroclastics, there are some fine-grained rocks within the G.M.D. which also show pyroclastic features. Amongst these is a reddish-brown rock (1795/4) which in thin section has proved to be tuffaceous. This rock contains chloritic pseudomorphs after biotite? phenocrysts (these consist dominantly of chlorite with an olive-green colour and sometimes have a core of epidote surrounded by chlorite with anomalous purple interference colours) in a groundmass of fine-grained plagioclase laths, carbonate and fine-grained oxides (Figs 20A). Near its boundary with the G.M.D., this rock contains fragments of G.M.D. and quartz (Fig. 20B) indicating that it is a basic tuff and not an intrusive. Unfortunately, it is not possible to determine whether this tuff separates two flows of G.M.D. or whether the drill hole has merely grazed the top of the G.M.D. (see Figs. 9 and 14). A pink rock (2128/4 on Figs. 9 and 14) containing disc-shaped chlorite-carbonate bodies aligned parallel to the foliation could be an intrusive but may also be a tuff. The pink colour disappears down hole and the rock assumes a greenish colour. The chloritic areas are set in a groundmass of small albite laths, granular quartz, sericite and carbonate; in thin section they are spindle-shaped and possibly represent flattened pumice
Fig. 19. G.M.D. fragments in basal black shales of the B.F.B.

A. Basal conglomerate containing pebbles of G.M.D. from units 9 (G9) and 10 (G10) and some tuffaceous material (T) in a matrix of black shale (S) (2501/4).

B. Reworked tuffaceous G.M.D. at the base of the B.F.B. Contains fragments of units 9 (G9) and 10 (G10) of the G.M.D. surrounded by tuffaceous material (T) and a little black shale (S) (2510/4).

C. Isolated fragments of G.M.D. (G) and some tuffaceous material (T) in black shale (S) (2546/4).
Fig. 20. Fine-grained tuff in upper part of G.M.D. (1795/4).

A. Chlorite pseudomorphs after biotite? phenocrysts. Note core of epidote (yellow) surrounded by chlorite with anomalous purple interference colours within chlorite with olive-green interference colours. Magnification 130X.

B. Fragment of G.M.D. in tuff. Magnification 33X.
fragments (Fig. 21). Similar rocks from the mining area were regarded by many earlier authors (Thompson, 1913; Feldtmann and Farquharson, 1913; Stillwell, 1929) as intrusive porphyrites but the possibility that many of these are tuffs or volcanics was recognized by Honman (1916).

Tomich (1976) includes photographs of drill core from the Enterprise mine showing irregular layers of carbonate and a dark material within G.M.D. Tomich concludes that these layers are thin beds of sediment which have been tightly folded with the G.M.D. If this interpretation is correct, it would imply that the G.M.D. consisted of a number of flows. However, Tomich's interpretation of the dark material as slate is open to question. Some black material which strongly resembled black shale in hand specimen was associated with carbonate in unit 9 of the G.M.D. in specimen 1793/4 (Fig. 22A); in polished section, it can be seen that this material actually consists of numerous tiny euhedral magnetite crystals in a matrix of carbonate, chlorite and quartz (Fig. 22B). The origin of this oxide and carbonate segregation is uncertain; it may have some genetic relationship with the fine-grained tuff previously described (1795/4) as the two are spatially associated (see Figs. 9 and 14) but it could be simply secondary in origin. It is possible that the interbedded "slates" illustrated by Tomich (1976) are also oxide segregations. Some of the dark green chlorite associated with quartz and carbonate stringers in the Kalgoorlie Enterprise drilling examined in this study could also conceivably be mistaken for slate. Until microscopic studies are carried out on the dark material illustrated by Tomich, its nature remains doubtful. No evidence was found in the south end drilling of sediments interbedded with the G.M.D. except at the very top of the flow in specimen 3104/4 from D.D.H. S.E.4 (Figs. 9 and 14).

Brecciated G.M.D. from the No. 13 level of the Perseverance mine ("K" lode stope) and the No. 2 level of the Associated mine (North lode area)
Fig. 21. Spindle shaped pumice fragment now consisting of chlorite (Cl) and carbonate (C) in pink tuff (2128/4).

A. Transmitted light. B. Crossed nicols.

Fig. 22. Segregated oxides and carbonates resembling a sediment band (1793/4).

A. Thick section (oxides are black, carbonates are white and G.M.D. is grey).

B. Reflected light micrograph showing that the "shale" contains numerous tiny magnetite crystals (white) in a matrix of chlorite, carbonate and quartz (grey).
has been interpreted by Tomich (1975, 1976) as breccia plug. Similar specimens from the North lode area have been examined by the author. These consist of angular fragments of altered G.M.D. with uniform grain size, cemented by carbonate (Fig. 23). It is very difficult to determine whether these breccias are primary volcanic features or are the result of later tectonic deformation. However, one sample from D.D.H. S.E.10 (3691/10) contains fragments of fine-grained G.M.D. and an aphanitic rock which could be either chilled G.M.D. or Paringa Basalt in a breccia zone in sharp juxtaposition with G.M.D. containing coarse-grained skeletal leucoxene (Fig. 24). Although a fault is marked on the Western Mining Corporation Ltd. cross section at this point (Fig. 16), the dolerite shows no sign of shearing and only a few late quartz-filled fractures are present. This sample possibly represents a volcanic breccia plug with the fragments being derived from the chilled volcanics below; this however does not readily explain the tuff-like matrix of the fragments or the lack of deformation in the adjacent G.M.D. The only alternative is that the sample represents a pyroclastic and, as it is situated well away from the top of the G.M.D. (Fig. 16) this would imply that the G.M.D. consists of more than one flow.

Indisputable flow top breccias are present at the top of the G.M.D. in parts of D.D.H. S.E.4: in specimen 2051/4 (Fig. 14), the flow top breccia consists of fine-grained G.M.D. enclosing fragments of coarser-grained G.M.D. (Fig. 25); in specimen 3104/4 (Fig. 14), a similar flow top breccia is interrupted by bands of shale. In both cases, the G.M.D. fragments become gradually coarser grained away from the upper contact. The G.M.D. in contact with the shale in specimen 3104/4, has an aphanitic, glassy texture (Fig. 26) and it is obvious that this breccia is primary and not some later tectonic feature.

