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THE UKAPARINGA SCHIST:

A COPPER-BEARING BIOTITE SCHIST NEAR WILLIAMSTOWN, SOUTH AUSTRALIA

A THESIS PRESENTED BY

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ABSTRACT

The geology and mineralogy of a copper-mineralized staurolite-grade schist at Ukaparinga near Williamstown, South Australia, was investigated by field and laboratory studies including electron-probe microanalysis. The schist, named the Ukaparinga Schist, contains an average of 0.3% copper with values up to 5%; it has been mapped over a strike length of 2.5 kilometres. The schist occurs within metasediments correlated with the Lower Proterozoic Burra Group.

The mineralogy of the schist is relatively simple, the main constituents being quartz, biotite, muscovite, chlorite and sulphides; minor minerals which may or may not be present in different samples include: tourmaline, plagioclase, titaniferous hematite, leucoxene, rutile, sphene, apatite, carbonate, epidote, staurolite, magnetite and hematite. The main sulphide is chalcopyrite but minor pyrite also occurs; the sulphides are believed to be of syngenetic origin.

The sulphides were recrystallized during prograde metamorphism, and subsequently slightly saline groundwater percolating through the schist under oxidising conditions extracted some of the copper ions and allowed their migration and incorporation into vermiculite formed by the normal weathering of primary biotite, giving rise to a very refractory copper-bearing rock which forms the major part of the schist above the base of oxidation.

PREFACE

This thesis has been compiled from mapping, laboratory studies, and ideas of my own, and to the best of my knowledge and belief, contains no material previously published or written by another person, except when due reference has been made in the text. No part of this thesis has been submitted previously for the award of any other degree or diploma in any university or tertiary institution.

D.G. Jones

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INTRODUCTION

LOCATION

The Ukaparinga Schist occurs as a series of north-trending outcrops east of Williamstown, in the centre of the northern Mount Lofty Ranges about 36 kilometres north-east of Adelaide.

ACCESS

Williamstown can be reached by bitumen road from Adelaide either by the Lower North-East Road via Anstey's Hill, Chain of Ponds and Kersbrook (53 kilometres) or by the Main North Road to Gawler and thence via Sandy Creek (60 kilometres). Either way the journey takes about one hour (Fig. 1).

From Williamstown, a network of roads ranging from bitumen highways to dirt tracks provides vehicular access to all outcrops of the schist (Fig. 2). On rare occasions after particularly heavy rain the lower-grade tracks can be hazardous for conventional vehicles.

CLIMATE

The general climate is the so-called 'Mediterranean' continental type typical of the Adelaide Hills. The winter is relatively mild and the bulk of the rainfall occurs in this season, while the summer is hot and dry. Differences in local elevation and aspect are important factors controlling the micrometeorology, and since the area is one of high relief a great variability in the climatic environment over short distances is common (Fig. 3). The most variable part of the climate is rainfall (Appendix 1). At Williamstown, the local mean annual rainfall is 683.8 mm. (26.92 inches) but can vary from 1125 mm. to below 310 mm. (Table 1). Other climatic factors of temperature, humidity, wind, radiation etc. are less variable about the annual means, and are therefore less significant in their effects on the relatively stable landscape and ground cover.

TABLE 1

23752 WILLIAMTOWN P.O. 34 DEG. 40 MIN.S. 138 DEG. 53 MIN.E. ELEVATION 1000 FT.

********** RAINFALL (POINTS)

NUMBER	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
23752	1880	-	-	-	-	-	-	-	-	-	-	-	21	-
23752	1881	257	0	13	152	382	601	205	360	184	182	53	8	2397
23752	1882	8	0	39	282	284	238	435	410	155	204	187	47	2289
23752	1883	3	43	75	151	617	472	536	436	313	215	214	128	3203
23752	1884	225	11	235	231	446	570	60	392	447	299	61	138	3115
23752	1885	36	127	68	82	267	643	365	412	301	225	13	40	2579
23752	1886	186	55	0	188	125	103	418	576	335	515	194	77	2772
23752	1887	26	10	103	199	329	712	467	239	434	303	218	93	3135
23752	1888	21	10	27	30	436	477	643	121	159	18	69	38	2049
23752	1889	302	27	44	1091	393	912	212	645	359	279	143	23	4430
23752	1890	263	113	120	118	178	727	829	682	295	342	301	58	4026
23752	1891	92	11	110	107	31	279	534	327	147	343	140	178	2299
23752	1892	99	33	42	168	167	366	330	558	265	439	105	270	2842
23752	1893	0	0	33	402	583	772	317	459	548	227	295	43	3679
23752	1894	63	0	322	205	182	426	578	489	287	376	32	240	3200
23752	1895	98	14	57	498	64	410	577	348	212	136	0	117	2531
23752	1896	177	47	116	429	218	457	165	193	58	87	40	154	2141
23752	1897	22	98	63	120	236	299	273	453	343	39	52	5	2003
23752	1898	0	151	87	523	584	441	400	255	116	193	149	10	2909
23752	1899	144	173	111	270	277	506	69	141	222	103	242	33	2291
23752	1900	97	0	312	420	160	515	140	759	262	107	111	51	2934
23752	1901	125	10	23	201	111	619	255	157	230	381	92	107	2311
23752	1902	46	74	284	12	72	693	226	165	174	186	33	351	2316
23752	1903	38	160	124	462	137	549	421	240	312	71	344	200	3058
23752	1904	302	72	21	146	110	652	355	280	65	213	145	0	2361
23752	1905	121	0	0	425	262	587	559	243	123	482	0	0	2802
23752	1906	0	23	154	162	182	616	503	481	409	282	339	147	3298
23752	1907	0	41	76	374	178	276	359	405	177	187	299	54	2426
23752	1908	48	55	202	72	596	599	248	347	493	346	24	50	3080
23752	1909	100	89	101	469	646	358	506	665	206	278	246	69	3733
23752	1910	34	0	368	41	602	396	503	374	301	451	192	333	3595
23752	1911	8	140	13	66	300	448	266	148	255	85	14	222	1965
23752	1912	5	126	127	155	53	400	317	386	541	175	336	164	2785
23752	1913	7	303	215	78	75	36	140	323	287	260	138	97	1959
23752	1914	101	46	77	260	182	61	196	25	30	0	156	88	1222
23752	1915	83	0	35	201	511	563	254	363	425	146	22	28	2631
23752	1916	112	31	64	108	172	1126	365	584	176	232	357	67	3394
23752	1917	64	201	172	100	687	396	696	523	507	228	129	104	3807
23752	1918	27	51	70	117	342	314	281	295	75	222	29	30	1853
23752	1919	8	257	0	20	202	224	176	331	279	137	10	134	1778
23752	1920	39	0	108	38	244	680	300	472	269	243	299	191	2883
23752	1921	225	115	179	55	374	205	247	225	405	207	235	85	2557
23752	1922	211	15	5	116	566	259	490	320	185	185	0	434	2786
23752	1923	25	14	0	4	761	942	572	406	661	231	85	199	3900
23752	1924	109	203	139	78	295	489	91	365	441	443	207	41	2901
23752	1925	47	110	55	147	246	254	366	303	624	128	57	0	2337
23752	1926	0	84	11	290	795	350	455	826	271	625	116	44	3867
23752	1927	47	115	92	38	386	211	405	637	147	70	218	155	2521
23752	1928	136	287	124	126	346	458	358	85	250	468	31	35	2704
23752	1929	125	57	20	66	150	424	240	201	279	91	146	339	2136
23752	1930	5	73	4	142	134	81	577	477	320	317	117	90	2337
23752	1931	57	16	107	134	416	713	588	413	619	55	37	29	3184
23752	1932	34	108	122	334	139	851	442	412	186	318	71	51	3068
23752	1933	414	5	85	106	641	100	201	454	538	91	56	90	2781
23752	1934	117	2	42	144	7	97	185	304	361	331	288	58	1936
23752	1935	97	0	246	204	205	325	278	344	356	216	70	39	2380
23752	1936	46	87	5	190	261	198	380	256	67	238	64	227	2019
23752	1937	325	122	60	117	281	204	161	453	393	40	124	285	2565
23752	1938	78	228	15	707	62	200	289	346	81	57	60	23	2146
23752	1939	61	278	113	297	295	492	335	684	147	114	469	33	3318
23752	1940	144	48	58	449	202	85	337	200	228	61	126	88	2026
23752	1941	473	58	263	83	121	262	522	302	586	226	102	38	3036
23752	1942	127	26	33	261	554	579	376	487	447	131	186	100	3307
23752	1943	75	277	0	304	67	322	344	371	243	107	55	74	2239
23752	1944	30	58	20	182	395	67	289	44	46	276	230	150	1787
23752	1945	93	53	0	3	178	297	203	243	315	361	258	124	2128
23752	1946	179	422	220	119	282	235	491	216	121	170	110	261	2826
23752	1947	0	61	350	188	119	292	460	369	266	324	308	161	2898
23752	1948	8	21	34	470	375	280	291	494	69	513	227	168	2950
23752	1949	57	216	7	17	246	81	284	162	141	696	254	22	2183
23752	1950	16	205	26	38	688	211	142	258	210	190	136	46	2166
23752	1951	23	105	2	324	466	500	646	484	46	353	81	186	3216
23752	1952	176	12	0	313	657	379	217	272	354	302	454	93	3229
23752	1953	44	13	9	135	198	589	416	331	273	220	145	196	2569
23752	1954	52	7	58	441	131	272	247	123	124	232	87	233	2007
23752	1955	8	259	81	204	602	790	292	570	196	321	209	94	3626
23752	1956	56	6	44	453	638	805	574	426	454	220	80	38	3794
23752	1957	2	0	44	153	140	275	359	204	186	212	147	22	1744
23752	1958	0	15	132	41	584	66	377	367	370	473	40	40	2505
23752	1959	1	145	139	4	55	39	123	271	173	168	42	231	1391
23752	1960	30	265	121	435	936	205	282	361	473	102	165	0	3375
23752	1961	6	74	30	527	111	345	259	248	180	82	120	64	2046
23752	1962	119	40	119	3	504	298	267	320	162	537	64	121	2554
23752	1963	200	15	4	217	375	650	704	436	200	59	36	9	2905
23752	1964	52	31	11	232	98	410	637	260	378	363	223	99	2794
23752	1965	0	0	38	109	367	131	340	308	184	38	206	157	1878
23752	1966	40	96	165	42	235	338	572	208	444	192	123	320	2775
23752	1967	70	161	8	22	136	106	247	315	133	110	0	75	1383
23752	1968	174	172	117	170	760	430	363	495	158	494	265	160	3758
23752	1969	59	394	157	150	338	134	543	185	325	9	120	172	2586
23752	1970	211	2	27	232	226	464	346	656	297	27	122	138	2746
23752	1971	42	1	104	532	460	492	330	429	434	182	234	125	3365
23752	1972	181	71	1	188	117	-	-	-	-	-	-	-	-
SUMS	***	8296	7850	8057	19509	29344	36801	33019	32988	25323	21213	13229	10270	245320
MEANS		90	85	88	212	319	404	363	363	278	233	145	112	2692
NO. OF OBS.		92	92	92	92	92	91	91	91	91	91	91	92	

GEOLOGY

RECENT GEOLOGICAL HISTORY

The geography of the area is intimately linked with the recent geological developments. The area, in common with a large part of Southern Australia, formed portion of a vast peneplain which existed in early Tertiary (Eocene-Oligocene) times, and persisted for a considerable period (Hossfeld, 1935). During this time considerable depths of sand, clay and ferruginous gravel were deposited in the beds of lakes and streams on the low-lying countryside. The pre-Tertiary surface was thus buried and subsequently re-exposed due to the erosion of the Eocene rocks, i.e. it is a stripped or exhumed surface. Remnants of the Eocene surface are preserved in places throughout the Mount Lofty Ranges, including the Williamstown district, where Oligocene sands and gravels occupy some hilltops.

During the closing stages of the Tertiary, most probably in the Pliocene, wet and warm climatic conditions are thought to have prevailed (Jackson, 1957). This climate, coupled with the flat land surface, resulted in intense leaching of the Oliogocene soil materials, leading to the formation of leached sands, laterites, silcretes and kaolinitic clays. Following this period of leaching the orogenic movements which gave rise to the mountain ranges of Southern Australia broke up the peneplain. The eastern side of the Kitchener Fault was raised relative to the west, and large amounts of soil were washed from the eastern ("Warren") hills into the Williamstown-Kersbrook valley. The leached Pliocene materials, being uppermost on the hills, were eroded first and thus deposited first in the valley. They became buried by material weathered from the Precambrian rocks which are now exposed on the hills, the soil thus derived being deposited as alluvium and colluvium during Pleistocene and Recent times.

The activities, both past and present, of what is now the South Para River and its tributaries were superimposed on the deposition of alluvium. This has largely removed the deposits in the valley, and changed the nature of much which still remains.

Finally, a period of great drought or aridity occurred in Recent times, tentatively about 4000-6000 years ago (Jackson, 1957).

PHYSIOGRAPHY

It has long been appreciated that the major relief of the Mount Lofty Ranges is consequent upon the tectonic structure, and the Williamstown area is an example, as outlined in the recent geological history. The South Para River dominates the drainage of the area, all of which lies within its catchment. The river flows from east to west, the drainage pattern having been rejuvenated from the pre-Pliocene peneplain. It is notable that the ancient plain surface is much higher on the northern sides of the rivers and creeks than on the southern sides, and that the valleys cut into the Precambrian bedrock are asymmetrical, the northern valley side almost invariably being the steeper.

The rate of dissection by the antecedent South Para River is strongly influenced by the nature of the rock; quartzites and sandstones resist erosion to produce rugged topography which contrasts with the rounded ridges and gentle slopes produced from the more easily weathered rocks. The rugged gorges make good dam sites, and the reservoirs of Warren and South Para are important contributors to the northern Adelaide metropolitan and rural water supply.

The area may be divided conveniently into three broad physiographic units, the approximate boundaries of which are shown in Figure 4. These correspond with the Western Belt, Central Plains and Eastern Uplands respectively of Miles (1950).

(a) KERSBROOK FOREST RESERVE

This, the western part of the area, corresponds to the well exposed Barossa Complex, and consists of steep and very steep hills and narrow gullies. Most slopes are from 12° to 18° but there are some as steep as 30°. The gullies are frequently no wider than the small creeks which occupy them; there are no areas of alluvial flats. The drainage pattern is typically the youthful trellis type.

(b) WILLIAMSTOWN-KERSBROOK VALLEY

The central portion of the area is occupied by a belt of low rolling hills, moderate to gentle slopes, and rather broad valleys (Plate 1). In addition there are several quartzite ridges striking north-south which are somewhat steeper. In general slopes do not exceed

12° and there are significant areas of alluvial flats and gentle slopes of less than 5°. The maximum relief is about 80 metres. The drainage is more mature, the South Para River and its tributaries having a low gradient and consequently some of the flats are slightly swampy, particularly in the winter.

(c) WARREN RESERVE

This occupies the eastern third of the area, and overlies metamorphic rocks which frequently outcrop or lie at shallow depths below the soils, which in most cases are formed directly from them. The western boundary is marked by the Kitchener Fault zone.

Slopes are fairly steep to undulating, seldom exceeding 12°. Drainage is typically dendritic, at the middle stage of landscape development.

SOILS

The geological events outlined above have produced a great variety of soils, but they can be divided into major groupings on the basis of physiography and underlying geology. The outstanding common feature of the soils is the marked change in texture from surface to subsoil. The change is often, but not always, sharp and is a reflection of the higher clay content of the subsoils, versus the sandy to loamy nature of the surface. Shallow skeletal soils occur on the higher, quartzitic ridges, but are a minor constituent of the soil pattern.

The surface soils and a great majority of the subsoils are acid, only the Mount Crawford and Burra Western associations containing free carbonate. The pre-Mesozoic soils on the older rocks are all of the mildly leached soil groups (chiefly red-brown earths) while those derived from Tertiary and Quaternary sediments are strongly leached (mainly podzolic) soils.

PREVIOUS INVESTIGATIONS

1850 - 1900

Although copper was being mined near Williamstown as early as 1844, it was not until the gold rushes in Victoria in 1851 removed a substantial proportion of the population that the South Australian Government considered having the area examined by a geologist. Babbage in 1856 presented a report to the Chairman of the Gold Search Committee on observations made on the nature of rocks in districts including Williamstown. Although this was after the discovery of the Echunga goldfields, the prime task of his exploration was the search for gold, and he suggested the appointment of a geologist to look for gold. Accordingly, in 1859 A.R.C. Selwyn, then Government Geologist of Victoria, was invited by the South Australian Government "to visit the colony for the purpose of examining into and reporting on the geological evidence of the probable extent and character of its gold-bearing rocks, . . . coalfields and . . . Artesian water, and in general on the geological structure". (Selwyn, 1869). Previously Burr (1846) had written his "Remarks on the Geology of South Australia" in which he suggested that the Mount Lofty rocks belonged to the Primary strata, probably corresponding to the Cambrian of Sedgwick, because they were unfossiliferous, but his book has passed into obscurity.

Selwyn accepted the invitation and in May 1859 set out from Cape Jervis, spending two months hurriedly examining the rocks north as far as Mount Serle in the Flinders Ranges. He recognised three distinct and unconformable formations (Fig. 7), though the lack of fossils prevented him from elucidating their relative ages. Perhaps influenced by the association of the Victorian goldfields with Silurian slates, Selwyn hopefully suggested the rocks might also be Silurian, and this identification was continued by the South Australian Government geological mapping for over 60 years.

The youngest group, which were represented in the watershed of the Onkaparinga River and contained the Echunga goldfields, "were also to be found in the neighbourhood of Mount Crawford." Selwyn recommended the testing of the Mount Crawford gravels and quartz reefs for gold. He also recognised "granitic and hornblendic rock" intruding his second rock group, the "slates, shales and sandstones with intercalated gneissose, euritic and micaceous schists, bands of quartz rock, and crystalline limestone" at certain localities from the Gawler River to Port Elliott, including the Mount Crawford-Pewsey Vale area. He commented that the rock differences "could be due to the metamorphic influence of the granite." (Selwyn, 1860).

It was ten years before Selwyn's predictions were proved correct. In October 1868 Job Harris "and mates" found gold in Spike Gully, and the richest diggings yet discovered in South Australia, the Barossa and Para Wirra goldfields, were pitted like anthills by hundreds of eager diggers.

Two years after the publication of Selwyn's report to Parliament, the Rev. J.E. Woods (1862) published his "Geological Observations in South Australia". Although concerned with the southeastern portion of the State, Woods reinforced Selwyn's opinion that the oldest rocks were Silurian by citing fossil evidence, particularly a "Cruziana cicurbita" found by his brother near Nuriootpa. However, in his "Manual of Geology", 2nd edition 1862, Jukes stated that the gneisses and mica schists of the Australian mountain chains were Pre-Cambrian.

The Philosophical Society of Adelaide published its first Transactions in 1878, and this Society, which two years later became the Royal Society of South Australia, stimulated greatly the scientific activity in the State. One of its foundation members was Gavin Scoular, the first geologist to examine the northern Mount Lofty Ranges in detail. Scoular (1878) criticised the "slender evidence upon which the Rev. J.E. Tenison (sic) Woods identifies . . . (the Barossa Range rocks) . . . with the Silurian . . . ." Later, Scoular (1880) cited the discovery of "Lower Silurian fossils in beds unconformably overlying the slaty cupriferous group of Selwyn" at Ardrossan to prove that the Barossa rocks were at least pre-Silurian and probably pre-Cambrian. He was ignored.