The upper chilled margin noted by Gustafson and Miller (1937) and
Travis et al. (1971) may indicate that the G.M.D. is intrusive in the mining area but could also be interpreted as a chilled flow top on relatively passively extruded G.M.D. If Tomich's (1976) interpretation of pyroclastic features in the G.M.D. from the South Kalgurli mine is correct, then the G.M.D. must be extrusive in the mine area.

In summary, the evidence is overwhelming that the upper part of the G.M.D. is, at least at the southern end of the field, extrusive. Some units, particularly the central Fe-rich units (6, 7 and 8), may, however, have been intruded into the volcanic pile. It is also possible that the G.M.D. as a whole is in part intrusive and in part extrusive. There is no conclusive evidence for the existence of more than one flow but in view of the volcanic breccia found in D.D.H. S.E.10, this possibility is not ruled out.

2.2.8 **Black Flag Beds**

The Black Flag Beds (B.F.B.), a series of sediments, tuffs and acid to intermediate volcanics overlying the G.M.D. and forming the uppermost unit of the Kalgoorlie succession, have received very little attention by previous workers. In view of the close association of the Golden Mile lodes with infolded B.F.B. in the Kalgoorlie Syncline, and the fact that many Canadian gold deposits are closely associated with felsic volcanics and volcanogenic sediments (Goodwin, 1965; Ridler, 1970), this volcanogenic/sedimentary series has been examined in some detail by the author.

Diamond drill core from the south end of the field has provided most of the sample material used in this study. D.D.H. S.E.4 has proved to be particularly useful as it passes in and out of the G.M.D.-B.F.B. contact several times (Figs. 9 and 14) and gives an indication of facies variations in going from west to east whilst D.D.H.s S.E. 7 (Fig. 17) and S.E.10 (Fig. 12) give facies changes to the south. The major lithotypes in the B.F.B.
and their distribution are listed in Table 6. These are described and discussed below.

**Black Shales.** Fine-grained carbonaceous sediments characterize the basal part of the B.P.B. in the Kalgoorlie Syncline in D.D.H. S.E.4 (Figs 9 and 14) and also make up a major portion of the sediments in the Boulder Dyke in the Golden Mile area. Black shales are also found interbedded with other lithotypes higher up in the sequence as illustrated in the drill core log of S.E.4 (Fig. 14).

Because of the fine-grained nature of the shales, and the dark colour imparted by finely divided carbonaceous material, it is difficult to establish their mineralogy by optical means. Sericite, chlorite, quartz, carbonate and albite were recognized in coarser grained patches. Rare zircons and xenotime grains were also observed.

Analyses of three different types of black shale are given in Table 7. They are characterized by high $K_2O$ values reflecting the abundance of sericite. All three shales are rich in carbonate and non-carbonate C. One of these shales (2691/4) was extremely difficult to analyse for C because it gave off hydrocarbons when heated and these tended to condense as a thick greenish-brown oil at the cool end of the furnace. The highest value was obtained when the sample was placed straight into the hottest part of the furnace, probably because the hydrocarbons were converted to $CO_2$ before they could escape. Since the rush of gases given off in the initial heating is likely to have resulted in some loss, the value of 4.0% is probably the minimum amount of non-carbonate C in the sample. The occurrence of hydrocarbons in shales as old as these is extremely interesting and it is hoped that organic geochemistry will eventually be carried out on these in order to establish their nature.
<table>
<thead>
<tr>
<th>Lithotype</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black shales</td>
<td>In the Kalgoorlie Syncline (Boulder Dyke) in the Mt. Charlotte mine, Golden Mile and in D.D.H's S.E.4 and S.E.13. Also interbedded with other lithotypes in the central syncline and east section of D.D.H. S.E.4 (see Figs. 9 and 15). None observed in B.F.B. of D.D.H's S.E. 7 and 10.</td>
</tr>
<tr>
<td>Laminated shales, siltstones and carbonate bearing sediments</td>
<td>These are particularly abundant in the central syncline of D.D.H. S.E.4. Also found in the Kalgoorlie syncline in the Golden Mile, D.D.H. S.E.4 and D.D.H. S.E.13, in the east section of D.D.H. S.E.4 and west of the Boulder Fault near Mt. Hunt and in Walsh's Quarry (see Fig. 2). None observed in D.D.H's S.E.7 and 10.</td>
</tr>
<tr>
<td>Greywackes and tuffaceous sediments</td>
<td>Central syncline and east section of D.D.H. S.E.4.</td>
</tr>
<tr>
<td>Lapilli tuffs</td>
<td>Central syncline and east section of D.D.H. S.E.4.</td>
</tr>
<tr>
<td>Volcanic breccias and conglomerates</td>
<td>Central syncline and east section of D.D.H. S.E.4, in D.D.H's S.E.7 and S.E.10 and in outcrop at the southern end of the field. None observed in the Golden Mile or Kalgoorlie syncline in D.D.H. S.E.4.</td>
</tr>
</tbody>
</table>
### Table 7