Scoular was a meticulous and accurate observer who made enormous contributions to an understanding of the Ranges, but curiously his work seems to have been forgotten. Later he described (Scoular, 1879) and subdivided correctly the section along Tenafeate Creek, the section which Howchin re-described in almost identical detail in 1926, but Howchin is given all the credit for unravelling the secrets of the base of the Adelaide System. From his detailed survey of the section "from the junction of the Para and Tenefete (sic) Creek" to three miles east of the junction with Victoria Creek, Scoular suggested that the rocks were "merely the eastern buttress and spring of a once stupendous arch of strata, which in times long past extended far to the west in a grand anticlinal curve." Although wrong in this opinion, he at least recognised the importance of folding in the formation of the Ranges, and also his deduction that the ultimate source of the Barossa gold was "vein deposits filled by hydrothermal action" (fissure filling) is probably correct. His geological map of the eastern half of the Hundred of Munno Para and the Barossa Goldfield on a scale of one inch to one mile pre-dates Brown's by five years. The section he drew from Smithfield Railway Station to the Humbug Scrub sanctuary is substantially correct; it is at least as good as Howchin's.

The Barossa goldfields had suffered their demise, and most of the diggers scattered or moved to the new discoveries at Watt's Gully, before the Government Geologist H.Y.L. Brown first reported on the Williamstown area (Brown, 1885). Brown produced a geological map of the district incorporating some of Scoular's mapping (for which he gave Scoular no credit), and although his report deals mainly with the gold drifts, he mapped and commented on the highly metamorphic basement rocks, and wrote a plausible account of the Tertiary river systems in the area based on his mapping of "outlying patches of Tertiary sand, gravel and clay . . . which have escaped denudation."

The Assistant Government Geologist reported on the Gumeracha and Mount Crawford goldfields (Woodward, 1886). Again the report naturally was mainly concerned with the gold-bearing Tertiary deposits, "lying directly on the old Palaeozoic and metamorphic rocks, which latter are here greatly broken and altered by numerous granite dykes.' Once again the basement is mapped as Silurian.

1900 - 1950

A twenty-year hiatus in the steady stream of geological comments on the Williamstown area was broken only twice. In 1889 the Inspector of Mines visited the Ukaparinga mine, long since defunct, and described the workings but not the geology (Brown, 1908). Professor Tate (1893) in his Inaugural Address to the Australasian Association for the Advancement on Science, made a passing reference to the generalisation of placing all crystalline rocks in the Silurian, saying this had been broken down by the discovery of unconformably superimposed Cambrian. Tate concluded that there was good reason to believe that the Barossa rocks were Archaean.

Howchin (1906) read a paper in which he corrected the Silurian dating for the older rocks of the Mount Lofty Ranges. His well-reasoned argument included the unconformity between his basal grits (which he dated as Cambrian) and the underlying Precambrian augen-gneisses near Menzies' Barossa Mine in the South Para River. Howchin described in detail the basal grits along the road from Williamstown to Mount Crawford, commenting on their metamorphism, the presence of "ilmenite" strikingly outlining the current bedding, and the common isolated large rounded pebbles in the grits. The first observation that these eastern metamorphosed basal grits were underlain by highly foliated Precambrian beds "of a very coarse pegmatite, penetrating a true mica schist (mostly biotite) with accessories of beryls, tourmalines, and other minerals" occurs in Howchin's paper. Although the exact junction was not seen "the change is abrupt and strongly defined" (Howchin, 1906).

Woolnough (1908) gave the name "Barossian" to the beds on the east side of the Mount Lofty Ranges assuming them to be older than those on the west which he called "Adelaidean". These beds are now referred to as the Kanmantoo Group.

Howchin (1925) gave the most comprehensive account of the area to that date. He rejected Woolnough's concept and suggested the name "Houghtonian" for the Barossa Complex rocks, on the basis of work published in 1909 by Benson on the petrology of the rocks near Houghton. Howchin repeated his 1906 description of the rocks east of the Kitchener Fault, and correlated them with the unmetamorphosed rocks to the south in the Torrens Gorge, and also those west of the Barossa Goldfield, particularly along Tenafeate Creek. No mention was made of the rocks between the present South Para dam and the Kitchener Fault, which fall within Howchin's "Axis" of the Mount Lofty Ranges. The assumption is that he believed them all to belong to his "Houghtonian". Howchin does record the basal grits overlying the "Older Series" in Dead Horse Gully.

Hossfeld (1934) presented a most important paper covering a wide area of the northern Mount Lofty Ranges, including the Williamstown district. In it he described the origin of the present Mount Lofty Ranges as a Tertiary peneplain uplifted by block faulting, and his maps are the first to show many of these faults. Hossfeld also corrected earlier writers by observing that the Palaeozoic folding was tight, in many cases isoclinal, and the overturning of the beds was the cause of much earlier confusion. He subdivided the Precambrian into three distinct periods, reverting to Woolnough's "Barossian" for the oldest, giving the term "Para Series" for the Lower Adelaide Series of Howchin, and "Narcoota Series" for Howchin's Upper Adelaide Series. The essentially sedimentary nature of the Barossa Range rocks was demonstrated by Hossfeld, and he recognized that although both the Humbug Scrub rocks (now Barossa Complex) and "Barossa Ranges" rocks (those around the Warren Reservoir) were pre-Adelaide Series, they were entirely different rock groups. Howchin's inference that the rocks in the Williamstown-Kersbrook valley were Houghtonian was corrected by Hossfeld, although Hossfeld incorrectly placed all the rocks from the Kitchener Fault east to Springton in his Barossa Series, while Howchin had correctly correlated those above the basal grits with his Adelaide Series rocks.

The puzzling presence of pebbles in the well-sorted beds of the basal grits was explained by Hossfeld as a normal consequence of a sediment formed along a shoreline (Plate 24). He also summarized comprehensively all the mineral deposits in the area.

Alderman (1938) suggested that the augen-gneisses in the Humbug Scrub area, "are the result of a period of intense injection-metamorphism followed by a period in which the metamorphism was of the dynamic type". He followed this (Alderman, 1942) with a study of metamorphism of the area immediately north of the Warren Reservoir in which he ascribed the formation of sillimanite and kyanite to alumina metasomatism. Alderman stated that the intense metamorphism of that area was quite local, the general grade of regional metamorphism being that of the biotite zone.

Sprigg (1945) published a paper on "The Geomorphology of Portion of the Mt. Lofty Ranges" in which he amplified the theory of the development of the Ranges as a fault-block system. His key plan includes the first publication of the name Kitchener Fault for the major high-angle meridional fault in the Williamstown area, and in a later paper (Sprigg, 1946) he suggested that this and other similar faults in the Ranges had been activated three times since the early Palaeozoic, the latest being the Tertiary "Kosciusko Epoch". Sprigg also described in detail the development of the early Tertiary peneplain and the subsequent cycles of burial, faulting and erosion from which the present land surface has evolved.

1950 - 1970

Spry (1950) mapped the "Houghton Inlier" (Barossa Complex) as part of an investigation of the genesis of the "Houghton Diorite". He concluded that it was in fact a metamorphosed sedimentary series. Spry disagreed with Hossfeld's assumption that the basal beds on the eastern and western sides of the Barossa Complex were of different ages. He recognised that three orogenies had affected the area; the first in the Archaean producing ptygmatic folding, the second (Palaeozoic) orogeny producing a pronounced regional schistosity parallel to the axes of the Archaean folds as well as extensive folding and faulting of the Adelaide System, and finally a Tertiary uplift revealed by large-scale faulting. Spry agreed with Sprigg that the faults originated in the Palaeozoic and were re-opened in the Tertiary.

Miles (1950) published the first detailed geological investigation of the Williamstown area. The water resources of the South Para River had been recognised since the first weir was constructed in 1902 near the present dam site. In 1940 geological investigations commenced on the proposed South Para Dam Site, culminating in the publication of "The Geology of the South Para Dam Project" in 1950. In this report Miles gives a strictly factual description of the rock types encountered in the area to be covered by the dam, concentrating on the engineering characteristics of the Barossa Complex rocks on which the abutments, foundations, spillway area and diversion tunnel were to be constructed. His maps and descriptions are a salutary example of correctness and factual detail.

The rapid increase in consumption of talc and the importance of South Australia in its production led to an investigation of the State's talc resources by the Mines Department. Mention is made of a talc deposit 1.6 kilometres ENE of Williamstown, its origin being ascribed to albitization of schists and marbles, and replacement of these by talc (Whittle, 1951). Whittle noted that the talc is associated with copper carbonates in a sequence immediately overlying the basal "ilmenitic" grits.

Campana (1953) favoured a metasomatic origin for the mica schists and granites in the Williamstown district, and suggested that the structure of the Mt. Lofty Ranges was due to an Early Palaeozoic orogeny folding the sediments under lateral compression. He said the Tertiary faulting "is related to a reactivation of the Early Palaeozoic folding".

Freytag (1957) mapped a small area immediately north-east of Williamstown as part of a study of the marbles in Victoria Creek. He correlated the basal arkosic grits with the Aldgate Sandstone, the dolomitic sequence with the Lower Phyllite, and the quartzites to the east with the Thick Quartzite of Howchin.

Mills (1963) considered the Mt. Crawford Granite Gneiss "to be the result of synkinematic granitisation of metasediments", and related the zone of retrograde metamorphism and hydrothermal activity surrounding the granite gneiss to the granitisation. Mills regarded his Sandy Mica Schists (Warren Schist) as a sedimentary facies variation stratigraphically underlying the sandstone (basal arkosic grit).

The modern approach to metamorphism and structure in the area pioneered by Mills was continued by Talbot (1963), who reported that the Barossa Complex rocks had undergone at least three periods of metamorphism, and that two or more phases of folding had affected the overlying Upper Precambrian rocks. Offler (1966) amplified these studies, and he recognized three phases of deformation, each accompanied by the formation of foliation, in the Upper Precambrian rocks.

RECENT INVESTIGATIONS

The present studies date from 25 November 1965, when Igor Moisseeff pegged claims over the area of the old Ukaparinga mine. Moisseeff and his partner, Niki Iwanow, in 1965-66 did considerable bull-dozing, some shaft-sinking and costeaning, prior to setting up a small plant for acid leaching. They selected about 150 tons of high-grade (5-6%) ore which they leached in concrete-lined troughs excavating on the leases, and produced 4½ tons of cement copper averaging about 55% copper, representing 30% recovery.

Between 1965 and 1966 the S.A. Mines Department financed considerable metallurgical work by AMDEL on behalf of the leaseholder. Attempts were made to concentrate the ore by gravity and flotation concentration and comprehensive treatment tests using percolation and agitation leaching were tried. Other experiments included recovery of copper from solution using lime, and using iron, and extraction tests by leaching after chloridizing roasts. None of these tests was entirely satisfactory, and results varied surprisingly with ore from different localities on the leases. AMDEL were, however, confident that a solution could be found but the Mines Department could not justify further expenses until sufficient tonnage of ore had been proved.

In conjunction with the above work the Mines Department carried out geological mapping and sampling of the deposit, and concluded that it contained 376,900 tons grading 0.77% copper. The copper was seen to be sporadically distributed throughout steeply dipping mica schist "regarded as overturned metamorphosed Burra Group beds resting on the Aldgate Sandstone" (Blissett, 1964).

Three induced polarization reconnaissance lines were run over the prospect in 1966 by Mines Exploration Pty. Ltd. in the course of a general reconnaissance of prospects in the Mt. Lofty Ranges. A few weak anomalies were obtained, but were not followed up.

The prospect was optioned to Aminco Pty. Ltd. in March 1966, and under the direction of their consultant, D.K. Sault, the company did some geochemical sampling, trenching and underground sampling in the main adit. A total of 72 samples was taken. Their conclusions were that optimistically the prospect contained 300,000 tons of about 1.2% copper. Leach tests done on their behalf by AMDEL suggested acid leaching as the best method of recovery, the operating costs approaching $6.15 per ton of ore then valued at $8.00 per ton. On this basis Aminco relinquished their option.

Aminco were followed by Mr. Warwick of Andamooka Enterprises who took an option over the leases in 1967. He carried out considerable exploratory surface excavation, sampling and extraction tests. Seven vertical holes were drilled in the top of the hill to a depth of 15 metres using a Gardner-Denver Airtrak. Apparently his requirement of 200,000 tons of 2% copper was not met, for he also relinquished the option.

The mine lay idle until 1969 when Crane Enfield Metals Pty. Ltd. purchased the leases from Moisseeff under a complex option arrangement. Detailed exploration commenced in August 1969 under the supervision of the author as Chief Geologist and Exploration Manager of G.E. Crane Holdings Ltd.

The lease area was mapped on a scale of 1" = 20 feet, and geochemical soil samples taken over a 100-foot grid. Sampling of the underground workings was also undertaken. A total of 47 percussion drill holes aggregating 2,000 metres were drilled over the deposit, followed by six diamond drill holes totalling 930 metres. On this basis ore reserves were calculated as 3 million tons of 0.7% copper, including 600,000 tons of 1.32% copper. Extension of the mapping and geochemical sampling, and a magnetometer survey, lead to the discovery of a similar deposit (the Southern Hills Prospect) 800 metres south of the Ukaparinga adit. Exploration of this deposit by 37 percussion holes totalling 1978 metres and five diamond drill holes totalling 886 metres indicated reserves of 1 million tons of 1.2% copper. Regional exploration north of Ukaparinga located another copper deposit in Ukaparinga

Schist (Rollick's Prospect) and the presence of copper carbonates in equivalent schist in several localities east of Williamstown.

Pilot plant leach tests on Ukaparinga ore confirmed that recovery of copper from the oxidised ore was too low to be economic, and since the success of the project depended on good recovery from this ore, a comprehensive metallurgical and mineralogical test programme was initiated. Conventional leaching and flotation, chloridising roasting followed by acid leaching, and ammonia leaching having proved unsuccessful, the CSIRO was given the task of finding some economic method of recovering the copper from the ore.

Between August 1970 and January 1972 an investigation of leaching behaviour was made by Mr. J.T. Woodcock, Principal Research Scientist in the CSIRO Division of Mineral Chemistry, in conjunction with the author. It was found that the low acid leaching yield was not substantially improved by finer grinding, the addition of ferric sulphate, or extending the leach time to as much as three days. Oxidising roasting, reducing roasting and ammonia leaching proved ineffective, but hot acid leaching with the addition of manganese dioxide improved extraction markedly. Other techniques tried included segregation and acetonitrile leaching, and leaching with six different types of halogen hydrothermal solutions under varying conditions. Only in the most severe leaching conditions was significant extraction achieved.

To provide information on the likely metallurgical behaviour of the Ukaparinga Schist, a concurrent mineralogical study under the author's direction was undertaken using optical microscopy, electron-probe analysis and X-ray diffraction studies to examine the distribution of the copper in the ore and leeched ore samples. This work was done both at the CSIRO and by Dr. Keith Henley at AMDEL, working closely with the author. The results suggested that a substantial portion of the oxidised copper was incorporated in the mica lattice, the mica being an interstratified vermiculite-biotite (hydrobiotite). Up to 3% copper was distributed throughout the vermiculite, probably in the interlayer or octahedral sites, and from the leaching behaviour was obviously very firmly held in the lattice. Electron-probe analysis of biotite in the unweathered ore showed no detectable copper (0.05%) and suggested that the copper in the vermiculite was of secondary origin. Hydrothermal leaching showed that the copper was absent from the biotite portion of the interstratified mica in the oxidised ore.

The information gained from this investigation of the Ukaparinga Schist forms the second part of this report, and the knowledge gained may be of considerable significance in the understanding of the formation of this and other, similar, ore deposits.

REGIONAL GEOLOGY

Williamstown is centrally located within the belt of folded and metamorphosed Precambrian to Lower Palaeozoic rocks which form the Mount Lofty Ranges, a structural high bounded to the east and west by Cainozoic sediments. The Mount Lofty Ranges rocks were deposited in part of a great synclinal trough (the Adelaide Geosyncline) extending from and beyond Kangaroo Island in the south through the Flinders Ranges to the north, thence northwest to the Peake and Denison Ranges and north-east to Broken Hill (Fig. 8). These sediments accumulated to more than 25,000 metres in thickness, yet the general conditions of sedimentation were those of relatively shallow water, hence the basement must have been gradually subsiding during sedimentation over a period of more than 800 million years from the Late Proterozoic to the Cambrian (Ludbrook and Johns, 1970). The sediments are believed to have been derived from the shield area to the west known as the Gawler Block, an extension of the crystalline basement of the Western Australian Shield (Parkin, 1969).

During the Cambrian a deep trough with steep margins developed along a number of fault lines in the southeastern part of the Adelaide Geosyncline, stretching from Kangaroo Island to Kapunda. In this Kanmantoo Trough were deposited rapidly some 18,000 metres of fine-grained deep-water sediments. These mark the end of deposition in the Adelaide Geosyncline before it was affected by crustal movements in the early Ordovician, when major folding and mountain-building movements formed the Mount Lofty and Flinders Ranges. During this orogeny granites dated at 490 million years were intruded (White _et al_, 1967), and metamorphism produced rocks of biotite grade over wide areas (Offler and Fleming, 1968).

A long period of erosion followed, which included a major continental ice age in the Permian (Parkin, 1969). The crustal troughs to the east and west of the Ranges began to develop in the Permian, and were mobile through the Mesozoic and Tertiary to the present (Parkin, 1969). Within these troughs mainly marine sediments were deposited (Fig. 9).

STRATIGRAPHY

The stratigraphic succession of the area investigated is complicated by a clear subdivision into two separate sub-areas on either side of the Kitchener Fault. The relatively unmetamorphosed rocks west of the Fault can be correlated reasonably well with the Torrensian Burra Group rocks, and in some cases can be traced through to the type areas near Riverton and Saddleworth. East of the Fault high-grade regional metamorphism has obliterated the original sedimentary features, and although the rocks clearly belong to the lower part of the Adelaide System they cannot be traced continuously into the type areas. Hence the rocks are discussed in two separate sections, and an attempt is made at correlation between the two.

WEST OF THE KITCHENER FAULT

The Lower Proterozoic Barossa Complex schists and gneisses are overlain unconformably by a sequence of lagoonal to shallow marine sediments correlated with the Torrensian Burra Group (Fig. 10). The sedimentary sequence commences with a clastic unit followed by a dominantly siltstone succession with a high proportion of sandy sediments, which terminates abruptly against the Kitchener Fault. The best exposures of these units are found along the banks of the South Para Dam when the water level is low, the action of waves on the surface of the water having laundered the rocks to facilitate observation.

BAROSSA COMPLEX

These crystalline rocks are generally accepted as the partly exposed surfaces of the basement block of the eastern edge of the Western Australian Shield (Thomson, 1970). Radiometric determinations indicate an age of at least 1,500 million years for equivalent rocks on the Gawler Block, but since these represent metamorphism the rocks can be expected to be much older (Compston, et al, 1966). They consist of high-grade schists and gneisses which have been exposed in the core of a broad anticline. The rocks resemble the Cleve Metamorphics of the Gawler Block (Thomson, in Parkin, 1969). Talbot (1963) showed that the rocks had undergone at least three periods of metamorphism, the earliest raising them to the upper amphibolite facies and two successive periods retrograding them to the lower greenschist facies. The two retrograde periods occurred prior to and after the deposition of the overlying Torrensian sediments respectively (Talbot, 1963).

The original nature of the rocks is problematical, the metamorphic events having destroyed any evidence of their principal texture, mineralogy, etc. However, it is my opinion that they were a normal, probably fairly lithologically variable, arenaceous and argillaceous sedimentary sequence. This can best be demonstrated by a traverse through the "metasediments" exposed in the South Para Gorge (Fig. 11).

The petrology of the rocks comprising the Barossa Complex exposed in the mapped area is quite variable, but they can be divided into four distinct units, which have been differentiated as follows:

(a) "Augen" gneiss
(b) Phyllonites
(c) Feldspathized schist
(d) Undifferentiated gneisses and schists.

(a) "Augen gneiss

This distinctive gneiss occurs on the north-western boundary of the mapped area, in the central part of the Barossa Complex. It was first mapped by Hossfeld (1935) and described in some detail by Alderman (1938).

The gneiss generally outcrops strongly, and forms the more rugged part of the South Para Gorge downstream from the old weir. An excellent exposure can be seen in the quarry downstream from the weir, adjacent to the road leading to Para Wirra National Park (Fig. 11).

In hand specimen it is a fine to medium grained, light grey to pale green rock which weathers yellow-brown. It is well foliated with distinctive quartz-feldspar augen. These augen range from 1 to 10 cm in size and are always orientated parallel to the foliation (Plate 5).

The pegmatitic appearance of the augen plus their alignment parallel to the foliation prompted Howchin (1906) to suggest they were formed from pegmatitic solutions injected along planes of weakness in the rock. The evidence against this proposal is that there are no pegmatite dykes or suitable granitic bodies in the vicinity to act as sources, and for such a considerable volume of pegmatitic material to be finely injected, a wide-spread source would be essential. An alternative to a granitic source would be a metamorphic-derivation of the pegmatitic solutions from the enclosing rocks, accompanied by segregation and slight permeation along cleavages and other planes of weakness.

However, a microscopic examination of the gneiss shows that such an explanation is also not totally feasible. The quartz-feldspar augen are intimately associated with the surrounding fine sericitic-quartz ground mass and gradational boundaries are common (Plate 6). Furthermore, feldspar grains within the fine sericitic groundmass are nearly always highly fractured, with fine sericite occupying the fractures, while the coarser feldspar grains belonging to the augen are relatively undeformed. Taking these features into account, the only feasible explanation would be a mechanism involving shearing with partial mylonitization and microbrecciation, along with retrogressive metamorphism of an originally coarsely crystalline massive gneiss. The partially mylonitized zones are represented by the groundmass of fine sericite, strained and fractured quartz and feldspar grains, while the relatively unsheared zones are represented by the coarser quartz-feldspar augen. The variations in size and abundance of the augen within the unit reflects variations in the degree of shearing and mylonitization.

The gneiss is predominantly composed of fine quartz and sericite within which are enclosed relics of quartz, microcline, muscovite and rarer plagioclase, along with augens of coarser quartz-feldspar grains. The extremely fine sericite, which in some cases constitutes up to 40% of the rock, is a typical product of combined mylonitization and retrograde metamorphism of feldspars, biotites and other aluminium silicates *(TS 4660). The sericite flakes appear to be aligned parallel to the foliation and often fill fractures developed in feldspar and quartz grains and to a far lesser extent occur as inclusions in feldspar grains. The considerable percentage and alignment of the extremely fine sericite often gives the gneiss a schistose appearance. Titaniferous hematite makes up 5 to 10% of these rocks (Table 2); the grains are usually ragged and less than ½ mm. in size and in some cases iron has been liberated from them to produce a ferruginous strain in the enclosing sericitic matrix. Very fine hematite often forms "tails" on larger grains which further emphasises the fact that these rocks have undergone considerable mylonitization and microbrecciation. Euhedral titaniferous hematite grains are rare, but if present they are thought to represent secondary recrystallization or grains that were not mylonitized. Quartz grains range in size from 0.1 to 2 mm. and occupy 20 to 60% of the rock. Almost all the quartz displays undulose extinction and many grains are considerably fractured. Microcline is the most abundant feldspar although traces of plagioclase were observed in some sections. Feldspar commonly comprises 20 to 30% of the rock but in some of the sections is completely absent. In cases where feldspars are completely absent the rock can be satisfactorily names a Quartz-Sericite Gneiss. Such gneisses are rare and occur as irregularly spaced parallel bands within the Feldspar-Quartz-Sericite Gneiss.

Some specimens display a rare "porphyroblastic" texture, with quartz "porphyroblasts" up to 1 cm in diameter (Plate 7). In hand specimen this texture can be easily confused with a true metamorphic

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*(TS 4660) refers to thin section number 4660, described in detail in Appendix 7. This convention will be followed throughout the thesis.

porphyroblastic texture. However, on microscopic examination it is found that the "porphyroblasts" have not grown in the groundmass but instead the previously enclosing grains have been altered to fine sericite through mylonitization and retrogressive metamorphism, leaving only the large quartz grains intact (TS 4662).

Thin bands of quartzite scattered within the augen gneiss were observed along a section of the South Para Gorge. These bands are up to 50 cms long and 10 cms wide and are orientated approximately parallel to the foliation and give the gneiss a bedded appearance. Similar layering was observed by Talbot (1963) in the Houghton area, where it was originally mapped as part of the Torrensian sequence. Spry (1950) proposed that this type of layering was of sedimentary origin and concluded that the gneisses and schists of the Barossa Complex are of sedimentary derivation.

The augen gneiss found in the area corresponds closely to Spry's (1950) "Humbug Scrub Gneisses" and Talbot's (1963) "Blastomylonites and Phyllonites" of the Houghton area.

(b) Phyllonites

Continuing upstream from the quarry, the augen become progressively smaller and the rock type grades into a micro-augen gneiss resembling a phyllite. This is equated with the phyllonite of Talbot (1963).

The segregation of minerals is less pronounced, the foliation planes becoming more even and regular (Plate 8). Quartz is more abundant, inter-leaved with dark green biotite and lighter feldspar. Epidote, actinolite, and diopside are found in some areas arranged along the foliation, and, where the mineral is abundant, forming cross-cutting veins. The degree of iron-staining is higher than in the augen gneiss, and in some areas micaceous hematite can be seen. Framboidal pyrite altered to marcasite was noted in some rare specimens.

In thin section the gneiss is rich in quartz, feldspar, muscovite and sericite with traces of biotite and opaques. The quartz grains can be quite coarse (up to 2 mm.) and comprise approximately 50% of the rock. Most of the grains show undulose extinction but unlike those in the augen gneiss, fracturing of grains is rare.

The dominant feldspar is plagioclase, which displays excellent multiple twinning, some of which is deformed. The feldspar grains only rarely show fracturing. A dark brown-green biotite is present as very ragged laths, often as intimate intergrowths with muscovite and containing inclusions of zircon. The flakes appear to be roughly oriented and concentrated in bands of 1 to 2 mm. across and comprise 15% of the rock. About 10% fine sericite is typical and the flakes appear to have no preferred orientation and are unevenly disseminated through the rock. Portions of the phyllonite are totally devoid of sericite and display a mosaic of interlocking quartz, feldspar and muscovite grains (Plate 9, TS 4663).

(c) Feldspathized Schist

Upstream from the weir, a quite distinctive change occurs from the largely unaltered phyllonite to a highly schistose rock, with abundant zones and lenses of silicified schist and quartzite. This unit makes up the bulk of the Barossa Complex within the mapped area.

The rocks have suffered considerable surface alteration, and now consist of thin kaolinized quartz-feldspar lenses interlaminated with phyllonite. Lenses up to 5 metres wide consisting of hard, blocky, fractured sugary quartz schist can be traced over lengths of 230-260 metres. The north-south trend and steep easterly dip of these lenses is identical to the foliation, which is remarkably uniform throughout the area mapped.

Alteration is clearly due to weathering, as progressive changes can be observed from kaolinized schist at the surface to fresh rock at 25-30 metres below ground level in the excavations for the South Para Dam. In thin section the unweathered rock is a quartz-muscovite-feldspar schist or gneiss, consisting essentially of isolated grains of quartz, feldspar and coarse muscovite set in a fine matrix of sericite and chlorite (TS 4676-79).

Quartz grains average about 0.5mm., elongated along the schistosity planes and often fractured at right angles to them, the interstices of the fractures being filled with fine-grained sericite. Most grains exhibit strain extinction.

The amount of coarser muscovite increases with the amount of quartz and feldspar, and the grain size is similar. The cleavage plates parallel the schistosity, and minute aggregates of rutile commonly occur between plates. Fine-grained muscovite up to 0.05mm. long, commonly altered to sericite, occurs in the matrix, together with rounded zircon grains and rare apatite.

The main feldspar is K-feldspar, rarely showing incipient alteration to sericite but generally quite fresh in appearance. Some plagioclase (oliogoclase) and apatite are associated with the K-feldspar, the general grain size also being about 0.5 mm.

The opaque minerals are chiefly martite or hematite after magnetite, the hematite commonly showing traces of alteration to limonite. These grains commonly occur in bands parallel to the schistosity, and associated with the hematite-rich bands are occasional tourmaline crystals up to 2 mm. long. Greenish-brown biotite flakes often rim the iron oxide grains.

A variation of this rock type occurs as a linear outcrop in the southern portion of the mapped area. It is more gneissic and resistant to weathering and protrudes as a ridge striking 030°, with a width ranging from 100 metres to 300 metres. It is generally more coarse-grained, and in hand specimen is a creamy-brown colour, with thin veins of hematite. The constituents are about 70% albite, 15% biotite, 10% sericite and minor opaques. The albite twins are stressed, being bent and even displaced in some cases. The sericite occurs as selvages along albite cleavages, twin boundaries and grain boundaries.

In some areas of poor outcrop in the southern part of the area, a quartz-mica gneiss consisting of 30% quartz, 30% albite, 20% sericite, 15% micas, 5% microcline and minor garnet, actinolite, sphene, tourmaline and rutile was located.

(d) Undifferentiated schists and gneisses

Where outcrop was insufficient to positively identify a rock as one of the above units, it was recorded as "undifferentiated". The schists were commonly a light grey colour and were usually well foliated. Outcrops were very sparse, but schist was seen in a road cutting in the extreme south of the area. It consisted mainly of sericite, chloritized biotite and minor quartz and feldspar. Some relict feldspar grains could still be seen, although now entirely replaced by sericite. Only minor quartz was present but commonly the strained quartz occurred as lens-like stringers, parallel to the schistosity.

BURRA GROUP

Throughout the Mt. Lofty Ranges, the Lower Proterozoic Barossa Complex basement inliers are bounded on the west by faulted unconformities, and unconformably overlain on the eastern side by a conglomerate (Plate 10), marking the commencement of a major cycle of sedimentation. This pattern is followed by the geology exposed in the mapped area.

The unconformity indicates a period of erosion before the deposition of the overlying sediments. That this period was of considerable length is suggested by the presence in the overlying conglomerate of boulders of Barossa Complex gneiss which had suffered two periods of metamorphism before sedimentation recommenced (Talbot, 1963). This prolonged erosion was terminated by a fairly abrupt marine transgression, as shown by the nature of the conglomerate discussed later. A shallow-water marine sequence at least 3500 metres thick was laid down within the mapped area.

At the base of the sequence is a unit which on stratigraphic, petrological, mineralogical and textural features can be recognized as the equivalent of the Rhynie Sandstone of Wilson (1952). His description of the rocks of the Adelaide System developed in the Clare-Riverton region, 65 kilometres north of Williamstown, is accepted as the type description of the Burra Group (Thomson, 1964). The upper member of the Williamstown sequence (the Saddleworth Formation) can be traced continuously through to Wilson's type area, and other units can be similarly traced but with some discontinuities, hence the correlation with the Burra Group seems reasonable. The equivalent units in the Torrens Gorge type area of Mawson and Sprigg (1950), 25 kilometres south of Williamstown are given in Fig. 10 but the structural complexity between Williamstown and the Torrens Gorge precludes any possibility of establishing a satisfactory correlation by tracing on the units directly. Thus, Wilson's terminology is used in preference to that of Mawson and Sprigg.

The sequence can be subdivided into four distinctive units. From youngest (e) to oldest (a) these are:

(e) Saddleworth Formation
(d) Undalya Quartzite
(c) Woolshed Flat Shale
(b) Skillogalee Dolomite
(a) Rhynie Sandstone

RHYNIE SANDSTONE

There was considerable erosion of the Barossa Complex rocks before the Rhynie Sandstone was deposited upon them with marked unconformity. While a strong contrast exists between the basement gneisses and the overlying sandstones when both are fresh, weathering of the gneisses reduced them to a clay-rich, friable sandy material which often resemble the sandstones. In such cases an accurate location of the unconformity is only possible if relict bedding structures or foliations can be observed in the weathered rock. Generally the unconformity contact is obscured by soil cover, but excellent exposure along sections of the South Para Reservoir enabled a close study of the contact. Elsewhere the unconformity could be located with difficulty within a few metres.

Principally there are two types of unconformity surfaces, each reflecting a rather different environment at the time of deposition of the basal beds. The most spectacular, and most common unconformity is shown in Plate 11. An extremely irregular surface is typical and the difference in height between adjacent highs and lows can be as great as one metre. The large elongate and circular pot holes in the surface suggest severe erosion by high energy water. These depressions often form excellent traps for the heavy mineral hematite which Whittle (1955) showed to be titaniferous. A pebbly coarse sandstone is in contact with this type of unconformity surface, the thickness varying considerably but never exceeding 2 metres. Rounded boulders and pebbles of vein quartz up to 20 cm. in size are incorporated in this horizon. The basement relics have been seen as large as 60 cm. in length and 30 cm. in width. The matrix surrounding these boulders and pebbles consists of coarse quartz, feldspar and titaniferous hematite grains. It is quite unsorted and tabular pebbles within it show no preferred orientation.

A less common unconformity surface observed in the area is shown in Plate 12. The erosional surface is smooth, with only an occasional pot hole. The pebbly coarse sandstone horizon, typical of the previous unconformity, is absent, although rare boulders up to 15 cm. in size can be found directly at the contact (Plate 10). In contact with this surface is a medium to coarse-grained titaniferous hematite-rich feldspathic sandstone; extremely well-bedded and displaying fine cross-bedding. The nature of the unconformity surface and that of the adjacent sediments suggest that deposition took place away from the wave action zone.

Following Miles (1950), the Rhynie Sandstone in the Williamstown area can be subdivided into four distinctive units. From the base (a) to the top (d) these are:

(d)	Feldspathic sandstone	340 metres
(c)	Hematite sandstone	0-5 metres
(b)	Ferruginous conglomerate	12-15 metres
(a)	White basal conglomerate	0-6 metres

The total thickness is about 365 metres.

(a) White basal conglomerate:

This consists of well-rounded quartz and quartzite pebbles in a soft kaolinitic clay and grit matrix. It is thin and discontinuous, and lenses out along strike, commonly into a white grit or sandstone.

(b) Ferruginous conglomerate:

This forms hard, blockly outcrops which form distinct continuous linear ridges overlying the white basal conglomerate. It consists of extremely well-rounded boulders and pebbles of quartz and quartzite set in a matrix of coarse quartz, feldspar and titaniferous hematite grains. Lenses of coarse sandstone less than 0.5 metres wide are common within the conglomerate, and it often grades along strike into a hematite grit with rare pebbles, similar to the overlying unit

(Plate 13). Although the pebbles and boulders are chiefly quartzitic, many different rock types are represented, including gneisses. A thin section of a typical boulder comprises 80% quartz, 10% sericite, 5% muscovite and minor blue-green tourmaline and opaques, and it appears similar to the quartzites within the feldspathized schist in the adjacent Barossa Complex.

(c) Hematite sandstone:

This unit is very lenticular, and occurs irregularly along the strike of the contact as far as the southern edge of the mapped area. The thicker lenses form prominent outcrops, but generally it can only be located from former prospecting trenches or drilling (Newbold General Refractories Ltd., pers. comm.).

The sandstone ranges from a grit similar to the underlying bed to bands of a remarkably pure dark blue micaceous hematite ore, the individual hematite lodes ranging generally from 15 cm to 60 cm. in width. A thicker lode up to 5 metres wide on the northern side of the present South Para spillway was mined for many years as the Mt. Bessemer mine (see chapter on Economic Geology) until the workings were covered by the waters of the reservoir.

The iron ore at Mt. Bessemer is quite different both texturally and chemically from the detrital hematite elsewhere in the Rhynie Sandstone. Specularite (micaceous hematite) is the main mineral, with occasional relict euhedra of martite, the only impurity present being rounded to subrounded detrital quartz grains intermittently dispersed throughout the lodes. The very low titanium content contrasts strongly with the titaniferous hematite found elsewhere in the Williamstown region (Table 2) and indicates a different source for the iron.

It is possible that the iron was originally chemically deposited in the form of ferruginous chert, subsequent metamorphism and shearing along the unconformity producing the present hematite schist. Similar deposits, for example, the quartz-hematite schists of Colombia, (Williams *et al.*, 1954), have been explained in this way.

TABLE 2

Analyses of Hematite from Mt. Bessemer Mine

(Assays by AMDEL)

Sample No.	Total Iron as Fe_2O_3%	TiO_2%	V_2O_5 ppm
1	87.33	0.37	100
2	84.33	0.46	100
3	65.57	1.11	100
4	86.30	0.21	100
5	84.52	0.26	100
6	65.78	0.64	100
Analyses of Iron Oxide Grains			
Barossa Complex (average of 28 samples)	90.50	7.83	1215
Detrital grains in Rhynie Sandstone (average of 8 samples)	77.10	10.90	680

(d) Feldspathic sandstone:

The bulk of the Rhynie Sandstone is made up of beds of medium to coarse-grained white to yellowish feldspathic sandstone which overlie the hematite beds conformably. In thin section the typical feldspathic sandstone consists of quartz, feldspar, detached hematite, and sericite, with traces of tourmaline and muscovite (TS 4669-71). It is poorly sorted and grains are angular to subrounded, the grain size ranging from 0.1 mm to 2.0 mm. Quartz grains occupy 50-60% of the rock and often display undulose extinction. Microcline is the dominant feldspar, and can make up as much as 20% of the rock, but considerable amounts of it have been kaolinized and sericitised. The hematite content tends to decrease as the distance from the unconformity increases. The grains are less than 0.5 mm in size, are usually angular and occupy from 5-10% of the rock. Hematite is disseminated through the rock but principally concentrated along bedding planes. It contains about 15-20% $FeTiO_2$ in solid solution, the high titanium content raising the specific gravity of the mineral quite markedly above that of normal hematite. Sericite, generally derived from alteration of feldspar, comprises about 20% of the rock as fine-grained matrix between the feldspar grains, though some appears detrital. Traces of dark blue-green schorl tourmaline, and muscovite flakes up to 0.25 mm, are accessories.

The sandstones grade from highly feldspathic, rather friable rocks to dense white sandstones with local coarse grit and pebbly facies, and interbedded thin shaly beds.

In hand specimen, the thin shale members are blue-grey and well cleaved. The alignment of fine sericite flakes along the cleavage planes gives the rock a phyllitic appearance (Plate 14). In thin section fine sericite occupies 30-60% of the rock and the fine flakes parallel the cleavage. Sometimes coarser-grained lenses of sericite are set in a finer sericitic matrix (TS 4665). They range in size from 1.0 mm to 4.0 mm, are oriented parallel to the cleavage and possibly represent portions of the rock that have undergone slightly greater recrystallization during low-grade metamorphism or shearing. An opaque mineral, which appears to be graphite, constitutes 15-30% of the rock often coating grains of quartz and clusters of sericite. The colour of this unit is strongly dependent on the percentage of fine graphite present and generally portions richer in quartz show a decrease in their opaque content. The quartz varies from 5-15%, the grains are angular and have slightly serrated edges. The high sericite content, the presence of carbon in the form of graphite, and the scarcity of arenaceous material suggest that the shale was originally a carbonaceous clay or mud. A coastal mud-flat environment is suggested, as this would account for the shale's irregular width and intertonguing relationship with the enclosing sandstones. Occasional well-rounded, elongate pebbles incorporated in the shales were probably introduced by streams that traversed the mud-flats during times of terrestrial flooding.