Analyses of sediments from the B.F.B.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>69.81</td>
<td>44.05</td>
<td>45.49</td>
<td>64.22</td>
<td>69.33</td>
<td>61.31</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.20</td>
<td>0.60</td>
<td>0.63</td>
<td>0.36</td>
<td>0.27</td>
<td>0.32</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.20</td>
<td>12.91</td>
<td>11.56</td>
<td>14.96</td>
<td>11.75</td>
<td>13.43</td>
</tr>
<tr>
<td>FeO*</td>
<td>2.64</td>
<td>12.42</td>
<td>11.79</td>
<td>2.09</td>
<td>2.07</td>
<td>3.16</td>
</tr>
<tr>
<td>MnO</td>
<td>0.04</td>
<td>0.04</td>
<td>0.10</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>MgO</td>
<td>1.89</td>
<td>2.06</td>
<td>5.78</td>
<td>1.77</td>
<td>1.31</td>
<td>1.89</td>
</tr>
<tr>
<td>CaO</td>
<td>1.87</td>
<td>3.91</td>
<td>5.11</td>
<td>3.64</td>
<td>3.51</td>
<td>5.41</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.33</td>
<td>3.08</td>
<td>2.15</td>
<td>2.92</td>
<td>2.30</td>
<td>2.25</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
<td>0.19</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.92</td>
<td>0.36</td>
<td>1.27</td>
<td>2.86</td>
<td>2.55</td>
<td>2.83</td>
</tr>
<tr>
<td>Ba</td>
<td>0.07</td>
<td>0.06</td>
<td>0.04</td>
<td>0.08</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>S</td>
<td>1.08</td>
<td>7.75</td>
<td>3.96</td>
<td>0.02</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>CO₂ (carbonate)</td>
<td>3.2</td>
<td>6.1</td>
<td>8.4</td>
<td>6.1</td>
<td>4.9</td>
<td>7.5</td>
</tr>
<tr>
<td>C (non-carbonate)</td>
<td>0.8</td>
<td>4.0</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.5</td>
<td>1.1</td>
<td>2.1</td>
<td>1.0</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Sr (ppm)</td>
<td>130</td>
<td>290</td>
<td>310</td>
<td>31</td>
<td>290</td>
<td>370</td>
</tr>
<tr>
<td>Total</td>
<td>98.62</td>
<td>98.51</td>
<td>99.36</td>
<td>100.03</td>
<td>99.31</td>
<td>99.53</td>
</tr>
</tbody>
</table>

*Total Fe as FeO.

1. 3080/4 Black shale with concentric carbonate bodies.
2. 2691/4 Black shale with bedded pyrite.
3. 2873/4 Black shale with pyrite nodules and fragments of underlying evaporite-bearing sediment.
4. 2832/4 Massive grey sediment with pseudomorphs after sulphates.
5. 2849/4a Light coloured sediment with pseudomorphs after sulphates.
6. 2849/4b Laminated sediment with pseudomorphs after sulphates.
Sulphides form a significant component of many of these black shales. Some of the least deformed shales contain fine-grained bedded pyrite with a form and size distribution suggestive of recrystallized frambooids (see Love and Amstutz, 1966; Oßwald and England, 1977) as illustrated in Figure 27. In places, the fine-grained pyrite has coalesced, either as a result of diagenesis or slight deformation to form irregular masses consisting of a recrystallized core surrounded by spongy pyrite which has nucleated about the fine-grained pyrite crystals. This segregated pyrite contains numerous small inclusions of chalcopyrite, sphalerite and galena (Fig. 28). The effect of deformation on these sulphides will be discussed in a later chapter.

Sulphide nodules are also common in many of the black shales. These nodules vary considerably in composition; some are composed of a mixture of pyrrhotite, sphalerite, chalcopyrite and more rarely, arsenopyrite in a matrix of carbonates and silicates whilst others are composed dominantly of pyrrhotite or pyrite. Those composed of pyrrhotite and mixed sulphides are thought to be primary or detrital or to be replacements of primary features as they generally lie on bedding planes (Fig. 29) but the origin of the pyrite nodules is uncertain; some pyrite nodules appear to be replacement features after carbonates or possibly sulphates (Fig. 30); others are probably diagenetic features.

A sample of black shale interbedded with felsic agglomerates in the uppermost part of the B.F.B. studied contained thin prismatic arsenopyrite crystals enclosed in bands of pyrrhotite (Fig. 31).

**Carbonate-bearing sediments, laminated shales, siltstones and sandstones.**

Black shales usually grade gradually into lighter coloured carbonate-bearing shales or laminated sediments although they show abrupt contacts with light coloured sediments in places. Carbonate commonly occurs as euhedral
crystals ($\frac{1}{2}$-1 mm across) scattered through the darker coloured shales. Although probably originally dolomite, the carbonate is now ankerite.

In the finely laminated sediments, carbonate is concentrated in the lighter coloured beds (Fig. 32). Other sediments show coarser wavy or lenticular bedding (Fig. 33) and in these, the lighter coloured layers are coarser grained (silt or fine-sand size) and contain a greater percentage of quartz and carbonate than the darker laminations.

Light grey carbonate-rich sediments interbedded with some of the black shales usually contain coarse-grained euhedral carbonate rhombs (Figs. 34, 35). However, some massive carbonate-rich rocks associated with the black shales consist of very fine-grained subhedral to irregular carbonate grains together with fine-grained quartz and sericite.

Oval-shaped concentrically-zoned structures are a characteristic feature of both the laminated and massive carbonate-bearing shales. These consist of an outer ring of dark-coloured siderite, a lighter inner ring of sericite, quartz and light-coloured carbonate and, in the larger ones, a core of siderite (Fig. 36). Within the vicinity of these pseudo-concretions, the matrix has been bleached and consists almost entirely of quartz, whilst away from these structures, but in identical beds, there is abundant iron-bearing carbonate (Fig. 32). This suggests that these structures are a diageneric feature rather than a primary feature.

The carbonate contents of some of these sediments are given in Table 8. Although carbonate is an important constituent of some of these sediments, it never becomes sufficiently abundant to form a limestone indicating either that there was a significant influx of siliclastic material or that carbonate has been lost as a result of silicification or other alteration processes.

Although, in general, the laminated and light-coloured carbonate-rich shales contain considerably less sulphides than the black shales, one
Fig. 32. Laminated sediment. Note highly contorted laminations (c) overlain by undeformed layers (u). Light coloured laminations are carbonate-rich. Note also the leaching of carbonate around the pseudo-concretions (p) (3038/4).

Fig. 33. Lenticular bedding. Light coloured material is coarse-grained, dark material is fine-grained (2519/4).

Fig. 34. Small scour in carbonate-rich sediments (carbonate appears white due to the etching of the surface with HCl). Detrital sulphides (s) are present in the scour (2601/4).

Fig. 35. Pyrite-rich carbonate-rock (c) interbedded with black shales (s) containing syn-sedimentary microfaults (F). Pyrite (p) is both stratiform and cross-cutting (2657/4).
specimen of carbonate-rich rock interbedded with black shales has abundant bedded and remobilized pyrite (Fig. 35). In places, carbonate rhombs have been partially replaced by sulphides (Fig. 37).

Small scale scour structures are common in the laminated shales and carbonate rocks (Fig. 38) and suggest shallow water deposition. Other features noted in these sediments include synsedimentary microfaults (Figs. 35 and 38) and contortion of the fine laminations in some of the shales (Fig. 32); these are soft sediment deformation features as in each case, the structures are overlain by undeformed sediment.

The rapid alternation of black shales with siltstones and carbonate-rich sediments, the presence of small scale scour structures (Fig. 34) and the soft sediment deformation features shown in Figures 32, 35 and 38 are suggestive of shallow water deposition. The strong resemblance of the finely laminated shales (Fig. 32) to algal laminated sediments forming in a modern tidal flat environment at Shark Bay, Western Australia, is also noteworthy. According to Reineck and Wunderlich (1968), lenticular bedding (Fig. 33) is characteristic of tidal environments with the sand-mud alternation resulting from the alternation of current or wave action and slack water. Recently, de Raff et al. (1977) have demonstrated that wave-generated lenticular bedding can also form on a shallow marine platform as the result of alternation of stormy and calm weather. However, the rapid alternation of sediment types, including carbonate-rich sediments is more suggestive of a tidal environment than a marine platform environment.

**Evaporite-bearing Sediments.** Massive grey sediments and some light-coloured laminated rocks containing numerous elongate, tapered carbonate bodies and blocky forms were intersected by D.D.H. S.E.4 at the southern end of the field. When sawn open, the laminated sediments bore such a strong superficial resemblance to algal-laminated sediments that thin
Fig. 36. Oval-shaped concentrically-zoned structures consisting of an outer ring of dark-coloured siderite, a lighter inner ring of sericite, quartz and light-coloured carbonates, and a dark core of siderite (3044/4). Magnification 14X.

Fig. 37. Carbonate crystal (grey) partially replaced by sulphides (white) (4465/4). Reflected light. Magnification 50X.

Fig. 38. Syn-sedimentary microfaults (F) forming small troughs which have been covered by the next layer of sediment (2556/4).
of both the laminated sediments and the massive
core by Dr. Malcolm Walter (B.M.R.) who kindly examined them.
I concluded that there were no distinctive algal
material in the sediments; hence their origin is uncertain.
I further interpreted the elongate, tapered carbonate bodies
as pseudomorphs after sulphates.
Sections cut from the massive, grey sediments yielded
of the massive carbonate pseudomorphs after sulphates. These
sections (Fig. 39B) which W. Keshitt (pers. comm.) considered
were those described by Masson (1955) from the Laguna Madre mar-
Walrath, Texas, and by Illing et al. (1965) from the Persian Gulf,
rosettes (Figs. 39B and F) in addition
tapered forms and blocky forms, some of which have pseudo-
sections (Fig. 39C). Although glassy volcanic fragments or
Carmack and Crossdale, 1972), squashed pumice fragments and even
some lines have some similarities with the elongate, tapered and
pseudomorphs observed, no volcanic products are likely to
be identified as pseudomorphs. These forms are so typical of
it can be accepted that these carbonate bodies are simply pseu-
mineral. The origin of the elongate and some of the mor-
less certain; these could be after gypsum but could also
barite or other sulphates (e.g. barite).
Massif pseudomorphs after sulphates were also observed in massive
core sediments from the Kalpoorlie Syncline in D.O.H. S.E.13, in
the Rutland sediments in the Boulder Dyke on the No. 6 Level
Minier Mine and in fragments from a conglomerate found in the
levels on the No. 11 level of the Mt. Charlotte mine (Fig. 40).
Fig. 39. Evaporite-bearing sediments from the B.F.B.

A. Drill core showing highly disturbed laminated sediments (2849/4).

B. Small section of above sample. Light coloured sulphate pseudomorphs (s) are just visible in the dark coloured laminations. Note disruption of the laminae by albite/carbonate balls (B) (2849/4).

C. Elongate tapered pseudomorph (2832/4).

D. Carbonate pseudomorphs after gypsum, including lens-like form (upper left) and interpenetrating twins (lower centre) (2847/4).

E. Carbonate pseudomorph after rosette (2852/4).

F. Carbonate (light) and sulphides (black) after rosette (2847/4).

G. Elongate and blocky pseudomorphs after sulphates. Note pseudo-hexagonal outlines of one of the pseudomorphs (2847/4).

H. Albite/carbonate ball (B) in laminated sediment (2849/4).

Scale bar on all photomicrographs is 0.5 mm long.
Table 8
Carbonate content of some sediments from the B.F.B.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>$\text{CO}_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3029/4</td>
<td>Siliceous, black carbonate-bearing shale.</td>
<td>8.33</td>
</tr>
<tr>
<td>3038/4</td>
<td>Laminated shale with carbonate-rich/carbonaceous rich laminae.</td>
<td>8.81</td>
</tr>
<tr>
<td>3057/4</td>
<td>Laminated shale.</td>
<td>2.86</td>
</tr>
<tr>
<td>3095/4</td>
<td>Black shale with carbonate-rich patches.</td>
<td>7.34</td>
</tr>
<tr>
<td>2657/4</td>
<td>Pyritic, carbonate rich sediment interbedded with black shales.</td>
<td>11.94</td>
</tr>
<tr>
<td>3014/4</td>
<td>Massive, light coloured, fine-grained sediment consisting of carbonate, quartz and sericite.</td>
<td>20.02</td>
</tr>
</tbody>
</table>
Possible examples of carbonate pseudomorphs after small anhydrite nodules (2-5 mm across) were found on the No. 6 Level of the Chaffers Mine. According to the nomenclature of Maiklem et al. (1969), these would be described as distorted nodular or nodular-mosaic (Fig. 41). These nodules are smaller than those found on modern tidal flats but are similar in size to those described by Gill (1977) from the Salina A-I sabkha cycles of the Michigan Basin. The nodules have a microcrystalline texture (Fig. 42) and show no evidence of the felted and subfelted textures typical of anhydrite (Maiklem et al., 1969); hence their origin cannot be assigned with certainty.