A very sharp contact exists between the shales and the underlying sandstones, but the upper boundary shale to sandstone is gradational. During deposition of the sandstone, severe scouring of the underlying sediments must have occurred, the scoured fragments being incorporated in the sediment. The size of these fragments varies considerably, and many are quite angular, suggesting that the sediment from which they were derived was partly consolidated. This partial consolidation is evidence of its origin in a coastal mud-flat, where sediments are often exposed and crusts of sun-baked mud are formed.

The lenses of pebbly and conglomeratic material which are also found intertonguing the feldspathic sandstone are similar to the ferruginous conglomerate in the base of the sequence, though more limited in extent. They probably represent stream channels traversing the coastal area.

SKILLOGALEE DOLOMITE

Overlying the Rhynie Sandstone in the South Para Reservoir area is a conformable sequence of phyllites and dolomites, which are tentatively correlated with the Skillogalee Dolomite (Wilson, 1952). Thomson (1969) in the ADELAIDE 1:250,000 geological map correlates the sequence with the Woolshed Flat Shale of Wilson, omitting entirely the Skillogalee Dolomite.

The problem of investigating an area midway between two type areas becomes apparent here, for this part of the sequence at Williamstown more nearly corresponds to that in the Torrens Gorge than to that in the Riverton-Clare area, but to be consistent I shall adhere to the latter nomenclature. Outcrop generally is very poor, but an excellent section can be obtained by traversing the north bank of the South Para Reservoir at "low tide".

The base is marked by a sharp transition from feldspathic sandstone to a brown to greenish phyllite. The pebbles which occurred in the thin shale bands within the feldspathic sandstone are absent. Weathered specimens of the phyllite take on a whitish appearance (Plate 15). Compositionally the phyllite is variable; prominent minerals are biotite and muscovite (60-65%) quartz (25%) with plagioclase, microcline, carbonates and opaques comprising the rest. Bedding is absent, but most outcrops show axial plane cleavage and a variety of other fractures and partings. Limonite pseudomorphs of pyrite ranging in size from 0.5-1.0mm, although not common, suggest a reducing environment, while the fine-grained nature of the rocks suggest off-short quiet water deposition of clayey sediments.

About 90-105 metres above the top of the Rhynie Sandstone numerous thin beds (ranging from 0.3 to 2.0 metres in thickness) of dense, fine-grained dark blue dolomite are interbedded with thin-bedded, dark-coloured calcareous phyllites. A total of five separate beds of dolomite were mapped within a stratigraphic thickness of 90 metres. The massive grey-blue dolomite beds carry occasional nodules and bands of chert (Plate 16), and in this and other respects resemble the Montacute Dolomite of Mawson and Sprigg (1950). It can also be compared lithologically with the upper part of the Skillogalee Dolomite described by Wilson (1962), which he equated with the Montacute Dolomite. The rock consists of dolomite (85%) and chert (10%) with minor plagioclase (2%), quartz (2%) and muscovite (1%). An average assay shows $CaCO_3$, 48%, $MgCO_3$, 38%.

The dolomite was probably deposited in a quiet lagoonal environment, with periodoc influx of clayey material producing the interbedded cclcareous phyllites. The chert was also probably chemically deposited originally as collodial silica, a hypothesis put forward by Barnes and Kleeman (1934) to explain the chert in the petrologically identical Beaumont Dolomite.

The dolomite beds lens out south of the reservoir, and merge into a sequence of phyllites identical to those underlying and overlying the carbonate sequence. The phyllites vary from 240 to 360 metres in stratigraphic thickness, becoming progressively sandier toward the top, indicating a gradual increase in the energy of the depositional environment. Mirams and Forbes (1964) defined the Woolshed Flat Shale as stratigraphically including all the shales from the Skillogalee Dolomite to the Undalya Quartzite, and conceivably this sequence of phyllites could be equated with the Woolshed Flat Shale. They correspond also to Mawson and Sprigg"s (1950) "Lower Slates (and phyllites) with included minor quartzites (340 metres)" overlying the Montacute Dolomite in the lower Mt. Lofty Ranges. At Williamstown the rocks are so poorly exposed, however, that the correlation must be regarded as tentative.

UNDALYA QUARTZITE

The boundary between this unit and the underlying unit is gradational, but it is taken as the first appearance of relatively continuous, mappable beds of hard quartzite (Plate 17). These range from less than one metre to up to 15 metres or more, and can be traced along strike for distances ranging from a few metres to thousands of metres, as their resistance to weathering provides relatively good outcrop. Interbedded with the quartzites are arkosic sandstones and phyllites. Crossbedding is a characteristic feature of the sandstones, and generally the rocks are well bedded. In contrast to the Rhynie Sandstone there are no conspicuous bands or concentrations of hematite grains, a feature also noted by Wilson (1952) when mapping the Undalya Quartzite in the type area. The sandstones are poorly sorted, the grain size varying from 0.1 mm to 1.5 mm. The grains are usually sub-angular with low to medium sphericity. In some of the coarser-grained beds, the outcrops are dense and massive, the grains having been cemented by silicification to form a hard, blocky quartzite.

The average composition of the blocky quartzites is 60-70% recrystallized quartz, 15% feldspar and 15% calcareous matrix, while the arkosic sandstones contain 55-60% quartz, 20-25% plagioclase and 20% calcareous matrix. In this respect the arenaceous rock types are similar petrologically to those in the Stonyfell Quartzite described by Heath (1963) and equated with the Undalya Quartzite. Similarly, the argillaceous rocks, now metamorphosed slightly to form a silky-grey phyllite, correspond to the poorly-sorted greywacke of Heath (1963).

The top of the bed is less easy to define than the bottom. On the ADELAIDE 1:250,000 geological sheet Thomson (1969) has taken the thick, continuous horizon of sandstone-quartzite near the Kersbrook-Williamstown road as marking the top, and this convention has been followed in this thesis. Thus the Undalya Quartzite is 440 to 490 metres thick in the Williamstown area, compared to 800 metres in the type area near Watervale and 300 metres in the Stonyfell Quartzite type area.

SADDLEWORTH FORMATION

The uppermost beds of the Precambrian sequence west of the Kitchener Fault comprise 1200 metres of grey and green phyllites interlaminated with dolomites and occasional massive quartzites. The top of the sequence is cut off by the Kitchener Fault, and the bottom is taken as the phyllite conformably overlying the thick quartzite near the Kersbrook-Williamstown road.

These beds can be traced without a break north to Saddleworth, the type area for the formation, which there consists of about 500 metres of grey, green fine-grained laminated calcareous siltstone (Parkin, 1969). These correspond to the lithologically identical Upper Slates (and phyllitic phases) of Mawson and Sprigg (1950). The black dolomite, minor black chert and dark calcareous siltstone interbedded with lenticular sandstone, which collectively form the Auburn Dolomite underlying the Saddleworth Formation in the type area, are missing at Williamstown. Since the formation change in the Riverton area is basically a facies change, this probably indicates the absence of a suitable environment at Williamstown, rather than a break in deposition.

Outcrop is generally poor, although when present the arenaceous units protrude markedly and form prominent hillocks in an otherwise quite subdued topography. One quartzite in particular, 540 metres stratigraphically above the base of the formation, forms the core of a prominent linear ridge over a distance of 4 kilometres, although its width is never greater than 50 metres. The quartzites and sandstones are generally massive, poorly sorted fine-grained to medium-grained rocks which occur usually as blocky, lenticular beds. In thin section a typical quartzite consists of 90-95% quartz and 5-10% feldspar, though some are cemented by a matrix of calcite which can occupy up to 20% of the rock; the accessories are usually opaques. The sandstones are typically quartz (65%) and feldspar (30%) with minor muscovite and chlorite. Sphericity is low and the grains are subangular, indicating an immature environment.

The dominant lithology in the Formation is a green to grey finely laminated phyllite, which in places has been altered to a schist. In thin section the rock is strongly foliated, thin bands (about 0.5 mm. wide) of fine-grained quartz and chlorite alternating with slightly wider bands of limonite and muscovite. The average grain size is about 0.2 mm. The quartz occupies 50-55%, limonite (after pyrite), plagioclase, chlorite and muscovite each comprising 5-10% of the rock.

Sedimentation conditions probably alternated rapidly during deposition of this sequence, as individual sandstone, quartzite and phyllite beds are thin and lenticular and grade into one another along strike.

Above the prominent quartzite marker bed previously mentioned, the carbonate content increases markedly, thin dolomite beds comprising initially 40% of the sequence, and as the Kitchener Fault is approached this percentage climbs to 60%. The dolomites are blue-grey and massive, individual beds averaging about 30 cm. in thickness, and they outcrop more prominently than the intervening phyllite. A detailed log of some 200 metres of section immediately overlying the quartzite marker in the vicinity of the Deloraine Mine is given in Figure 12 to give some idea of the composition of this part of the formation. The increase in carbonate content and the prominent quartzite marker bed correspond with the description by Sprigg (1946) of his "Upper Phyllites" which grade into the Beaumont Dolomites in the lower Mt. Lofty Ranges. These have been correlated by Thomson (1964) with the Saddleworth Formation.

The abundance of disseminated pyrite suggests a quiet lagoonal environment of deposition of dolomitic clays and oozes under highly anaerobic conditions, an occasional terrestrial flood sweeping in coarser material to form the minor quartzite beds in this part of the sequence.

As shown in the stratigraphic column and correlation chart, the sediments described west of the Kitchener Fault conform with the typical sedimentary sequence developed throughout the Mt. Lofty Ranges and their northern extension. A convincing correlation between the beds can be fairly clearly established, as the stratigraphic succession is readily unravelled.

TERTIARY

Following the deposition, consolidation, metamorphism and folding of the Precambrian rocks there was a long period in which no sediments were deposited and the area was progressively denuded. If the Permian glaciation affected the Williamstown area, no trace of its effects remains. The next sedimentary beds to be deposited in the Williamstown area were a series of non-marine cemented grits, sands and gravels, the remnants of which occur as a thin layer (about 3 metres thick at most) on some of the hill-tops in the west and especially the north-western part of the area (Plate 18). The presence of strong cut-and-fill effects, disconformities and steep cross-bedding in these sands and gravels indicate a fluviatile and deltaic environment, while some interbedded laminated silts and clays may have been deposited under lacustrine conditions. Glaessner (1953) suggests that on the evidence of the limited contained fossils (mainly wood and leaves) their age is Lower Tertiary, and he tentatively correlates them with the North Maslin Sands of Eocene age.

Glaessner (1953) showed that these sediments were deposited on a surface of moderate relief, from which harder rocks seemed to have been projecting as ridges up to 100 metres high. Between these ridges deposition took place in a system of lakes and rivers. Remnants of the old peneplain can be seen in the flat areas northwest of the South Para Reservoir which lie at an elevation of 318 metres (Plate 19). The old land surface is characterized by deeply weathered, kaolinized or ferruginized rock, and it slopes progressively downwards south to Malcolm Creek, where it lies at an elevation of 275 metres. This may be partially a reflection of the later fault movements, although it is possibly an original slope feature.

The Tertiary sediments consist of occasional thin deposits of red, iron-stained clay shale lying directly on the old land surface, overlain by the more common lithified remains of old river gravels, which are now horizontally bedded ferruginous grits and conglomerates. The conglomerates consist of clasts of milky white quartz and quartzite, ranging in size from 1 cm. to 10 cm., together with blades of schist, gneiss and phyllite, cemented by a ferruginous grit or sandstone. The quartz clasts vary from angular fragments to extremely well rounded boulders.

After the deposition of the Tertiary gravels the materials resting on the low erosion surface were lateritised, the rocks being affected to a considerable depth. The ferruginous cement binding the present Tertiary sediments was formed at this time, making them strongly resistant to erosion while the exposed older rocks were lateritised to varying depths often to as much as 12 metres. This lack of uniformity in the depth of lateritisation may be due simply to subsequent gentle warping of the landscape, or to an original uneven lateritisation governed by the chemical condition of the surface, the water, or both.

QUATERNARY

According to Sprigg (1946) and Campana and Wilson (1955), late in the Tertiary a cycle of orogenic movements commenced which uplifted the general area and in fact formed the present Mt. Lofty Ranges orography.

During this period the valleys of the present major water courses developed, and fresh rock below the level of lateritisation was exposed, for example in the eastern part of the Williamstown area. After this episode of rapid erosion of the valleys, there followed a period of infilling, and relatively sandy alluvium was deposited in the extensive plains north of Williamstown, and along the major streams. There is some evidence for two levels of alluvium in places in the wider alluvial plains and along Malcolm Creek, where there are sands on the higher banks and clays on the lower. This would indicate some change in conditions, but the difference in height is less than one metre so the relationship is difficult to interpret.

The maximum thickness of alluvium is probably no more than 3-4 metres, and it generally consists of ill-sorted coarse boulders, gravel and silt, overlain by brownish-grey sand with silty clay loam throughout. The general colour varies from dark brownish-grey at the surface to a very light brownish-grey at about one metre.

EAST OF KITCHENER FAULT

The Kitchener Fault separates low-grade phyllites on the west from high-grade (amphibolite facies) metasediments on the east. Gradational changes from slates through phyllites to schists are observable in the northern continuation of the sequence in the vicinity of Tanunda and Greenock (Campana, 1955) which confirms their correlation with the Burra Group rocks. The correlation to the south is obliterated by structural complexity.

Andalusite, sillimanite, kyanite and staurolite in gneisses, schists and calc-silicate rocks abut low-grade chloritic and biotite-rich phyllites for the full length of the Kitchener Fault in the Williamstown area, a distance of over 12 kilometres. Offler and Fleming (1968) suggest this anomalous metamorphic zone boundary was due to shifting by fault movement. Experiments (Appendix 4) indicate that this implies a throw of 6000 metres on the Kitchener Fault. If one accepts a correlation of the sediments on either side of the fault, an examination of the section across the fault shows 3400 metres of missing section, indicating a throw of 3000 metres. A gravity survey by Bennett (1968) suggested a throw of 500 metres for the Kitchener Fault just north of Williamstown. The very great disparity in these estimates required explanation, and the problem is discussed more fully later.

The metamorphic rocks east of the Kitchener Fault can be subdivided on the basis of their mineralogy, and to some extent their lithology. The most common rock types are mica schists and gneisses, with lesser quartzites and calc-silicates. Some of these beds can be traced continuously over distances of 2-3 kilometres, although in the upper part of the sequence they tend to grade laterally into one another, e.g. quartzites become calc-silicate rocks. Sedimentary structures above the basal grits are rare, and generally confined to the quartzites which show cross-bedding and heavy mineral layering.

None of the units described below can be traced continuously to either of the type areas mentioned in the previous sections. Some fairly positive correlations can be drawn for one or two units (e.g., Rhynie Sandstone), but for the rest any correlation is wholly speculative

(Fig. 13). For convenience, the units have been named in accordance with the Australian Code of Stratigraphic Nomenclature (Revised Edition 1973), and where applicable the name has been submitted (and accepted) for inclusion in the Central Register of Australian Stratigraphic Names (Warren Schist, Ukaparinga Schist).

The high grade of metamorphism and some structural dislocation has rendered the concept of a stratigraphic thickness for these beds quite meaningless, as much material may have been added or subtracted. Where given, thicknesses refer to the true thickness of a measured section, but this does not imply an original stratigraphic thickness.

The subdivision is as follows, from oldest (a) to youngest (h):

(h) Undalaya Quartzite Equivalent
(g) Pewsey Vale Formation
(f) Pipeline Schist
(e) Victoria Creek Marble
(d) Ukaparinga Schist
(c) Springfield Sub-Group
(b) Rhynie Sandstone Equivalent
(a) Warren Schist

WARREN SCHIST

This unit forms the core of the complex Lookout Tower Anticline (Campana, 1955) east of the Kitchener Fault, and Mills (1973) proposed calling this exposure of basement rock the Warren Inlier. It underlies the Rhynie Sandstone equivalent with pronounced unconformity; the base of the unit is not exposed. Two main rock groups can be differentiated; a gneissic core and an overlying schist. Metamorphism has almost completely obliterated original sedimentary structures, although occasional layers of pebbles and grit bands containing hematite can be seen (Mills, 1963).

Campana (1955) regarded the Warren Schist as an alkali metasomatised facies variation of the Rhynie Sandstone, while Mills (1963) regarded it as a sedimentary facies variation stratigraphically underlying the sandstone. Offler and Fleming (1968) on later advice from Mills show the Warren Schist as a Lower Precambrian inlier comparable to the Barossa Complex inliers elsewhere in the Mt. Lofty Ranges. Although the Warren Schist resembles the Barossa Complex rocks in that it underlies the base of the Burra Group equivalents with marked unconformity, it appears to be younger than the Barossa Complex. The two rock types have a remarkable similarity in their quite characteristic aeromagnetic patterns (Fig. 14), but this could be interpreted as the proximity to the surface of underlying Barossa Complex rocks. There is considerable evidence to suggest that the original sediments which now form the Warren Schist were derived from Barossa Complex rocks. The schist contains detrital titaniferous hematite chemically identical with that found as crystals in the Barossa Complex, and it contains pebbles mineralogically and texturally identical with the quartzites in the phyllonite rocks of the Barossa Complex. The Warren Schist, unlike the Barossa Complex rocks, shows no sign of chloritisation or other evidence of hydrolytic alteration or retrogressive metamorphism. Thus the Warren Schist occupies a time sequence post-dating the consolidation and high-grade metamorphism of the Barossa Complex, and predating the commencement of deposition of the basal sediments of the Burra Group. Recognizing this, Thomson (1969) has the Warren Schist shown on the ADELAIDE 1:250,000 geological sheet as possibly equivalent to the River Wakefield Group of Wilson (1952), and this seems a logical correlation. Metamorphism has removed any chance of a more comprehensive lithological, mineralogical or chemical comparison of the Warren Schist with other units of similar age in the Mt. Lofty Ranges and Flinders Ranges.

(i) Quartz-feldspar-biotite gneiss

This rock type is found in two separate locations in the Warren Inlier. In both cases it appears to be underlying the younger schist unit, the occurrences being within the cores of anticlines west of the Warren Reservoir weir and south of the Lookout Tower. Both areas are covered by dense scrub, and although the terrain is rugged, outcrop is rather poor.

The rock is a coarser-grained gneiss than that found in the Barossa Complex, and the minerals are well segregated into parallel foliae about 5-10 mm thick (Plate 20). In thin section a characteristic rock contains 30% plagioclase (Ab_{90}), 25% recrystallized quartz, 20% biotite, 20% sericite and minor opaques (TS 4650). The sericite bands sometimes contain small amounts of elongate quartz and plagioclase, but generally the segregation is almost perfect. Biotite occurs both in green and brown-coloured varieties, indicating growth under two different metamorphic conditions.

(ii) Crenulated coarse muscovite schist

Typically, this is a silvery-green to grey felted, medium to coarse-grained muscovite schist with conspicuous crenulations. This rock outcrops fairly well in the rugged country within the Hale National Park. It is composed of medium-grained (1.0 mm.) quartz (30%), muscovite (50-60%), biotite (10-20%), tourmaline, and limonite pseudomorphing pyrite (1-2%) (TS 4516). Feldspar was rarely, if ever, seen in any of the specimens examined.

The strong foliation is caused by aligned muscovite flakes interspersed with rare biotite and layers of granoblastic quartz, which also occurs as sparse individual grains scattered throughout the micas. The rocks show a broad folded crenulation with axial crumpling of micaceous layers (Plate 21), and folding appears to have been contemporaneous with the crystallization.