The disrupted nature of the laminated sediments in D.D.H. S.E.4 (Fig. 39A) is probably the result of soft sediment deformation; if the laminations represent algal mats, then dessication and disruption would be expected. However, the presence of evaporite-minerals would also make the sediments more susceptible to later tectonic deformation.

Numerous dark rounded blebs consisting of carbonate and albite interrupt the bedding in the laminated sediments (Figs. 39A and H). These may represent altered clastic feldspar grains; another possibility is that they are replacements after nodular anhydrite or aragonite/algal balls. Albite grains and aggregates up to 7 mm long are also scattered through the massive grey material.

Apart from the albite grains and sulphate pseudomorphs, both the massive material and the laminated material are very fine-grained and appear to consist mainly of quartz, sericite and carbonate. Fine bands of carbonaceous material define some of the layers in the laminated material but overall, the carbonaceous content is very low.

Chemically, both the massive grey material and the laminated material resemble the more silica rich black shales (compare analyses 4, 5 and 6...
Fig. 40. Conglomerate from the Boulder Dyke, Mt. Charlotte mine containing rock fragments with possible sulphate pseudomorphs (p) (MC11/4).

Fig. 41. Possible pseudomorphs after anhydrite nodules (light grey) in black, carbonate rich shale from the Boulder Dyke, No. 6 Level of the Chaffers Mine (11/6C).

Fig. 42. Photomicrograph of possible pseudomorphs after anhydrite nodules. The nodules are composed of microcrystalline carbonate. The micaceous mineral separating the nodules is sericite. Quartz, carbonate and carbon are also present in the groundmass (11/6C). Transmitted light. Magnification 7.5X.
with analysis 1, Table 7) although the shales have a lower $\text{Na}_2\text{O}$ and $\text{P}_2\text{O}_5$ content and high C content.

The sulphate pseudomorphs now consist of carbonate and a little sericite. Some have been partially replaced by sulphides (sphalerite, chalcopyrite and gersdorffite) as illustrated in Figure 39G but in general the S content of these rocks is low (Table 7) indicating significant loss of S during diagenesis or at some later stage. Sr and Ba, two other elements characteristically found in evaporites are only moderately enriched in these rocks but could also have been lost from the system.

**Mud-chip and Mud-flake Conglomerates.** Mud chip or flat pebble conglomerates containing angular fragments of shale in a matrix of coarse-grained carbonate, sericite and quartz are closely associated with laminated shales and carbonate-bearing sediments in D.D.H. S.E.4 (Fig. 43). Similar features have been recognized in modern tidal flat environments and have been interpreted by Shinn et al. (1965), Ginsburg (1975) and Laporte (1975) as reworked mud-cracked polygons or pieces of indurated crust eroded from the tidal flat by high waters and incorporated in the mudstones.

Pyrrhotite is abundant in some of the mud-chip conglomerates (Fig. 43B) but its source is uncertain. The rounded form of many of the sulphide grains suggests that they are detrital but replacement features are evident in some of the grains under the reflecting microscope. It is possible that some of these grains were derived by erosion of sulphide nodules from the surrounding shales and that recrystallization has slightly modified their original textures.

At one locality, the mud-chip conglomerate grades into a sandstone with fine-grained mud chips (Fig. 43C). Fine-grained mud-chip or mud-flake conglomerates are common in the Boulder Dyke on the No. 6 Level of the Chaffers mine (Fig. 44). Similar thin mud-flakes in the Salina A-1 sabkha cycles of
Fig. 43. Mud-chip conglomerates from the B.F.B. in D.D.H. S.E.4.

A. Conglomerate with flat-pebbles of black shale in a lighter grey carbonate-rich matrix (3099/4).

B. Mud-chips (m) and pyrrhotite (p) in a coarse-grained carbonate-rich matrix (2578/4).

C. Mud-chip conglomerate (c) grading into a sandstone (s) (2572/4).

Fig. 44. Mud-flake conglomerate from the Boulder Dyke, Chafers Mine. The mud-flakes are black. The light-coloured, irregular patches are possibly carbonate pseudomorphs after anhydrite nodules. Transmitted light. Magnification 7.5X.

Fig. 45. Brecciated black shale and quartz-carbonate filled cavities (2738/4).
Albite is ubiquitous in the tuffs of the B.F.B; it is usually present as euhedral, tabular crystals but also occurs in aggregates with the individual crystals having irregular, sometimes sutured, boundaries. Sericite is generally present and in some tuffs becomes so abundant that it imparts a characteristic pale green colour to the rock. Some of the tuffs contain abundant quartz clasts whilst others are essentially free of this mineral. Fine-grained rock fragments, chiefly of acid or intermediate volcanic origin, are also abundant in some tuffs but are rare or absent in others. Lithic tuffs show a gradual transition to volcanic breccias and, where reworked, to greywackes.

One sample of poorly sorted lithic tuff (4283/4), which in drill core has the appearance of a greywacke, contains accretionary lapilli. These lapilli are oval in shape and compositionally similar to the matrix of the tuff consisting of quartz, carbonate and albite grains in a fine-grained matrix of quartz and sericite. The rims of these oval-shaped bodies are marked by a concentration of sericite (Fig. 47). According to Moore and Peck (1962), accretionary lapilli "probably developed in an ash-charged volcanic cloud by accretion of ash around a core due to the condensation of moisture on the core, and fell to the ground like hailstones". The presence of accretionary lapilli indicates that the enclosing lithic tuff is extrusive in origin and probably related to "Surtseyan" type volcanism (i.e., volcanic activity exemplified by the explosive opening stages of the Surtsey eruptions) as suggested by Walker and Croasdale (1972). Since accretionary lapilli are held together only by moisture, Moore and Peck conclude that they were deposited on land or possibly shallow water.

In addition to accretionary lapilli, one other line of evidence for the presence of moisture or rainflushing at the time of deposition of volcanic ash is the presence of near-spherical air bubbles (Walker and Croasdale, 1972).
A possible example from Kalgoorlie is a fine-grained spotted tuff, sample 3477/4 on the log of D.D.H. S.E.4 (Fig. 15). This tuff consists of layers rich in chlorite and fine-grained ilmenite alternating with layers composed of quartz, sericite and a little chlorite. Fine-grained carbon imparts a dark colouration to some bands. Spots are present in both chlorite and quartz-sericite rich layers. They now consist of carbonate surrounded by a rim of quartz, sericite and carbonate (Fig. 48) but may well have been air bubbles originally. However it is possible that these spots are diagenetic. It should be noted that in drill core, these spotted tuffs bear a strong resemblance to the variolitic unit 10 of the G.M.D. which they overlie and it is possibly this similarity which led Larcombe (1911) to conclude that there was every gradation between the G.M.D. (referred to as andesite) and the black shales in the Boulder Dyke and hence to the belief that the black shales represented sheared G.M.D. with metamorphically introduced carbon. It was not until Stillwell (1929) pointed out the normal sedimentary bedding features of the black shales that a sedimentary origin became accepted.

In view of the diversity in mineralogy of the tuffs, it is not surprising that they show variable chemistry; some are very rich in sodium (analyses 1 and 2, Table 9) whilst others are rich in potassium (analysis 3, Table 9).

**Volcanic Breccias and Conglomerates.** Volcanic breccias (pyroclastics with greater than 50 percent fragments over 1 mm) and their reworked equivalents form a significant proportion of the B.F.B; these show a considerable range in composition.

Basic volcaniclastic comprised principally of G.M.D. fragments have been discussed previously and will not be discussed again here.

Although volcanics of intermediate composition are common in the Canadian Archaean (Goodwin, 1965), they were previously regarded as rare
Table 9
Analyses of pyroclastics from the B.F.B. on a volatile free basis

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>67.18</td>
<td>69.60</td>
<td>64.49</td>
<td>71.97</td>
<td>65.13</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.50</td>
<td>0.43</td>
<td>0.54</td>
<td>0.32</td>
<td>0.40</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.68</td>
<td>15.25</td>
<td>19.62</td>
<td>13.80</td>
<td>16.38</td>
</tr>
<tr>
<td>FeO*</td>
<td>2.92</td>
<td>2.28</td>
<td>3.43</td>
<td>2.70</td>
<td>4.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.05</td>
<td>0.04</td>
<td>0.10</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>MgO</td>
<td>2.31</td>
<td>1.76</td>
<td>1.19</td>
<td>1.92</td>
<td>3.31</td>
</tr>
<tr>
<td>CaO</td>
<td>3.24</td>
<td>2.90</td>
<td>4.14</td>
<td>2.59</td>
<td>3.49</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.91</td>
<td>1.36</td>
<td>4.28</td>
<td>0.59</td>
<td>0.55</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.13</td>
<td>0.13</td>
<td>0.29</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>Na₂O</td>
<td>7.02</td>
<td>6.19</td>
<td>1.44</td>
<td>5.77</td>
<td>6.36</td>
</tr>
<tr>
<td>Ba</td>
<td>0.02</td>
<td>0.03</td>
<td>0.20</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>S</td>
<td>0.04</td>
<td>0.03</td>
<td>0.21</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>5.4</td>
<td>5.6</td>
<td>7.5</td>
<td>3.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Sr (ppm)</td>
<td>350</td>
<td>130</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Total Fe as FeO

1. 2955/4 Albite tuff
2. 2970/4 Albite-sericite tuff
3. 6243/4 Sericite tuff
4. 4327/4 Altered hornblende-bearing intermediate volcanic fragment
5. 6316/4 Altered albite-rich volcanic fragment
in the Archaean of the Eastern Goldfields region of Western Australia where Hallberg (1972) found a bimodal distribution of volcanics with acid and mafic compositions predominating. However, calc-alkaline complexes have recently been described from other areas of the Yilgarn Block (Hallberg, Carter and West, 1976; Hallberg, Johnston and Bye, 1976). Whilst no intermediate flows have been detected in this study, volcanic breccias and lithic tuffs containing fragments of intermediate volcanics are abundant in the B.F.B. of the central syncline in D.D.H. S.E.4 (Fig. 15). The majority of rock fragments at this locality contain phenocrysts of albite and zoned hornblende in a fine-grained quartzo-feldspathic groundmass (Fig. 49). These rock fragments closely resemble the porphyritic hornblende dacite from the Meekatharra area described by Hallberg, Carter and West (1976) and although altered, their chemistry is consistent with that of a dacite (analysis 4, Table 9). In addition to these intermediate rock fragments, there are rare fragments of G.M.D. (Fig. 50), chert and black shale. The presence of relatively fresh G.M.D. fragments in this pyroclastic suggests that the source vent passed through the G.M.D. and other members of the Kalgoorlie succession and was not lateral to this mafic pile as in the case of the Meekatharra andesites (Hallberg, Carter and West, 1976). In specimen 4327/4, the intermediate rock fragments reach 30 cm in diameter suggesting that they are close to the source vent. Further away, the breccia becomes finer grained and grades into a lithic tuff and eventually a greywacke (see Fig. 15).

Rock fragments of possible andesitic composition were observed in a fine-grained volcanic breccia from S.E.10. These contain tabular crystals of albite with albite and pericline twins and occasional remnants of biotite (now largely pseudomorphed by sericite and carbonate) in a matrix of fine-grained albite laths and granular quartz with some alteration carbonate
Fig. 49. Intermediate volcanic rock fragment containing phenocrysts of albite and zoned hornblende in a fine-grained quartzo-feldspathic groundmass (4397/4). Crossed nicols. Magnification 49X.

Fig. 50. G.M.D. fragment in intermediate volcanic breccia (4397/4). Crossed nicols. Magnification 27X.
and sericite. Felted flow textures are developed in places (see Fig. 51). Unfortunately these fragments were too small for analysis (less than 5 cm across). Some of these rocks contain possible pumice fragments pseudomorphed by sericite (Fig. 52).