In thin section the biotite appears quite fresh (Plate 21) and although pleochroic from pale yellow to dark green, pleochroic haloes are absent (TS 4489). The quartz grains show straining, and undulose extinction is common. Tourmaline occurs concentrated in certain bands as abundant small well-rounded grains, suggesting that it is of detrital origin, and the bands may be relict bedding. The only sericite present occurs as small concentrations of flakes 5 mm. long and 1 mm. wide apparently pseudomorphing kyanite crystals and aligned along the foliation plane.

RHYNIE SANDSTONE EQUIVALENT

Overlying the Warren Schist unconformably is a sequence of about 190 metres of arkosic grits that is correlated with the Rhynie Sandstone. The rationale behind this correlation is based firstly on the stratigraphic evidence of a sandstone unit unconformably overlying Lower Proterozoic schists and gneisses, and secondly on the mineralogical fact of a high percentage of titaniferous hematite as thin laminae outlining cross-bedding and other shallow-water sedimentary features. Both of these facts are typical of the Rhynie Sandstone and its equivalents throughout the Mt. Lofty Ranges, and are not recorded from any other sandstone in the sequence.

The unconformity is best seen along the pipeline track flanking the South Para Gorge at a spot 1500 metres northwest of the Warren Reservoir weir (Plate 22). The boundary between the two rock units can be reasonably well located elsewhere to within 15 cm. or so, and its irregularity indicates that the erosional surface was quite uneven. When tracing the boundary, it can be seen to deviate by as much as 2-3 metres, even where structural movement is absent.

The basal unit of the Rhynie Sandstone equivalent consists of a few metres of coarse to very coarse grit grading to a conglomerate, above which is a poorly sorted arkose displaying thick (up to 30 cm.) black heavy mineral bands which are not found in the underlying schist; thus the source areas for the two units may have been different. Polished sections of a heavy mineral concentrate from the Rhynie Sandstone equivalent (Plate 23) showed grains of relatively pure hematite with common lamellar twinning, each grain containing plentiful exsolution lamellae of ilmenite oriented with the grains along rhombohedral directions. The proportion of ilmenite within the hematite is in the range 5-10% (Table 3). Other minor heavy mineral grains were goethite, magnetite, topaz, tourmaline, zircon and amphibole.

Original sedimentary features are fairly well preserved throughout the Rhynie Sandstone equivalent; as well as the black titaniferous hematite bands indicating bedding and cross-bedding some rare ripple marks can be seen. Occasional elongate to spherical well-rounded quartzite pebbles up to 5 cm. long can be observed lying along the bedding planes, which tend to curve slightly around them as though the pebbles had squashed the sand as they rolled to rest on a sandy seashore. The pebbles are generally

TABLE 3

RHYNIE SANDSTONE (EAST)-SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSIS OF HEAVY MINERAL FRACTION

(Analysis done by AMDEL)

Element	ppm
Barium	120
Chromium	200
Copper	3
Gallium	10
Lead	3
Lithium	2
Manganese	300
Nickel	5
Potassium	500
Rubidium	10
Silver	0.8
Sodium	300
Tin	5
Titanium	10,000
Vanadium	200
Zinc	30

smooth, waterworn massive quartzites, some containing thin hematite lamellae. Similar sediments can be seen forming on the beaches along the eastern side of St. Vincents Gulf today, from Marino south to Normanville (Plate 24).

A typical sandstone consists of quartz (50%), plagioclase (25%), microcline (20%), mica (5%) and minor hematite bands. The quartz is a milky-white variety characteristic of the Rhynie Sandstone and its equivalents, and it is strongly lineated. Coarse-grained muscovite and biotite are commonly present in layers, and both the quartz and feldspars have been extensively recrystallized. The muscovite is a pale green variety which occurs as small aggregates of stumpy flakes in decussate arrangement throughout the rock.

At the top of the Rhynie Sandstone equivalent on the western side of Hale National Park there is a transition zone of some 4 metres, where the pale yellow-brown sandstone passes into more shaly beds which at the surface are heavily iron-stained and then a sharp change into a brown sandy schist. At the contact there is a very much brecciated and comminuted rock, which has been extensively altered and argillised along the permeable shear zones. Over a width of some 5 cm., the rock consisting almost entirely of granular quartz and microcline becomes interlaminated with remnants of schistose rock very much chloritised and sericitised, the sericite merging into muscovite. Minor relicts of biotite are also present. Subhedral fractured tourmaline grains are present in rare localised concentrations; magnetite is very rarely present. These textural features were observed in all specimens of core taken from holes drilled through the contact over a strike distance of 1000 metres, and strong evidence of shearing can be observed at the contact exposed in the main adit at the Ukaparinga Mine. Thus in the mine area the contact between the Rhynie Sandstone equivalent and the overlying schist is probably a fault. Similarly, the contacts in all locations on the mapped area except southeast of the Lookout Tower show evidence of shearing. In the latter location there is a sharp change to a coarse grained mica schist.

SPRINGFIELD SUB-GROUP

Overlying the Rhynie Sandstone equivalent on the eastern side of the Warren Inlier is a thick sequence of micaceous schists and gneisses to which has been given the name Springfield Sub-Group (Plate 25). The name is taken from the historic Springfield property, first settled by John Warren in 1839.

Several rock units within the Springfield Sub-Group have been the subject of intensive studies, including the Mt. Crawford Granite Gneiss (Mills, 1963) and the Kyanite-damourite schists (Alderman, 1942). Mills (1973) placed this rock group within his "sillimanite-muscovite zone" east of the Lookout Tower, and his description of the rocks is quite comprehensive, hence only a cursory reference will be made in this thesis.

The abrupt change from cross-bedded sandstone to a coarse-grained recrystallised quartz-muscovite-sericite schist can be clearly traced from a point 400 metres east of the Lookout Tower south to the head of Speck Gully. North of the Lookout Tower the Springfield Sub-Group abuts the Warren Schist, implying that the Rhynie Sandstone equivalent has been sheared out, though no actual fault plane could be located for certain.

The basal portion of the Sub-Group typically consists of quartz (50%), chlorite after biotite (30%), muscovite (5%), sericite (15%), with accessory iron oxides and zircon. Of interest is the common presence of sericite as fibrous knots in conjunction with quartz grains containing minute inclusions of sillimanite, suggesting that the sericite may be an alteration from sillimanite (TS 4592).

Forty to sixty metres above the base a thin tremolite marble bed (TS 4591) outcrops intermittently from Speck Gully north to Victoria Creek and beyond the area shown in the map. Although never more than 10 metres wide, this distinctive bed outcrops well and is a useful marker horizon. Its resistance to erosion may have been assisted by common surface alteration to opaline chalcedony, a feature first noted by

Hossfeld (1935). This phenomenon appears to be a feature of this bed for all outcrops invariably showed siliceous material reacting with and replacing carbonate. Serpentinization has also occurred, and in combination with the tremolite gives the rock an attractive pale green colour. These alteration effects were generally rare or absent from the dolomitic marbles present in other units in the Williamstown area.

The marble is overlain by schist identical with that at the base, although the schist quickly becomes richer in quartz. About 20 metres above the top of the marble a thin rather massive fine-grained (0.5 mm.) micaceous sandstone outcrops intermittently (TS 4593). Its composition is quartz (65%), sericite (after muscovite) 25%, chlorite (after biotite) 5%, muscovite 5%, with accessory biotite, hematite (after magnetite) and zircon. The maximum thickness is about 10 metres, and the sandstone grades back into the typical schist.

From here to the top of the Springfield Sub-Group a sequence in excess of 600 metres of coarse-grained micaceous schists and gneisses occurs. These rocks are divisible into a number of different varieties, but unlike those units at the base a stratigraphic subdivision is impossible, as the variation is more the result of differential response to metamorphism than original sedimentary changes.

The schists vary from quartz-feldspar-mica schists with rare sericite to schists containing up to 80% sericite (TS 4597), the latter mineral generally present as irregular knots which appear to be relicts after sillimanite. Some rocks containing fresh sillimanite show that this mineral has formed by replacement of biotite and muscovite, releasing the iron as magnetite and hematite.

In the southeastern part of the area the schists become rich in feldspar and develop a gneissic banding, particularly near the contact with the Mt. Crawford Granite Gneiss, which is probably a replacement body developed from the metasediments within the Springfield Sub-Group (Mills, 1963). To the north other alteration effects have produced the kyanite-damourite schists (Plate 26) described in detail by Alderman (1942).

East of the granite, a thin coarse-grained quartz-muscovite-sericite schist occurs. This is cut off by the Murray Vale Thrust Fault, whose presence was conclusively established by Mills (1973); the fault has removed the top portion of the Springfield Sub-Group.

As discussed by Mills (1973) and confirmed independently by this author's research, the beds overlying the Springfield Sub-Group are markedly different from the latter. The grain size is universally smaller, original bedding can often be distinguished, and the primary planar schistosity has generally not suffered the second-stage crumpling forming the crenulations common in the Springfield Sub-Group. Mills (1973) grouped the above rock sequences into two zones based on their metamorphic assemblages, but I have preferred to describe them in terms of their stratigraphic sequence. The lowest member of the "kyanite-andalusite zone" of Mills (1973) is the Ukaparinga Schist, which is dealt with fully in a later section. However, in keeping with the pattern established in this thesis, a stratigraphic description of this unit follows.

UKAPARINGA SCHIST

The Ukaparinga Schist outcrops intermittently around the western and northern sides of the Warren Inlier. It takes its name from the Ukaparinga Mine, 2.2 kilometres south-east of Williamstown. The type section is measured in the main adit of the mine, although here, as elsewhere, the lower contact appears to be sheared (Fig. 15). The same rock overlies the Rhynie Sandstone equivalent in the vicinity of the Williamstown oval and along Victoria Creek. All outcrops typically show extensive staining with copper carbonates.

In the type section which is 45 metres thick, the base of the unit is a brown sandy medium-grained feldspathic rock, the contact with the underlying yellow-brown arkosic grit of the Rhynie Sandstone equivalent showing evidence of shearing (Plate 27). The micas, chiefly biotite and some muscovite, are weakly aligned giving the rock a poor schistosity, though the layering of the microcline, plagioclase and quartz is more suggestive of gneissosity. Accessory minerals include tourmaline (probably introduced), magnetite and apatite. Five metres above the base the rock becomes a banded gneiss, showing narrow darker bands consisting of biotite, muscovite and chlorite, with felsic bands of interlocking grains of quartz, oligoclase and microcline in anhedral grains up to 0.5 mm. in diameter. Quartz is also present in coarse vein-like structures parallel to the gneissose foliation, containing coarse anhedral crystals often considerably constricted within the vein, but having a length of several millimetres. The veins are up to 5 cm. wide and 30 cm. long.

Thirteen metres above the base of the formation a band one metre thick consisting of white to silvery-grey quartz-sericite schist occurs (Plate 28). This marks the first occurrence of abundant copper mineralization, here characterized by the presence of copper carbonates. From 14 metres above the base the rock is a quartz-biotite-chlorite-sericite schist, with somewhat less quartz in the ground mass and more platy minerals than the upper horizon. However, the overall quartz content is boosted by the presence of numerous large lenses and blebs of vein quartz, some up to 100 cm. long, averaging about 30 cm. long, the widest part being about ¼ the total length (Plate 29).

In thin section the quartz grains are fairly clear, and are more-or-less elongated parallel to the banding (TS 4445). The original detrital texture has been nearly obliterated by mutual solution and recrystallization at the interfaces. Occasional feldspar grains intergrown with the quartz are extensively altered to clouded patches of clay and sericite. Rare large laths of altered feldspar lie oblique to the schistosity. Small inclusions of apatite and laths of biotite have become included in the recrystallized quartz. The larger mica flakes generally have a common orientation parallel to the banding; however, patches of fine chlorite (probably derived from feldspar) contain flakes with random orientation. Most of the chlorite has derived from biotite, and streaks and grains of iron oxide along the cleavages of chlorite probably formed during this alteration. Some of the fine chlorite is commonly intergrown with sericite. Minor grains and rare clumps of epidote occur in the chlorite-sericite-patches. The type and degree of alteration is suggestive of hydrothermal (or metasomatic) alteration.

Minute shear planes have developed parallel to the foliation and schistosity. These have caused the rupture and distortion of the mica laths and have provided zones of weakness along which deposition of malachite and azurite has occurred. The same stress system has caused minor fracturing and development of strain in the quartz grains.

Abundant (5%) subhedral to euhedral, roughly equi-dimensional grains of magnetite are evenly scattered throughout the rock (TS 4445). Some of these crystals have corroded margins, being extensively altered along the margins and crystallographic axes to hematite (variety martite).

The horizon is 20 metres in true thickness, and grades of up to 1.85% copper have been found over lengths of 1.5 metres. The overall grade is 0.77% copper. Within this horizon there is another one-metre thick band of white quartz-sericite-muscovite schist, located 26 metres above the base of the formation.

The top 11 metres of the Ukaparinga Schist is a recrystallized, crenulated quartz-chlorite-biotite schist, relatively barren in copper (average about 500 ppm). In thin section the quartz and chlorite are intimately intergrown, the aggregate having a very well developed plane of schistosity (TS 4444). The chlorite has developed by alteration from biotite. The s-planes are fairly evenly buckled forming a set of parallel slip planes oriented obliquely to the primary foliation. The stress system associated with this has also caused parting parallel to the primary foliation, and secondarily recrystallized vein-like quartz has become localised along these partings. In addition, randomly oriented quartz veins cut the rock, some carrying small patches of hematite-limonite which in places appears to pseudomorph pre-existing pyrite.

Sharp variations in composition both laterally and in section are shown by abrupt colour changes due to variations in the relative percentage contribution of the constituents.

At the top, the Ukaparinga Schist grades (over an interval varying from 10 cm. to 2 metres) into a metamorphosed carbonate bed, which Freytag (1957) named the Victoria Creek marble (Plate 30). The copper content drops sharply from an average 0.32% to less than 100 ppm as the black biotite schist passes into a talc-rich schist and then into a marble (Table 4).

VICTORIA CREEK MARBLE

The Ukaparinga Schist grades rapidly, in most areas, into a tremolite marble. The unit was loosely named by Freytag (1957), who studied various marble outcrops in detail in the Victoria Creek area east of Williamstown. His name has been applied to this thesis specificially to the marble unit overlying the Ukaparinga Schist conformably, and underlying the Pipeline Schist. Mills (1963) found a similar marble, which he referred to as the Upper Tremolite, outcropping east of the Mt. Crawford Granite Gneiss.

In the Ukaparinga area the marble has been studied in some detail by this author, and the observations are given below. They substantially agree with those of Mills and Freytag, though the interpretations differ somewhat. Although Freytag adequately described the petrology of the variety of marbles he found, he did not attempt to place them sufficiently accurately in a stratigraphic context. I shall attempt to do that, bearing in mind the strong influence metamorphism has had on the marbles in this area.

The Victoria Creek Marble varies enormously in thickness, from nil to one metre to as much as 47 metres. The type section is taken as that exposed at the Southern Hills Prospect, 3.2 kilometres south of Williamstown (Plate 31). Although this is 3.4 kilometres southwest of Victoria Creek where Freytag concentrated his work, it is felt that the exposures in the Southern Hills area are superior. These are supported by five complete diamond drill core intersections and an additional five partial intersections, and numerous percussion drill intersections. Assay data in 1.5 metre sections is available, and a total of 40 thin and polished sections throughout the diamond drill intersections have been examined. Since Freytag established no type section for his Victoria Creek marble, the present author feels justified in taking this liberty, although the concept of a stratigraphic description in the correct sense here is dubious in view of the degree of metasomatism involved.

VICTORIA CREEK MARBLE - LOWER SECTION

TRUE HEIGHT ABOVE BASE (m)	ASSAY %						MINERALOGY %									STRUCTURE		
	Cu(ppm)	CaO	MgO	SiO_2	FeO	Al_2O_3	QUARTZ	CALCITE	DOLOMITE	TALC	CHLORITE	FELDSPAR	BIOTITE	PYRITE	OTHER	AVERAGE GRAINSIZE (mm)	TEXTURE	REMA
22	2	31.2	24.69	9.10	0.39	0.17			70-80	20	trace	1		1-2		0.3	Granular, structureless	
21	10	21.0	23.4	20.5	0.84	1.90	nil	6	60	32	trace			2		0.3	"	
20	10	22.95	23.57	15.76	0.02	0.62	nil	2	73	25								
19	10	23.3	22.7	17.2	0.90	2.02	nil	6	65	27				2				
18	10	24.36	22.32	10.66	0.78	0.86	nil	2	79	17				2				
17	5	24.97	22.79	11.54	0.25	0.01	nil	2	80	18						0.5		
16	10	23.8	21.6	17.2	0.86	2.25	trace		60	25	10			1-2	Tremolite 3-5			
15	15	25.94	14.92	22.62	2.26	2.33	nil	8	50-60	20-30	15-20	1		1				
14	10	23.69	21.1	16.79	0.80	[illegible]	nil	10	57	27	5			1	Apatite	1.0	Granular, weak schistosity	
13	10	22.4	[illegible]	20.7	1.02	2.62	nil	18	46	25	7			2				
12	10	[illegible]	[illegible]	18.8	1.05	2.42	nil	15	50	24	10			1	Antigorite	0.8	Granular, weak schistosity	
11	15	[illegible]	[illegible]	14.08	1.76	2.00	1-2	65	12	5	15			1	Tremolite, apatite, tourmaline			
10	30	[illegible]	[illegible]	28.03	[illegible]	[illegible]	5	35	10	30	20				Rutile	0.5		
9	10	23.7	21.0	15.7	1.10	2.60	nil	20	50	20	10			1-2		0.5		
8	10	20.5	20.1	22.5	1.21	3.27	5	30	40	15	10					0.5	Granular, weakly schistose	
7	10	31.35	13.56	18.27	1.13	1.84	10	40	40		10			1-2		0.3		
6	10	39.39	10.41	15.42	1.19	2.52	5	57	23	5	10			1				
5	10	[illegible]	[illegible]	11.48	0.73	[illegible]	5	60	25		10			1				
4	45	14.92	20.85	36.45	2.98	1.04	20	25	10	5	25	15		1				
3	10	14.91	20.60	28.84	3.89	[illegible]	20	25	10	6	12	25		1				
2	10	14.91	20.60	28.84	3.89	4.62	20	25	10	6	12	25		[illegible]				
1	50	0.38	16.58	50.18	[illegible]	10.92	20	2		10	20	50		[illegible]				
0	2760	0.26	17.78	52.99	[illegible]	10.26	20	[illegible]		10	20	50		2				
-1	1400	0.31	6.92	60.62	[illegible]	[illegible]	25				30	50		5	Sericite 1% [illegible]	[illegible]		

VICTORIA CREEK MARBLE - UPPER SECTION

TRUE HEIGHT ABOVE BASE [m]	ASSAY %						MINERALOGY %									STRUCTURE		
	Cu (ppm)	CaO	MgO	SiO_2	FeO	Al_2O_3	QUARTZ	CALCITE	DOLOMITE	TALC	CHLORITE	FELDSPAR	BIOTITE	PYRITE	OTHER	AVERAGE GRAINSIZE [mm]	TEXTURE	REMARKS
46	10	2.71	5.70	59.30	5.39	13.30	20-30		2-3		3-5	30-40	30	1-2	Rutile 2 Tourmaline 1-2	0.3	Layered, granular schistose.	
45	10	9.94	13.90	45.80	3.64	9.43	1		15-20	10-15	10	55	5-7	5	Tremolite 5%	0.3	Layered, granular schistose.	
44	10	27.12	22.88	6.94	0.47	0.41			90	5		1		1	Tremolite 1%	0.3	Granular	
43																		
42	10	19.0	11.8	38.6	2.64	7.32	1-2		60-70	20-30	5	3						
41																		
40																		
39									70-80	20		2-3		1-2				
38																		
37	10	28.26	22.28	6.78	0.50	0.41			90	5		3		1	Tremolite 1%			
36																		
35	10	17.5	20.5	27.9	1.55	3.80	1-2		50-60	20-30		5-7		2-3	Tremolite 5%			
34																		
33																		
32	10	23.0	21.1	18.1	0.98	3.44			75	10		5			Tremolite 10%			
31	10	25.50	20.14	9.09	0.70	1.34			85	7		5		2-3				
30	10	18.3	19.9	33.7	1.05	2.06	5		30	40		5			Tremolite 20%			
29	10	28.65	22.17	5.93	0.41	0.53			90	7		1		1	Tremolite 1%	2.0	Granular, structureless	
28	10	20.5	21.3	25.4	0.88	1.51	5		50	30		5			Tremolite 10%	1.0	"	
27	10	25.4	21.7	13.3	0.73	2.07			85	10		2			Tremolite 3%	2.0	"	
26	10	27.84	22.16	7.81	0.71	1.06			90	7		1-2		1-2		2.0	"	
25	10	27.4	13.3	24.3	4.04	3.86		30	35	15		10			Tremolite 10%	0.5	"	
24	10	21.4	21.7	18.1	0.96	3.10			70	10		15			Tremolite 5%	0.3	"	
23	10	22.37	20.53	18.25	1.20	2.69		1	70	15		1-2				0.3	"	

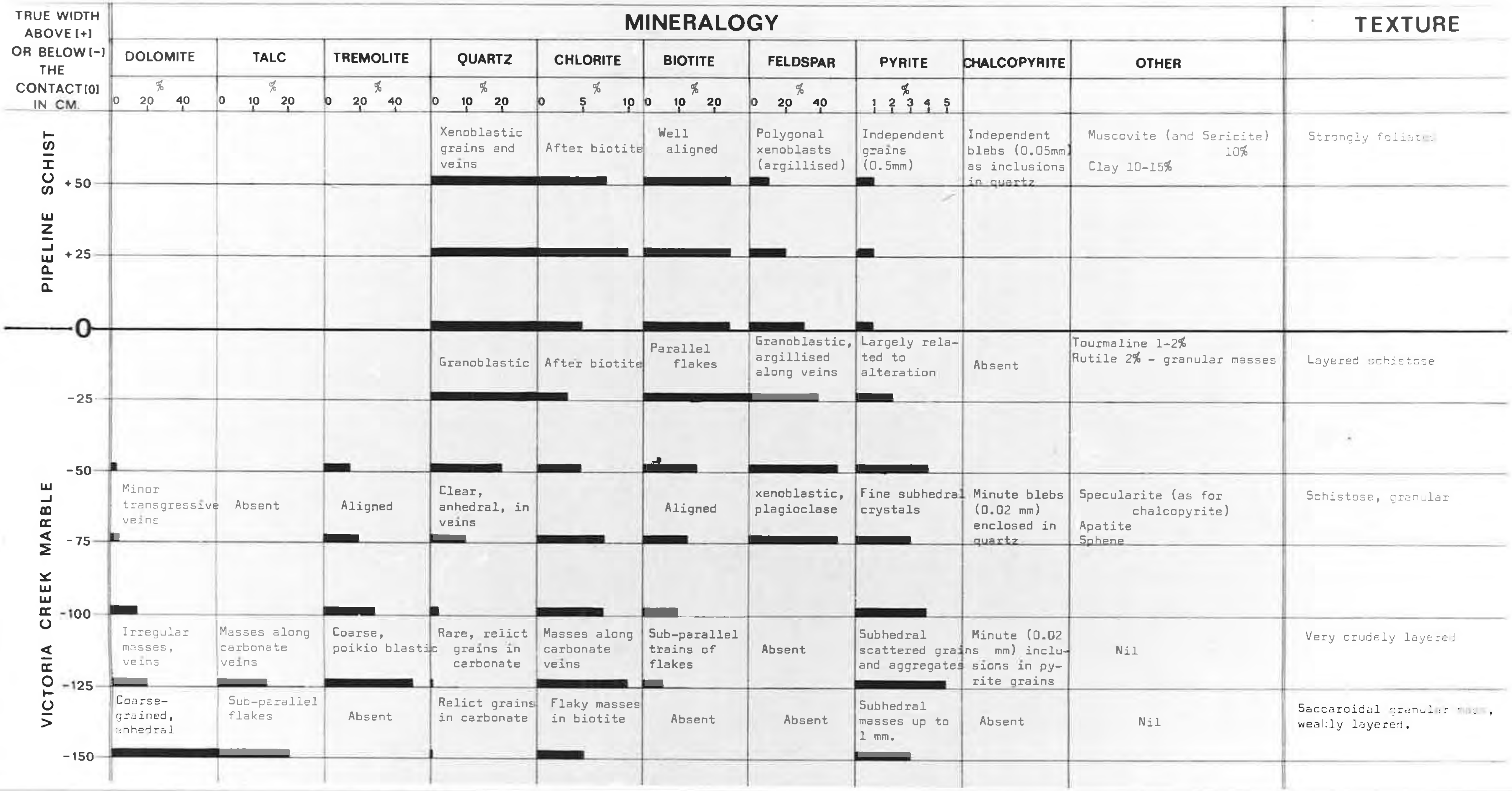
At the base there is a rapid transition from the Ukaparinga Schist to the marble, as previously described. Here compositionally and petrologically the carbonate is calcite with very low magnesian content, but within a few metres the carbonate chemically approaches a true dolomite (Table 4). Towards the top of the unit, the magnesia content progressively increases (Table 5). The ratio of CaO:MgO is 2:1 at the base, 1.1:1 from 4 metres to 30 metres, and 0.9:1 from 30 metres to the top.

Mineralogically the marble is quite simple. The main constituents are dolomite, talc and minor chlorite (TS 4317-19 and 4324-29). Pyrite is the only sulphide mineral found (Plate 32); chalcopyrite is almost completely absent both as single grains and as inclusion in pyrite (TS 4316), in contrast to the overlying and underlying schists.

The origin of the marble is problematical, as traces of the textures and mineralogy of the pre-metamorphic rock are entirely lacking (Plate 33). In the Ukaparinga area evidence for replacement of quartz by calcite at the base is quite strong. The Ukaparinga Schist adjacent to the carbonate rock shows hydrothermal alteration effects manifest in argillisation of feldspars, scattered tourmaline and rutile crystals, chloritisation and secondary orthoclase (potash metasomatism) adjacent to quartz veins. At the top the marble grades into carbonatised and chloritised quartz-feldspar-mica gneisses and schists which become progressively less altered (TS 4315-17). This gradation from massive marble, through altered rocks, to less altered rocks, suggest that the marble zones in the Ukaparinga, Southern Hills and Victoria Creek areas have been affected by extensive CO_2 metasomatism and replacement of the original rock, which was an impure dolomitic limestone. South of the South Para River, the Victoria Creek marble bed in the Southern Hills prospect gradually grades into a fine-grained, grey-blue impure dolomitic limestone. The invasion by carbonate was possibly influenced by cataclastic breakdown in a shear zone, as small shears are locally developed in the section examined in detail. At the top the marble grades progressively into quartz-feldspar-mica gneisses and schists over an interval of some 2-3 metres, the contact being taken as the last appearance of carbonate in the rock (Table 6).

TABLE 6

VICTORIA CREEK MARBLE - PIPELINE SCHIST CONTACT



TRUE WIDTH ABOVE [+] OR BELOW [-] THE CONTACT [0] IN CM.	MINERALOGY										TEXTURE
	DOLOMITE % 0 20 40	TALC % 0 10 20	TREMOLITE % 0 20 40	QUARTZ % 0 10 20	CHLORITE % 0 5 10	BIOTITE % 0 10 20	FELDSPAR % 0 20 40	PYRITE % 1 2 3 4 5	CHALCOPYRITE	OTHER	
PIPELINE SCHIST +50				Xenoblastic grains and veins	After biotite	Well aligned	Polygonal xenoblasts (argillised)	Independent grains (0.5mm)	Independent blebs (0.05mm) as inclusions in quartz	Muscovite (and Sericite) 10% Clay 10-15%	Strongly foliated
-25				Granoblastic	After biotite	Parallel flakes	Granoblastic, argillised along veins	Largely related to alteration	Absent	Tourmaline 1-2% Rutile 2% - granular masses	Layered schistose
VICTORIA CREEK MARBLE -75	Minor transgressive veins	Absent	Aligned	Clear, anhedral, in veins		Aligned	xenoblastic, plagioclase	Fine subhedral crystals	Minute blebs (0.02 mm) enclosed in quartz	Specularite (as for chalcopyrite) Apatite Sphene	Schistose, granular
-125	Irregular masses, veins	Masses along carbonate veins	Coarse, poikio blastic	Rare, relict grains in carbonate	Masses along carbonate veins	Sub-parallel trains of flakes	Absent	Subhedral scattered grains and aggregates	Minute (0.02 mm) inclusions in pyrite grains	Nil	Very crudely layered
-150	Coarse-grained, anhedral	Sub-parallel flakes	Absent	Relict grains in carbonate	Flaky masses in biotite	Absent	Absent	Subhedral masses up to 1 mm.	Absent	Nil	Saccaroidal granular mass, weakly layered.

East of the Mt. Crawford Granite Gneiss, Mills (1963) described an "upper tremolite" bed which the author inspected cursorily during the course of field work associated with this thesis, and initially placed stratigraphically well above the Victoria Creek Marble. However, the existence of the Murray Vale Thrust and Fault proposed by Mills (1973) has forced a reassessment, and check field work has confirmed a strong likelihood that Mills' (1963) "upper tremolite" is in fact a repetition of the Victoria Creek Marble. In all respects it is identical (TS 4604-05), and stratigraphically it is located within a sequence identical to that studied by this author in the Ukaparinga area. This opens exciting possibilities for further exploration, as repetitions of Ukaparinga Schist may well be located underlying the "upper tremolite", which can be traced from Speck Gully, through Victoria Creek, to Tweedie Gully, well north of the mapped area.

TABLE 7

TYPE SECTION - PIPELINE SCHIST

SOUTHERN HILLS AREA

TRUE HEIGHT ABOVE BASE (metres)	MINERALOGY %									TEXTURE
	QUARTZ	FELDSPAR	BIOTITE	CHLORITE	MUSCOVITE	TOUR-MALINE	PYRITE	CHALCO-PYRITE	OTHER	
PEWSEY VALE FORMATION										
		45		10					Scapolite 10 Biotite Epidote 10 Zircon Sphene Hornblende 20	Massive, granuloblastic
		40-50	5-10				2-3		Actinolite 50	Massive, fibrous
		30					trace		Tremolite 33 Epidote 30 Diopside 10-15	Sphene 3-5
QUARTZ - BIOTITE - FELDSPAR SCHIST	30-40	10	15	10-15	nil	1	1-2	nil	Sericite 20-30	Very fine-grained, weakly foliated.
120										
	30	10	20				1		Kyanite 1-2 Sericite 40 Zircon Apatite	0.1 mm.
100	40	30	15	5	10	1			Apatite, Zircon	Schistose
	30-40	5-10	nil	nil	nil	nil	5	nil	Sericite 40-50 Clay 5-10	SERICITE-QUARTZ SCHIST
FELDSPAR - QUARTZ - MICA SCHIST										
80	50	25	10	1	5	trace	1	nil		Weakly layered
	50	40			10		1		Rutile	0.4 mm.
	22	70	6	1	trace	1	trace	nil	Rutile, apatite	Weakly layered
	25	50	3	5	15	trace	1-2	nil	Zircon, rutile, Apatite	Weakly schistose
60	90	5-8	nil	1-2	nil	nil	trace	nil	Carbonate 1	QUARTZITE MARKER
	30-40	30-40	3-5	20	5	nil	1-2	trace	Rutile 1-2 Epidote, zircon	Weakly banded
	40	30-40	2	5-7	10-15	nil	3-5	nil	Rutile 1	Gneissic
QUARTZ - MICA - FELDSPAR SCHIST	20-30	30-40	10-15	10	10	nil	1	nil	Rutile 1-2	Very fine-grained, schistose
	40	20-30	20	5	5-8	nil	2-3	nil	Sphene 1	Weakly laminated schist
40	30	20	40	nil	10	nil	nil	nil	Apatite, zircon	Fine-grained, schistose 0.4 mm.
	60-70	20-30	1-2	3-5	1-2	nil	5	nil		Granoblastic mosaic
	40	50	nil	3	2-3	nil	rare	nil	Hematite 2-3	Granuloblastic
	20-30	30-40	20-25	10	5	access	1	rare	Zircon	Medium-grained, schistose
	20-30	30-40	10	5	10	nil	1	nil	Rutile	Schistose, 0.5 mm.
20	30	30	5-7	10	20	nil	1-2	nil	Specularite 1 Apatite, rutile	Schistose
	10-15	30-40	30-40	10-15	nil	1-2	nil	rare		Strongly foliated, schistose
	20	30-40	30-40	nil	1-2	1-2	1	nil	Apatite	Layered, schistose, 0.4 mm.
	20	30-40	40	5-10	1-2	1-2	trace	trace		Fine-grained, foliated, schistose.
	30	10-20	20-30	5-7	10	1	1	trace		Strongly foliated, schistose.
0 MARBLE	20-30	30-40	30	3-5	-	1-2	1-2	nil	Carbonate 2-3 Rutile 2	Gneissic

PIPELINE SCHIST

The Victoria Creek Marble in the type area grades up into a distinctive quartz-feldspar-mica schist which was dubbed "Pipeline Schist" by the drillers during the exploration programme over the Ukaparinga Mine area, because it was intersected in the vicinity of the Warren-Kapunda pipeline. Subsequent regional mapped showed that the Pipeline Schist was a mappable unit within the broad belt of gneissic and schistose rocks surrounding the Warren Inlier.

As with the Victoria Creek Marble, the type section is located at the Southern Hills Prospect, 3.2 kilometres south of Williamstown, and is supported by similar outcrop and diamond drill core data. A summary of the detailed 124 metre true thickness investigated is shown in Table 9. The rocks are medium-grained at the base to fine-grained at the top, and consist chiefly of quartz-mica-feldspar schists (Plates 36 and 37). The feldspar is sometimes oligoclase and sometimes microcline, or both. Pyrite is ubiquitous (Plate 38) and mineragraphic examination of drill cores showed minor chalcopyrite mineralization present. About 55 metres above the base thin (5 metre) persistent pink arkosic sandstone bed occurs (Plate 40) which forms a useful marker horizon within the sequence (TS 4262).

Towards the top, the Pipeline Schist becomes a fine-grained quartz-biotite-feldspar schist, the schistosity paralleling the bedding which is shown by flattened porphyroblastic knots of sericite. Within these knots tiny (0.05 mm) grains of kyanite (TS 4611) could be discerned similar to those recorded by Mills (1963) from equivalent rocks in the Mt. Crawford Forest. At the top there is a sharp contact with the calc-silicate rocks of the overlying Pewsey Vale Formation.

PEWSEY VALE FORMATION

Overlying the Pipeline Schist is a series of calc-silicate rocks and calc-schists of variable thickness interbedded with fine-grained quartz-biotite-feldspar schists. These have been named the Pewsey Vale Formation, after the prominent Pewsey Vale Peak (630 metres above sea level) located 17.0 km northeast of Williamstown. Although not located within the present thesis area, Pewsey Vale Peak and its surrounding hills are composed of these rocks and they have been studied in detail by Offler (1967). In 1972-73 the sequence was traced continuously from the Pewsey Vale area to Mt. Crawford in the course of the investigation of a Special Mining Lease for Crane Enfield Metals, Pty. Ltd.; hence the appropriate name is retained for this calc-silicate rock group in the Williamstown area.

Because the calc-silicates and the schists are intimately interlayered and lens into one another along strike, no attempt has been made to establish a type section. The base is taken as the first appearance of calc-silicate rock above the sericitic Pipeline Schist, and the top is marked by the transition to a preponderance of thick, massive quartzites. The average true thickness is about 500 metres.

The calc-silicates are generally finely-banded, green to whitish rocks; those in excess of 3 metres thick weather out prominently and can be followed continuously for up to 2-3 kilometres. The textures vary, the more siliceous ones having a saccharoidal appearance (Plate 43) while others may be massive or fine-grained. There is a wide range of mineralogical variations, but quartz is ubiquitous and diopside, actinolite, K feldspar and scapolite are almost invariably present. Epidote was noted on the western side of the Warren Inlier, but none was seen in the calc-silicates east of the Inlier. They were probably originally shaly or feldspathic limestones interbedded with dolomitic shales and argillaceous sediments.

The interbedded schists are silvery-brown micaceous rocks of varying composition and appearance. They are strongly foliated, resulting in platy outcrops, and grade into actinolite schists (Plate 42) transitional to the calc-silicate beds. Some range to garnet-bearing more gneissic types, where coarse quartz segregations become common. They are probably derived from pelitic and magnesian-rich argillaceous sediments.

UNDALYA QUARTZITE EQUIVALENT

At the top, the Pewsey Vale Formation passes into a prominent massive saccharoidal quartzite, which forms the high ridge known as "Blue Rocks" northeast of Williamstown. Above this quartzite the sequence becomes very much more arenaceous, and a number of quartzite bands occur, ranging from 30 cm. to 6 metres in thickness. They form quite prominent ridges in the northeastern part of the mapped area. Most are well-bedded, but cross-bedding is rare. They are strongly jointed, and consist of glassy quartz (95%) with microcline, plagioclase, muscovite, tourmaline, biotite and zircon.

The quartzites are interbedded with mica-schists and minor calc-silicates similar to the Pewsey Vale Formation. On the rather tenuous grounds that these are the first arenaceous beds above a dominantly dolomitic and argillaceous sequence overlying the Rhynie Sandstone, the group of quartzites are equated with the Undalya Quartzite.

MINERAL VEINS

A large number of mineral veins, occurring both as sheet-like bodies parallel to the foliation and also as irregular bodies discordant to the foliation, are found throughout the area mapped. They show many features common to the vein deposits which occur throughout the Mt. Lofty Ranges. The most common are simple massive quartz veins, which may contain minor rutile and very rare free gold. Pegmatites are relatively abundant east of the Kitchener Fault, and these have been the focus of some sillimanite, kyanite, beryl, mica and feldspar mining activity in the past. Minor amphibolite dykes also occur east of the Kitchener Fault.

QUARTZ VEINS

Narrow veins of milky or translucent quartz occur in all formations in the area, though they are most abundant in the schistose rocks and in the vicinity of faults. They are mostly short, although some up to 20 metres long occur within the Mt. Crawford Granite Gneiss, and one vein almost 150 metres long occurs in the Barossa Complex near the spillway. Minerals other than quartz are rare, although coarsely crystalline irregular aggregates of titaniferous hematite are scattered through veins in most formations. Some veins in the Barossa Complex and east of the Kitchener Fault carry tourmaline, large isolated feldspar crystals and occasionally a few large muscovite flakes, though these are probably quartz-rich pegmatites rather than true quartz veins. The latter have probably been derived from the containing rock by lateral secretion into tension fractures and in the vicinity of these fissure fillings there is some alteration of micaceous minerals to sericite.

The gold-bearing quartz veins, for example in the Deloraine field, commonly contain abundant pyrite, and high gold assays are generally reflected by the presence of copper sulphides, the richer veins assaying up to 9% Cu. Here the quartz is cavernous, with honeycomb structure containing abundant quartz crystals.

PEGMATITES

Pegmatites are common in the higher grade metasediments east of the Kitchener Fault, but are absent from the biotite-grade rocks west of the Kitchener Fault. Two types of pegmatite can be distinguished; the forcefully emplaced dilational type and the passively emplaced replacement type. The mineralogy of both types conforms with the "simple pegmatite" classification of Turner and Verhoogen (1960).