Light buff coloured volcanic fragments which are almost devoid of mafic minerals are characteristic of the volcanic breccias of the B.F.B. in the most easterly part of D.D.H. S.E.4, in D.D.Hs S.E.7 and S.E.10 and in outcrop to the south-east of Kalgoorlie. Some of these are highly porphyritic with coarse-grained albite crystals (up to 5 mm) and occasional quartz crystals with four and six-sided cross-sections in a fine-grained feldspathic groundmass containing sericite, carbonate, chlorite and granular quartz as alteration products (Fig. 53). Although logged as acid on the basis of colour, these fragments are chemically similar (analysis 5, Table 9) to the darker coloured hornblende-bearing dacites previously described (analysis 4, Table 7). Ankerite probably accounts for most of the Fe and Mg reported in the analysis of the light coloured porphyrite with the colour being a reflection of the degree of carbonatization of the mafic minerals. Finer-grained, less obviously porphyritic fragments are also found in these light coloured volcanic breccias. These contain small (less than 0.5 mm) albite phenocrysts in a fine-grained quartzo-feldspathic groundmass; sericite and carbonate are ubiquitous as alteration products. Although quartz phenocrysts are rare in the volcanic fragments, quartz is an important part of the tuffaceous matrix along with albite, possible pseudomorphs after alkali feldspars, sericite and carbonate and may be the product of more explosive acid volcanic activity. Rock fragments of varying grain size, composition and degree of alteration are frequently seen together (Fig. 54) suggesting some degree of reworking of the fragments either by sedimentary processes or subsequent explosive volcanic activity. Sulphide fragments up
Fig. 51. Andesitic flow texture in intermediate volcanic fragment (5162/10). Crossed nicols. Magnification 87X.

Fig. 52. Volcanic breccia from the B.F.B. containing sericitic pseudomorph after possible pumice fragment (P) intermediate flow-textured rock fragments (R) in a quartz-rich groundmass. A. Plane-polarized light. B. Crossed nicols (5162/10). Magnification 6X.
Fig. 53. Porphyritic albite-rich volcanic fragment from light coloured volcanic breccia, B.F.B. (6316/4). Crossed nicols. Magnification 20X.

Fig. 54. Reworked volcanic breccia showing fragments of variable size and composition. A pyrrhotite fragment (P) is present near the top of the core. The black material is siliceous shale.

Fig. 55. Contact of intrusive albite porphyry (P) with G.M.D. (G).
to 2 cm long have been observed in these breccias and are possibly primary in origin. However, unlike the sulphides in "mill rocks" about some Canadian volcanic centres (Sangster, 1972), these sulphides are predominantly pyrrhotite with only minor chalcopyrite.

2.2.9 Porphyries and Porphyrites

In the early literature, the terms porphyry and porphyrite were applied almost indiscriminantly to all porphyritic rocks in the Kalgoorlie area regardless of whether they were extrusive or intrusive. Generally, the term porphyry was given to light coloured (white or pink) porphyritic rocks whilst the term porphyrite was given to darker coloured rocks with phenocrysts of hornblende in addition to plagioclase in a fine-grained feldspathic groundmass with trachytic texture (Thompson, 1913; Feldtmann and Farquharson, 1913 and Stillwell, 1929). O'Beirne (1968) suggested an alternative classification based on the normative mineralogy and textures. According to this classification, the mine porphyries are intrusive sodic rhyolites and the porphyrites are altered equivalents of the intrusive porphyritic dacites from Mt. Shea. However, O'Beirne points out that some samples from the Morrison dyke (at the southern end of the Golden Mile), previously described as porphyrite, contain abundant ilmenite suggesting that at least parts of this "dyke" are sheared G.M.D.

The chemistry of the porphyries and porphyrites has been studied in detail by O'Beirne. He has shown that these rocks belong to the calc-alkaline suite and are characterized by high Na₂O and Al₂O₃ and by high ratios of Na₂O to K₂O, K to Rb, and Sr to Rb. On the basis of major and trace-element geochemistry, O'Beirne concludes that none of the porphyries in the Kalgoorlie area are related to the internal granites in the greenstone belt.
Albite Porphyries

Cross cutting albite porphyry dykes are found in the Hainault, Kalgurli, South Kalgurli and Associated mines (Stillwell, 1929) and the author was shown another example in the Mt. Charlotte mine but in general, the dykes trend approximately parallel to the strike of the foliation and it is difficult to determine whether they are intrusive or not. Some of these conformable porphyries, particularly the pink ones with chloritic inclusions parallel to foliation (Thompson, 1913) may actually represent altered tuffs rather than intrusives; examples are the pink "porphyries" (2128/4 and 1795/4) in D.D.H. S.E.4 (Fig. 15, p.39) which have been described in the subsection on the G.M.D. Tomich (1974) also suggested that most of the conformable "porphyries" in the Boulder Dyke were tuffites (volcanogenic sediments with greater than 50 percent pyroclastic material). However, a white albite porphyry interfingered with units 8 and 9 of the G.M.D. in D.D.H. S.E.13 is probably intrusive as the dolerite shows signs of recrystallization near the contact (Fig. 55).

Porphyritic sodic rhyolite fragments in the B.F.B. were interpreted by O'Beirne as fragments of the intrusive albite porphyries. Light-coloured fragments petrologically similar to the mine porphyries were also observed in the B.F.B. by the author in both G.M.D. breccias (Fig. 18B) and acid to intermediate volcanic breccias (Fig. 54) and where these make up a considerable part of the rock, they are almost certainly the result of explosive volcanic activity as indicated in previous sections. It is conceivable that the explosive volcanic activity was accompanied by quieter intrusive activity in its closing stages. However, the B.F.B. and younger sediments (which are possibly equivalent to the Kurrawang Beds) at Wongi Dam have been intruded by porphyritic sodic rhyolite according to O'Beirne, so it is probable that intrusion occurred over a long period of time.
Porphyrites

The porphyrites or porphyritic dacites have been considered to be intrusive by most authors (including Feldtmann and Farquharson, 1913; Stillwell, 1929; O'Beirne, 1968 and Tomich, 1974) because of their generally transgressive relationship to the surrounding rocks; according to Stillwell (1929), porphyrites cut G.M.D. in the South Kalgurli mine and the Associated mine and occur in Paringa Basalt in the Associated Northern mine and the Crocus mine. However, Honman (1916) recognized hornblende-bearing rocks petrologically similar to the hornblende porphyrites described by Feldtmann and Farquharson (1913) interbedded with agglomerates and slates at Peysville (to the south of Kalgoorlie) and concluded that the hornblende porphyrite was a trachyte. The hornblende-bearing volcanic fragments in the intermediate volcanic breccia from D.D.H. S.E.4 (described previously) are likewise similar in appearance to the intrusive porphyrites. As in the case of the albite porphyries, this could indicate that explosive volcanic activity and passive intrusion were closely related or that intrusion extended over a considerable period of time.