(a) Dilational

These are almost always conformable with the foliation in the surrounding country rock, and may form dykes up to 20 metres wide. Most are about 50 metres long. The wall rock foliation around many of the larger bodies is strongly warped (Plate 44) and closely conforms to irregularities in the pegmatites, suggesting forceful emplacement (Chadwick, 1958). Alteration of the rocks adjacent to the pegmatite veins is also common, generally exhibited by replacement of biotite by muscovite or sericite. The muscovite within the surrounding foliae is generally heavily stained with limonite, and may contain rutile crystals.

The grain size and mineral composition of the dilational pegmatites is extremely variable, but microcline and plagioclase (An_{10}) are the commonest constituents (TS 4433). Quartz is also a major constituent, and rarely faint zoning consisting of quartz and albite layers is present, though more commonly quartz occurs in graphic intergrowth with the feldspars. Muscovite sometimes occurs in concentrations sufficient to have prompted some past mining activity. In the book form it tends to occur, with quartz, in the core and the outermost zones of the zoned pegmatites, but elsewhere it occurs as sporadic aggregates of sheets up to 30 cm. in diameter. Heavy staining and fracturing have reduced the sheets to scrap grade. Similarly, minor concentrations of beryl in some of these pegmatite dyles have attracted prospecting interest. The beryl crystals, which rarely exceed 5 cm in diameter, occur in various colours, the most common being a yellow-green variety. The concentrations are insufficient to support a mining operation. Tourmaline appears more common in the zoned pegmatites than in the unzoned bodies, the stumpy black crystals aligned radially outwards from the core. Tiny fractured bluish-green apatite crystals are disseminated widely throughout the pegmatites, and bright red transparent almandine garnets occur very rarely in some pegmatites as small (1 mm) euhedral grains.

(b) Replacement

These pegmatites generally occupy joints or other fissures and form irregular pods (Plate 45) which often cut across the foliation. They commonly grade diffusely into the surrounding rock, as opposed to the sharp contacts of the dilational type. This gradational contact suggests that these pegmatites formed by late stage solutions percolating through available fissures from local sources adjacent to the veins. Their mineralogy is strictly analogous to that of the containing rocks, and the grain size varies with the thickness, the thickest pods being the coarsest. They often have a central (coarser) core of quartz, grading out to fine-grained minerals (generally feldspar) at the contact. The feldspar is well-twinned subhedral to enhedral microcline, the absence of plagioclase distinguishing them from the dilational type. Both the quartz and the feldspar grains show no sign of strain, as opposed to those in the surrounding schistose rocks, hence they must have been passively emplaced during or subsequent to the last period of deformation.

AMPHIBOLITES

Amphibolite rocks are common in the Springfield Sub-group, and are particularly well developed south of the Warren Reservoir and north of Victoria Creek. Although they are not exclusive to the Springfield Sub-group, occurrences in other formations are rare, which is rather puzzling as they are clearly of intrusive origin. Mills (1963) showed that on the basis of their composition and environment they could be regarded as igneous dykes and sills, probably originally of dolerite composition. The dykes range up to 30 metres in width, and can reach 800 metres in length. Most show a weakly developed schistosity or crude gneissosity, and consist of large porphyroblastic hornblende crystals (Plate 44) usually very strongly pleochroic pale yellowish-brown to deep bluish green, set in a ground mass of plagioclase and quartz. The plagioclase is generally albite-oligoclase.

An amphibolite dyke 3 metres thick was intersected at a depth 200 metres below ground level by one of the drill holes in the Southern Hills prospect. The dyke, which had intruded the Ukaparinga Schist, was a medium grained (5 mm.) granoblastic rock consisting of 95% dark green pleochroic hornblende with small interstitial grains of plagioclase (An_{50}) (TS 4627). Iron ore was commonly present as scattered grains. No other observations of amphibolite were made either on the surface or subsurface west of the Warren Reservoir.

METAMORPHISM

Offler and Fleming (1968) discussed the regional metamorphism of the Mt. Lofty Ranges, and divided the region into metamorphic zones based on the maximum areal distribution of a specific index mineral, following the traditional terminology developed in Scotland for the formation of the Daldradian schists by metamorphism of a pelitic sedimentary sequence (Barrow, 1893). In the Williamstown area, the Kitchener Fault separates their biotite zone to the west from the sillimanite zone on the eastern side (Fig. 16). Mills (1973) further subdivided the eastern side into a sillimanite-muscovite zone and a kyanite-andalusite zone, using terminology which he appears to have developed himself. I prefer the Scottish terminology, and in particular the logical approach to metamorphic zones and facies expressed by Winkler (1967) whose "Barrovian-type Facies Series" corresponds well with metamorphic facies developed in the Mt. Lofty Ranges.

Several metamorphic events have been postulated to have affected the sediments in the Mt. Lofty Ranges. Talbot (1963) proposed that three periods of metamorphism had affected rocks of the Barossa Complex, the last two low-grade ones respectively occurring prior to and subsequent to the deposition of the Burra Group. Copper and Compston (1971) suggest that another high-grade event metamorphosed the Barossa Complex to the upper amphibolite facies about 870 million years ago, though Talbot (1972) disputes this as being incompatible with their data. The final Palaeozoic metamorphism has been dated at 490 million years, during the Lower Ordovician Delamerian orogeny (White, et al., 1967). This event overprinted a green schist facies metamorphism on all rocks within the Mount Lofty Ranges. Difficulties with the age dating methods has cast all these proposed ages in a somewhat dubious light.

BIOTITE ZONE

Within this zone fall the fine grained rocks west of the Kitchener Fault, including the Barossa Complex. The Barossa Complex has undergone at least two distinct phases of metamorphism, corresponding initially to the upper amphibolite facies of Winkler (1967), and subsequently having been retrogressed to an intermediate green schist facies. This can be seen in thin section, where original diopside, sillimanite and garnet observable sporadically throughout the Complex represent an original sillimanite-almandine-orthoclase subfacies of Winkler's upper amphibolite. Retrogression is demonstrated by replacement of diopside by actinolite, feldspar by sericite, plagioclase by epidote, the assemblage (which includes biotite) typifying the intermediate temperature quartz-albite-epidote-biotite subfacies within the greenschist facies of Winkler (1967).

Talbot (1963) found feldspar gneiss pebbles in the basal conglomerate overlying the Barossa Complex which he equated with the lower greenschist facies of Fyfe _et al_. (1958), suggesting that a third metamorphic event had preceded the deposition of the Burra Group. It is difficult to either prove or disprove this suggestion, as this corresponds with the present degree of metamorphism of the enclosing Burra Group sediments.

Within the overlying Burra Group sediments, the phyllites are the best indicators of metamorphic grade. Their mineralogy includes quartz, biotite, chlorite, minor feldspar and in some cases, carbonate. The biotite is invariably pleochroic from pale green to brown. Rocks rich in platy minerals develop a good cleavage. However, many of the feldspathic sandstones still have clastic grains although these are strained. Strain shadows are often observed passing from the clastic grains into the adjacent cement, indicating that the sediment has been strained since its deposition. The dolomites, particularly those close to the fault, show complete recrystallization and any quartz grains present are deformed. Their mineralogy, which includes calcite, tremolite, quartz and epidote close to the fault, indicates that temperatures of around 450°C operating under high fluid pressures had metamorphosed siliceous carbonate rocks to the greenschist facies (Winkler, 1967). Away from the fault, tremolite and epidote become rare and a common mineral assemblage is quartz, dolomite, calcite, biotite and chlorite, suggesting a lower temperature range.

KYANITE ZONE

The medium-grained rocks surrounding the Warren Inlier east of the Kitchener Fault can be placed in this metamorphic zone. Typical diagnostic minerals of the metamorphosed pelitic rocks include andalusite and kyanite (now generally retrogressed to sericite), with muscovite, biotite, plagioclase (oligoclase) and quartz. The presence of staurolite restricts these rocks to the kyanite-almandine-muscovite subfacies of the almandine-amphibolite facies of Turner and Verhoogen (1960), terminology also used by Winkler (1967).

The lower section of the Victoria Creek Marble, with its assemblage of dolomite, talc and calcite, suggests low temperature metamorphism of siliceous dolomite. Metz and Winkler (1963) showed experimentally that at a fluid pressure of two kilobars, these minerals would be in equilibrium at 425°C. For each increase in pressure of one kilobar, the temperature must be about 20°C higher. However, since the temperature is strongly dependent on the composition of the fluid phase, and no estimate of load pressure can be made, this information is of little use in determining the actual conditions of metamorphism.

The absence of calcite and presence of tremolite in the upper section of the Victoria Creek Marble is interesting. This mineralogy corresponds with low-temperature metamorphism of a magnesite-bearing siliceous dolomite, although once again the dependence on partial pressure of CO_2 suggests that this is not a reliable temperature indicator (Winkler, 1967).

The calc-silicate rocks overlying the Pipeline Schist contain plagioclase, epidote, hornblende, and diopside, which are diagnostic of marls metamorphosed to the almandine-amphibolite facies. The presence of epidote restricts them to the lower grades of this facies (Winkler, 1967).

Thus in balance, the available experimental data suggest that temperatures in excess of 450°C (probably closer to 550°C) and pressures in excess of 2.5 kilobars (probably closer to 6 kilobars) prevailed in the Kyanite Zone.

SILLIMANITE ZONE

The coarse-grained rocks of the Warren Inlier and its unconformably overlying blanket of Rhynie Sandstone Equivalent, together with the beds of argillaceous origin in the variable assemblage within the Springfield Sub-Group, all have one thing in common. This is the presence of sillimanite in lieu of kyanite, noted independently by the author and by Mills (1973). The co-existence of sillimanite and muscovite reported by Mills (1973) defined the so-called first sillimanite zone of the Barrovian-type facies series, and restricts the conditions to temperatures between 600 and 650°C and pressures in excess of 2.5 kilobars (Winkler, 1967). The metamorphism in this zone has been thoroughly discussed in Mills (1973) and my own work largely duplicates his description.

Later retrogression of these rocks, probably the same greenschist facies metamorphism which affected all the rocks within the Williamstown area, downgraded much of the sillimanite to sericite.

STRUCTURE

FOLDING

Offler and Fleming (1968) show that two, and in some cases, three periods of deformation had affected the rocks on the eastern side of the Mt. Lofty Ranges. Each deformation was accompanied by the formation of both planar and linear elements, and the symbols used by Offler and Fleming will be used in this discussion:

F_1, F_2, F_3 = first, second and third generation fold structures.

S_O = surface which can clearly be demonstrated to be original bedding.

S = surface formed by metamorphic effects or where bedding has been transposed.

S_1 = slaty cleavage or foliation parallel to the axial surface of F_1 folds.

S_2, S_3 = crenulation cleavage or foliation parallel to the axial surface of F_2, F_3 folds or crenulations.

L_1 = lineation parallel to F_1 folds or intersections of S_O and S_1.

L_2 = lineation defined by crenulations in S_1.

L_3 = lineation defined by crenulations in S_2.

The meridional F_1 folding commenced during prograde metamorphism, the peak amphibolite facies metamorphic event occurring at the end of F_1 or the commencement of F_2. This has been dated by White, Compston & Kleeman (1967) at 490 million years. The F_2 and F_3 fold periods were accompanied by retrograde metamorphism to greenschist facies, and probably occurred during the same orogeny (the Delamerian orogeny) as the F_1 folding.

Surface creep (Plate 48) is severe in most of the hilly areas, and care must be taken to ensure the accuracy of structural readings.

FIRST DEFORMATION

Good examples of the first phase of deformation are comparatively rare in the schistose rocks, as the bedding has generally been completely destroyed by recrystallization. However, it is well shown in rocks where S_0 is clearly preserved, such as the Burra Group rocks west of the Kitchener Fault (Plate 49) and the Rhynie Sandstone Equivalent east of the Kitchener Fault (Fig. 25). In these rocks S_1 is seen as a foliation defined by the preferred orientation of platy minerals, producing a well-developed cleavage in shales and phyllites. In the more massive rocks a fracture cleavage is developed.

The style of the F_1 folds is demonstrated by the anticline, overturned to the west, which comprises the Barossa Complex. This fold is assymetric, the eastern limb of the anticline being longer than the western limb, and shows the regional scale of the F_1 folding. In the Burra Group rocks the F_1 folds have axial planes striking north to north-north-east with axes generally plunging 5-20° south, although some north plunging folds can be seen. For example, in the Deloraine Mine area structural analysis of an open anticline gave an F_1 fold axis plunging 24° to 028°. A more typical broad adjacent syncline in the same area showed a horizontal axis trending 005°. The anticline in the Warren Schist east of the Ukaparinga mine showed an axial surface striking 010° and dipping steeply eastwards, and the fold axis plunges 10° north.

The schists, particularly those in the Ukaparinga mine area, show a well-developed lineation parallel to the F_1 fold axes which is seen as a preferred orientation of prismatic crystals such as hornblende, tourmaline, sillimanite, etc. The lineation is also shown by the intersection of the simple planar schistosity S_1 with S_0, seen most clearly in the Rhynie Sandstone Equivalent, although here S_1 is parallel, or at a very small angle, to S_0. The alignment, of relict sillimanite in particular, parallel to L_1 suggests that metamorphic temperatures reached their peak during or at the end of the F_1 episode.

SECOND DEFORMATION

Very few major second-generation structures were seen in the Williamstown area, though F_2 folding on a mesoscopic scale is quite common in all rock units. An excellent crenulation cleavage S_2 is developed parallel to the axial surfaces of the F_2 folds in most rock types (Plate 51). This cleavage has evolved from the bending of the S_1 surface, and varies from mild, open crenulations through tight sawtooth folds (Plate 50) to an almost complete transposition of S_1 to a new gneissose S_2 fabric. The style of folding varies similarly from open low amplitude symmetrical folds with high-angle axial planes to S-shaped concentric folds with low-angle (10-15°) axial planes. Most F_2 axes plunge north-west at shallow angles (Fig. 26). In contrast to the F_1 folds, overturning is uncommon, and their orientation is generally NW-SE, producing dome and basin patterns when refolding F_1 structures.

A well-developed lineation L_2 lying along S_2 is seen in most rocks exhibiting crenulation cleavage, and is formed by the intersection of S_1 and S_2. Where S_1 has been completely transposed to a new gneissic S_2, some mineral lineation defines L_2. The alignment of hornblende prisms in the amphibolites is generally parallel to L_2.

THIRD DEFORMATION

The presence of a third period of deformation was suggested by the occasional observation of warping of the S_2 crenulation cleavage (Plate 53). These inferred F_3 folds were unevenly distributed throughout the Williamstown area, and were best developed in schists of the Springfield Sub-Group.

The F_3 folding in these rocks was generally a quite open concentric style, with wavelengths of several metres. No S_3 were observed in these rocks, but in some schists east of the Kitchener Fault where tighter folds were found an incipient S_3 crenulation cleavage had developed. The tighter folds had axial surfaces that dipped steeply east (Fig. 27) and the strike was quite variable, though statistically NW-SE was the most common.

FAULTING

The importance of large-scale faulting in the formation of the Mt. Lofty Ranges has been recognized since the turn of the century (Howchin, 1906). Within the Williamstown area, the largest and one of the most important faults in the Ranges, the Kitchener Fault, dominates the geology. As well as this, a number of large strike faults and many cross faults have been recognised. Faulting appears to be related to the Delamerian orogeny, occurring subsequent to the metamorphism when the colder, more brittle rocks responded to compressional stress by breaking rather than folding.

KITCHENER FAULT

This fault has been traced continuously from Tarlee in the Mid-North of South Australia, through Williamstown to Lobethal, a distance of 70 kilometres (Thomson, 1969). An offset fault from Lobethal, south 45 kilometres to Mt. Magnificent on Fleurieu Peninsular is probably a continuation of the Kitchener Fault, and Thomson (in Parkin, 1969) links this with the Cygnet Fault through the centre of Kangaroo Island, giving a combined length of 260 kilometres. Thomson (in Parkin, 1969), following Sprigg (1946), classified the Kitchener Fault as a steep reverse fault, which agrees with observations made in the Williamstown area. There the thrust plane, which dips 60°-70° east, appears to be related to the axial plane of the large first generation overturned syncline which occupied the Williamstown-Kersbrook valley. The fault zone is visible only on the north side of the South Para River, where it is seen to be less than 30 cm. wide, but elsewhere in the area its actual location is obscured by soil cover and it is difficult to locate it precisely (Plate 56).

Since the fault brings kyanite-grade rocks into contact with biotite-grade rocks, movement must have been subsequent to the cooling of the metamorphic rocks, and thus post-dates the F_3 folds. The actual displacement is enormous - certainly in excess of 3000 metres and perhaps as much as 6000 metres (Appendix 4) - and this suggests activity extending through a long period, with possible reactivation in subsequent orogenic episodes. Sprigg (1945) believed movement had occurred during the

Tertiary and Recent, though Mills (1973) discounts this, describing the prominent scarp as a result of differential erosion. However, north and south of the Williamstown area, where rocks of similar properties occur on either side of the fault (for example north-west of Seppeltsfield) the scarp is still visible, so Sprigg's interpretation is more likely. This was confirmed by the gravity survey (Fig. 17), which showed that the scarp corresponded to the actual fault trace at Williamstown, and that the fault trace was some 400 metres east of the position given by Mills (1973).

UKAPARINGA FAULT

Mills (1973) describes several thrust sheets in the metamorphic rocks east of the Kitchener Fault. Only one of these, his Murray Vale thrust fault, was observed independently by the author, though the existence of the Ukaparinga Fault had been suspected as early as 1969. The latter fault can be observed directly in the adit of the Ukaparinga mine (Plate 27), where a contorted zone about two metres wide occurs at the boundary of the Rhynie Sandstone and the Ukaparinga Schist. Mills (1973) infers that the copper lies in the brecciated zone of the Ukaparinga Fault, but my studies quite clearly refute Mills' assumption. The copper is restricted to the Ukaparinga Schist, which is demonstrably an independent stratigraphic unit, and quite unrelated to the fault.

Drilling shows that the Ukaparinga Fault dips 70°-80° east in the northern part of the mine area, through vertical in the central part, to 70°-80° west in the Southern Hills. Displacement along the fault may have been large, as Mills (1973) suggests it displaces the kyanite and sillimanite zone boundaries, but I found it difficult to make any estimate as I was unable to confirm sillimanite grade metamorphism of the Rhynie Sandstone on the mine area. If the Ukaparinga Schist and Victoria Creek Marble are equivalents of the Skillogalee Dolomite, movement of a hundred metres or so at most would be indicated.

MINOR FAULTS

A large number of minor faults locally disrupt the rocks. Many are expressed by large blocky outcrops of hydrothermally deposited quartz filling fracture zones, particularly in the quartz-rich metasediments, while disrupted bedding, breccias and shear zones mark other faults. Movements are generally of the order of two metres or so, and the attitudes are commonly vertical. The minor faults appear to form a conjugate set, being parallel to the limbs of macroscopic F_1 folds. They are commonly thrust faults, though normal faults also occur. The vein-fillings are sometimes the host of gold, and to a lesser extent copper mineralization, and are discussed in more detail in the next section.

ECONOMIC GEOLOGY

MINERAL DEPOSITS

The mining industry has been represented in the Williamstown district from the first days of settlement in 1839. John Hammatt found copper east of what is now the Deloraine Gold mine in 1844, as well as at Ukaparinga and several pockets north to Lyndoch, his most successful operation being the Enterprise mine which opened in that year.