Potassic Porphyries

O'Beirne has found pebbles of extrusive potassic rhyolite in the basal conglomerates of the B.P.B. at Lake Gidgi. A possible chemical equivalent of this was found in D.D.H. S.E.7 between the G.M.D. and Paringa Basalt (Fig. 17, p.42) but as the rock was highly altered and contained abundant sericite, the potassium may have been introduced. No unaltered potassium-rich porphyries were observed in the South-end drilling or mining area. The relationship of the extrusive potassic rhyolites to sodic rhyolites and porphyritic dacites is uncertain.
2.2.10 **Summary and Conclusions**

Serpentinized peridotites, high-Mg basalts and a layered sill with komatiitic affinities form the lower part of the Kalgoorlie succession. These are followed by the Paringa Basalt, a series of pillowed basalts and interflow sediments. The Paringa Basalt is Mg-rich at its base but has a tholeiitic chemistry in the upper parts, suggesting a genetic relationship between the komatiitic and tholeiitic suites.

The Paringa Basalt is succeeded by the G.M.D. The fact that the top of the G.M.D. at the southern end of the field is composed of volcanic breccias and tuffs clearly indicates that the upper part of the G.M.D. is, at least at the southern end of the field, extrusive. Chilled flow top breccias and the occurrence of fragments of G.M.D. in the overlying B.F.B. provide further evidence of the extrusive nature of the G.M.D. and the relative age of the G.M.D. and the B.F.B. The central Fe-rich units of the G.M.D. possibly represent a late stage differentiate which has intruded the volcanic pile. There is no conclusive evidence for the existence of more than one flow but if the G.M.D. breccia found in D.D.H. S.E.10 (3691/10) is a pyroclastic and not part of a breccia plug, then the G.M.D. would have to consist of at least two flows.

The coarse-grained texture of the G.M.D. differs significantly from the fine-grained, pillowled texture of the chemically similar Paringa Basalt indicating that they formed under very different conditions. The pillowled nature of much of the Paringa Basalt suggests that it was extruded under water. It is possible that the G.M.D. was extruded subaerially or in extremely shallow water. It is suggested that the presence of a limited amount of water resulted in localized explosive volcanic activity during the end phases of extrusion. Where volcanism was less explosive, normal flow-top breccias and chilled tops formed. However, it is possible that some of
the chilled margins noted by Gustafson and Miller (1937) and Travis et al. (1971) may be the result of failure of the G.M.D. to break through to the surface in these places.

The sedimentary lithotypes in the B.F.B. are remarkably similar to those described from modern tidal flat environments; the association of mud-chip conglomerates and evaporite-bearing sediments is indicative of subareal exposure and suggests conditions approaching those of modern sabkhas.

The association of evaporite-bearing sediments and bituminous black shales is also commonly found in ancient tidal flat deposits (Ginsburg, 1975) and is characteristic of many of the major oil-producing fields. Until recently, it was thought that evaporites were not deposited before Late Proterozoic times and some models for the hydrospheric evolution of the earth were based on this assumption (Cloud, 1968; 1972). However, there is evidence of major sulphate evaporite deposits in association with the mid-Proterozoic (1.6-1.4 b.y. old) Pb-Zn-Ag deposit at McArthur River, Northern Territory (Walker et al., 1977). In addition, barite has been reported from the Fig Tree Series, South Africa (Perry et al., 1971), anhydrite from the Fёdorovka Group in the Aldan Shield, Eastern Siberia (Vinogradov et al., 1977) and possible pseudomorphs after gypsum from the Onverwacht Group (3.4 b.y. old), Transvaal, South Africa (Lowe and Knauth, 1977). This suggests that sedimentation processes have changed very little since Archaean times.

Although the type sabkhas of the Persian Gulf are developed in almost pure carbonates because of the lack of terrigenous input, Kinsman (1969) has refined the definition of sabkha to include all salt flats which are inundated only occasionally; Kinsman thus regards the clay-rich tidal flat sediments of the Colorado-River delta area, Baja California as an alluvial fan-sabkha association. The mineralogy and geochemistry of the Kalgoorlie vaporitic sediments indicate that they, like the Baja California sediments,
are composed dominantly of clastic material. At Kalgoorlie, the presence of albite grains suggests that this material may have a significant volcanogenic component. However, there are some sediments which are quite rich in carbonate (see Table 8) and it is possible that there was originally a lot more carbonate present but that it has been lost as a result of silicification of the sediments.

Although halite encrusts most recent sabkha deposits, Kinsman (1969) points out that this is frequently only an ephemeral phase and may be leached away completely. In the Laguna Madre wind-tidal flats, highly organic black clay marks the position of former salt pans and it is possible that some of the carbonaceous shales at Kalgoorlie have a similar origin. The presence of oil in these shales is strong evidence of the existence of organisms in the environment.

According to Illing et al. (1965), Kinsman (1969), Miller (1975) and others, the formation of evaporite minerals is a diagenetic process and depends on the production of interstitial brines which in turn is controlled by the balance between evaporation and dilution of pore waters. An arid climate and high temperatures favour the development of evaporite minerals.

At Kalgoorlie, conditions favourable for sulphate formation must have existed for a long period of time as the sediments are very thick (with an intersection of 41 m in D.D.H. S.E.4 giving a true thickness of 38.5 m) and, if the evaporite-bearing sediments in D.D.H. S.E.13 are equivalent to those in D.D.H. S.E.4, the deposit has a width of at least 1000 m. Since evaporite-bearing sediments have been found in the mining area as well as in the South End Drilling, the deposit may extend for many kilometers.

One difference, possibly significant, between the Kalgoorlie sediments and modern tidal flat sequences, is the close association of the Kalgoorlie