In 1858 Job Harris and his mates discovered alluvial gold in Spike Gully, near the present Barossa Reservoir. The diggings flourished and died quickly, but in 1884 Watts made a timely discovery in Watts Gully, a tributary of Dead Horse Creek, which revived interest in the area. These gold rushes, and the later ones from 1909 associated with the Deloraine goldfield, brought transient increases in population. The longest running operation is the clay quarry at Springfield, which has been active since the 1940's. Other minerals mined at one time or another include iron, barite, feldspar, mica, rutile and beryl, but the mining industry can never be claimed to have been the mainstay of Williamstown's economy.

GOLD

The Barossa and Mt. Crawford Gold fields both lie within the mapped area, and have been discussed by Brown (1885), Woodward (1886) and Brown (1908). Basically alluvial diggings, they comprise hundreds of shallow pits and shafts, and I do not propose to discuss them as they have been adequately described by the previous authors. The Deloraine goldfield, however, has not been so well reported. It contains interesting gold and copper mineralization in hydrothermal veins, hence it is worth some study.

Deloraine Goldfield

The first discovery of gold in this field was made by Hewlett and Scanlon, in an ironstained quartz gossan on Section 1548, Hundred of Para Wirra (Anon., 1909). They called their prospect the Day Spring, and the first crushing at the Mt. Torrens Government Battery yield 190 gm. of gold from 19 tonnes of stone. Because the mine was beside a small watercourse locally known as Deloraine Creek, the field became known as the Deloraine.

A company was formed in 1910, and work proceeded vigorously in opening up the mine with shaft-sinking, driving, cross-cutting, and erecting buildings and machinery. By mid-1914 total tonnage treated amounted to 4,000 tonnes, with a gross value to £12,500, and workings extended to 100 metres below ground level. In its peak years from 1915 to 1920, up to 5,000 tonnes of ore containing 15 gm. of gold per tonne and 0.5% copper were being treated annually. The mine became unprofitable in 1921 and was shut down. In 1923 a syndicate prospecting outside the limits of the old workings found gold, and the Deloraine South Gold Mine Company N.L. was formed. However, the operation was unsuccessful and in 1925 the company merged with the Deloraine North property to form Deloraine Consolidated Gold Mine, N.L., concentrating its activities on a new discovery north of the old mine (Fig. 28). After sinking a shaft to 30 metres and driving along the lode at this level, the company went into liquidation in 1926.

Little was done until 1929, when the New Deloraine Gold Mining Company was formed for the purpose of re-opening the original Deloraine mine. This company successfully worked the mine for 11 years, during which time it was the chief gold-producer in the State. The main shaft eventually reached a total depth of 190 metres, with six working levels and underground workings totalling over 1500 metres. The mine was closed and the company went into voluntary liquidation in 1941.

During the lifetime of the Deloraine field over a dozen gold mines were worked over an auriferous belt of country some 6 kilometres in length; mines which included the Uraparinga, Prairie Deloraine, Deloraine King, Deloraine Blocks, Deloraine South, Deloraine North, Sheoak Ridge, Deloraine Queen, Lady Emily, Easter Gift, Birthday Gift, Gira, Telfer North, Michael's Mine, Pearce's Find, etc. None, however, achieved the success of the original discovery, from which over 100,000 tonnes of ore averaging over 15 gm of gold per tonne were extracted.

In all the mines, the occurrence of the gold was identical, and the Deloraine mine is the best example. Here dolomitic phyllites of the Saddleworth Formation have been fractured, and the fissures filled with ferruginous milky quartz forming veins of honeycomb quartz and quartz crystals. The cavernous quartz lodes exposed in the mine contain traces of chalcopyrite and more commonly chalcocite, covellite, and native copper, together with limonite, pyrite and barite. Free gold is associated with the copper, and assays of some ore parcels ranged as high as 9% Cu. The hydrothermal introduction of the quartz has caused alteration of the phyllite, with the development of sericite halos around the veins.

The average width of the main lode in the Deloraine mine was one metre, but it often pinched out to nothing, and occasionally swelled out into bulges up to 2 metres wide. In some of these wider zones the gold content went as high as 130 gm. per tonne.

A detailed microscopic study of the lode zone intersected in the Department of Mines diamond drill hole No. 3 was carried out by the author (Appendix 5). This showed that the zone is characterised by a magnetite-pyrite-chalco pyrite-specularite assemblage in a quartz-calcite-tourmaline-sericite-chlorite-apatite gangue. The paragenesis suggests that this is a hydrothermal, partly pneumatolytic ore with transitional mesothermal-epithermal characteristics. Injection of the veins under extreme stress is shown by the intense optical strain in the quartz components. An examination of several smaller, incipient lode structures elsewhere in the drill core demonstrated that the initial stages of mineralisation by small amounts of magnetite, pyrite, chalcopyrite, tourmaline and calcite occurred in zones where excessive shear had developed within the phyllite.

Magnetite was the first mineral to form: it was usually accompanied by tourmaline even in the weakest mineralised zones. There is a fall-off in magnetite as the intensity of alteration diminishes away from the veins, and this may be a basis for further geophysical exploration in the area. Mineralisation occurred when quartz-calcite-tourmaline veins introduced elongate fine-grained chalcopyrite into the rock. The sulphide displays a direct association with the coarse-grained calcite and rather finer-grained tourmaline within the vein structures. Although no gold was found in the cores examined, one would expect it to be associated with the chalcopyrite. Brief studies of the other gold mines in the field suggest a similar origin for all of them.

IRON

Second to gold, mining of iron has been an important activity in the district. The source of the iron ore was the Hematite Sandstone member of the Rhynie Sandstone, discussed on pages 28 - 29. The presence of iron in this horizon has been known since the 1880's (Scoular, 1879) and it has been worked from time to time since then as a source of iron flux. Some experimental smelting of the ore was attempted around the turn of the century, when pig iron is reported to have produced at Gawler (Jack, 1922) but the deposit was too small and the ore too soft, micaceous and excessively siliceous for use in smelting.

The main workings, known as the Mt. Bessemer mine, were located on the ridge at the northern side of the present South Para Dam, and are now covered by the waters of the reservoir. Ward (1912) estimated that this deposit contained about 500,000 tonnes of ore grading about 60% iron, but with SiO_2 ranging up to 30%. At that time about 40,000 tonnes had been mined as flux. In the 1930's limited mining was carried out to provide ingredients for cement making and for pigments, while during World War II 6759 tonnes were mined for use in the manufacture of explosives. Newbold General Refractories Ltd. carried out test drilling along the hematite sandstone bed south of the reservoir in 1973 in an attempt to prove sufficient reserves of fluxing ore to justify a new mining operation, but were unsuccessful.

BARITE

Just south of the South Para Reservoir, near Mary Gully, an adit was found following a barite vein within phyllonites of the Barossa Complex. Known as the Williamstown barytes mine, it was first mined in

1909, closed down, reopened from 1918 to 1925 and briefly from 1936 to 1938. Total production amounted to 133 tons. The area became part of the Kersbrook Forest Reserve in 1938, and no further mining is allowed.

The vein was about 60 cm. wide, containing medium-grade barite (S.G. about 4.0 compared with pure barite 4.5), and was apparently worked to a depth of about 6 metres, where it split into several smaller branches and finally lensed out completely. The general strike of the vein was northwest-southeast, with a steep north-easterly dip, cutting across the foliation of the phyllonite.

COPPER

Two types of copper mineralization occur in the district: the syngenetic stratiform deposits within the Ukaparinga Schist, which are thoroughly discussed later, and the hydrothermal vein deposits associated with Deloraine type gold mineralization, discussed previously.

MINOR MINERALS ASSOCIATED WITH PEGMATITES

A great deal of prospecting has been carried out in the past throughout the pegmatite swarm which occupies the eastern part of the area. Many small pits and workings testify to the activities of miners seeking precious stones or other rare minerals in the pegmatite veins, but most of their work has proved fruitless.

Beryl

A small excavation 1500 metres east-south-east of Williamstown, and a number of diggings south of the Warren Reservoir, disclose decomposed feldspar-quartz-beryl dykes. The beryl crystals are generally small and scattered, and much fractured, with little commercial value. It is doubtful if any flawless beryl prisms or emeralds will be found.

Feldspar

The principal occurrence is within a large irregular pegmatite dyke about 110 metres long and of variable width ranging from 2 to 5 metres which outcrops near the crest of Black Ridge, 1000 metres due east of the Southern Hills prospect. The deposit was first investigated around the turn of the century by prospectors searching for gems and subsequently investigated by the Department of Mines in 1924. The feldspar is quite coarse-grained, typically pale brownish in colour, with minor iron-staining due to iron oxides, and typically contains between 1½-2% Fe_2O_3. The latter would make it most undesirable for glass manufacture, which demands less than 0.5% Fe_2O_3 for even low-quality amber glass.

The dyke appears to average 70 to 75% feldspar, generally containing a higher proportion of plagioclase (soda feldspar) than potassium feldspar. The main impurity, quartz, accounts for about 20 to 25% of the rock, which would make the rock a little too refractory for use in the ceramic industry without expensive hand picking, and much too abrasive for miscellaneous uses such as in soaps. The deposit would appear to have little potential while the current ex-mine value of concentrated feldspar remains around $15.00 per tonne.

Mica

The mica deposits occur in the same type of orebody as, and often in conjunction with, the feldspar deposits. Several deposits occur just south of the Warren Reservoir, near the new road bridge. The pegmatite dyke hosts commonly reach 100 metres in length, with variable widths up to 3 metres the coarsest mica being found near the contacts with schist. Shafts up to 20 metres deep and pits up to 40 metres wide mark the old workings. The mica is invariably muscovite, occurring as books about 5 cm. thick with a maximum size of 20 cm. by 25 cm. However, the mica books are extensively fractured and the maximum commercial size is considerably less, averaging about 8 cm. across. In addition, many of the books are crenulated, and the mica is heavily clay and iron-stained. None of the deposits would justify commercial production, even if a ready market for mica still existed.

MINERALS ASSOCIATED WITH THRUST FAULTING

The Murray Vale thrust fault and, to a lesser extent, the other thrust faults in the area have narrow but intense shear zones associated with them. These zones are commonly the locus of strong hydrothermal alteration, which was probably facilitated by the increased permeability in the shear. Generally the alteration is typified by the production of massive beds of sericite, and the regression of biotite to chlorite. In the latter reaction, if the biotite is titanium-rich, and biotites containing up to 4.27% TiO_2 have been recorded, then the titanium is released as rutile, together with quartz:

$$4(Mg,Fe)_3(Fe,Al,Ti)\ Si_3O_{10}(OH)_2 \rightleftharpoons \underset{\text{chlorite}}{8H_2O\ (Mg,Al,Fe)_{12}\ (Si,Al)_8\ O_{20}\ (OH)_{16}} + \underset{\text{rutile}}{4TiO_2} + \underset{\text{quartz}}{4SiO_2} + 2K_2O$$

This is the probable explanation for the rutile concentrations in quartz and clay beds adjacent to the Murray Vale thrust fault, and in Mills' (1973) Wirrianda fault.

Rutile

A large number of occurrences have been noted in the Mt. Crawford forest area. The largest deposit is located just south of the Warren Reservoir, close to Wirrianda homestead. Rutile is finely disseminated through quartz-mica schist, grading about 3% TiO_2, as well as forming quite rich veins within the schist and particularly in laminated quartz reefs, where concentration up to 20% TiO_2 occur. Some ilmenite is also present in places and tourmaline occurs in an adjacent pegmatite dyke. The workings consist of an open cut, about 60 metres long by 10 metres wide, and about 5 metres deep. A deposit of similar size occurs north of Springfield homestead, and rutile is finely disseminated throughout the clay in the A.I.M. sillimanite quarry.

Clay

Several pods of sillimanite and kyanite, occasionally associated with rutile, occur between the Warren Reservoir and Victoria Creek. Around Springfield homestead, these have been hydrothermally altered as outlined above, the sillimanite retrogressing to mica and corundum and in places right through to clay. Kyanite and muscovite have regressed to damourite. The largest deposit has been quarried since 1914, initially by Broken Hill Associated Smelters to make firebricks for the zinc smelters at Port Pirie. Since 1938 it has been operated by Australian Industrial Minerals No Liability (A.I.M.), and the deposit has been reported on variously by Alderman (1942), Armstrong (1949) Gaskin and Sampson (1951) Betheras (1953), Cochrane (1954) and Hillwood (1959). The products are sold under three categories, the most valuable being rock sillimanite which sells for $28.00 per ton bulk loaded on the mine. The rock sillimanite is used in high alumina refractories, and demand is very erratic, ranging from 100 tonnes to 500 tonnes per annum. Reserves are estimated by the company to be about 20,000 tonnes of material assaying 51-55% Al_2O_3 (cf. pure sillimanite 62% Al_2O_3), which is sufficient for over 40 years at maximum production.

The sillimanite occurs as boulders disseminated through a kaolinized sillimanite clay (Fig. 29), which makes up the bulk of the product sold. Sales of this product under the name of "dickite" average a round 100,000 tonnes per annum. The main mineral in it is kaolinite as relatively coarse flakes, plus about 5% of the fine-grained sillimanite, quartz, damourite and rutile. Its lack of plasticity, high firing shrinkage, and lack of uniformity in mineral content limit its usefulness, but satisfactory sales are made to the refractory, paper and print industries in Adelaide. Reserves are quoted as 155,000 tonnes, sufficient for 15 years production.

Alteration of kyanite and muscovite along the Murray Vale thrust fault zone which forms the eastern boundary of the quarry has formed damourite, which is selectively mined and accounts for sales of about 500 tonnes per annum. The chief consumer is the paint industry which adds the mica to anti-corrosive and outside house paint to form a "weathershield" created by the alignment of flakes.

Talc

Pneumatolysis associated with shearing has converted portions of the dolomite beds in the area to talc. The talcose bodies are discontinuous impure lenses elongated parallel to the regional foliation in the dolomites and dolomitic marbles, the contacts generally being gradational. Fine to medium grained talc comprises an average between 15-30% of the dolomites, but occasional lenses are found containing up to 56% talc. Albitization of the surrounding sediments is absent in the

Williamstown area, in contrast to the Pewsey Vale area to the north (Offler 1966), and the talc formation is clearly related to retrograde regional metamorphism of the portions of the dolomite which were selectively tremolitized during the earlier prograde metamorphism of the area to kyanite grade. One deposit which lies just north of Victoria Creek, east of the oval, was worked in 1944 when 56 tons of soapstone were produced (Whittle, 1951) but has not been worked since. The talc in this deposit is snowy white and medium to coarse-grained, except where contaminated by copper carbonates which were disseminated through the rock.

No other deposits have been worked in the area, and because of the discontinuity of the lenses it is unlikely that they would form a workable reserve on their own. However, as a byproduct from open-cut copper mining of the Ukaparinga Schist, the talc could, together with the dolomitic marble, have some economic significance.

OTHER ECONOMIC MINERALS

Dolomitic Marble

The massive dolomitic marble which comprises the Victoria Creek Marble and other dolomitic lenses in the area could be considered as a potential "mineral" resource, particularly if it was recovered as a by-product from open-cut copper mining of the Ukaparinga Schist. The mineralogy and petrology of the marble has been well described in the section on stratigraphy. It is generally medium to coarse-grained, and the numerous assays (Table 4) suggest that selected portions would be suitable as feed for cement or refractory purposes. On the whole, however, it has far too high in silica content to be suitable for refractory purposes, and has too little CaO for cement making. The less chemically attractive portions would suffice for road metal, while the clean talcose lens could be separated for sale in powdered form as raw talc for a multitude of uses.

Sandstone

The Rhynie Sandstone has been quarried on a small scale by the Highways Department for use as road-bed, for which it is eminently suited, and base course under sealed roads. It is unlikely that any large-scale mining would be undertaken, but a ready market for the sandstone, which would form the bulk of the waste material in any open-cut mining project centred in the Ukaparinga Schist, is assured.

MINERALOGY

INTRODUCTION

Metallurgical problems with the Ukaparinga ore probably date back to its original discovery and exploitation, but little information is available. The present study began in November, 1963, when Igor Moisseef pegged claims over the mine, and together with his partner Niki Iwanow in 1964 did considerable bull-dozing, some shallow shaft-sinking and costeaning, prior to setting up a small plant for acid leaching. They selected about 200 tonnes of high-grade (5.6% Cu) ore and produced 9.7 tonnes of cement copper averaging about 55% Cu, representing a recovery of less than 50%. This poor recovery prompted the leaseholders to seek the assistance of the S.A. Mines Department.

Between 1964 and 1966 the Mines Dept. financed considerable metallurgical work by AMDEL on behalf of the leaseholder at the cost of some $4500 to the Government. Unfortunately, most of that work was done on selected ore of grades varying from 13% to 3% copper which was supplied by the leaseholders, while only very small quantities of this grade material were actually found, the overall grade being less than 1% Cu.

A summary of these tests follows:

1. Gravity Concentration by tabling 13.3%, 8.5% and 3.4% copper ore samples with only low recoveries (less than 50%), apparently due to the fineness of the copper (Weir, 1964).

2. Percolation Acid Leaching tests on 7.1% copper ore samples from the shaft and surface workings, indicating a 98% recovery after a two-month leach, but considerable trouble was anticipated because of clogging in the leach bed. The acid consumption was indicated to be about 80 kgm. of acid per tonne of ore. Various practical recommendations were made, such as withdrawing the leach liquor at pH 2-2.5 (Hall and Waters, 1965).

3. Agitation Acid Leaching tests on

(a) 2.88% tailings and 3.4% ore samples with up to 90% recovery for an acid consumption of 45 kgm. per tonne of ore. Timed tests showed that most of the acid was used in the first half-hour. Heating was shown to improve the extraction slightly (Blesing and Hall, 1965).

(b) 1.27% copper ore from the adit with the best recovery 77% for an acid consumption of 60 kgm. per tonne of ore (Haddow and Waters, 1966).

(c) 0.96% copper bulk sample from the open cut north of the shaft showing only 30% recovery despite acid addition up to 110 kgm. per tonne of ore. Some of the gangue was attacked resulting in a very impure leach liquor containing a high proportion of iron and aluminum. An investigation of the residues indicated that fine copper may be interleaved with the mica or even interleaved with it in a relatively insoluble form. This test was very significant, for it was the only one done in representative ore (Haddow, Hayton and Waters, 1966).

(d) 4.95% ore sample reported to give 95% extraction for an acid consumption of 80 kgm. per tonne (Tavender, 1966).

4. Flotation tests on 0.96% copper bulk sample from the open cut with under 30% recovery despite experiments with a number of different reagents. It was noted that 23% of the copper in the residues was under 10 μm in size (Haddow, Hayton and Waters, 1966).

5. Chloridizing Roast and Leaching on 0.96% copper bulk sample. On the whole, the best copper extractions obtained were of the same order as those obtained by simple leaching so there was little inducement to continue (Gooden, 1968).

In addition to the tests described above on recovery of copper from the ore, some tests were done on recovery of copper from leach liquor. Using lime to precipitate the copper as hydroxide, 98% extraction was achieved with a copper product containing 36% copper for a consumption of 1.7 kgm of lime per kgm. of copper extracted. The other insoluble product was calcium sulphate.

Using iron to precipitate the copper from leach liquor, a 78% recovery rate from solution was achieved, with a consumption of 1 kgm of clean unwashed iron turnings used to 1 kgm of copper. Smelting of this cement copper slowly with charcoal in the presence of air yielded ingot copper assaying 99.1% Cu. Spectrographic analysis indicated that the major impurities were silver (0.02%) and iron (0.01%). No gold was detected (Hall and Waters, 1965).

From this mass of data the following conclusions could be drawn:

(a) The ore was not amenable to concentration either by gravity or flotation, apparently due partly to the fine grain size (less than 10 μm) of the copper minerals.

(b) The high clay content of the ore made percolation acid leaching unacceptable due to clogging, although over a long period (two months) recovery was good (98%).

(c) Agitation leaching gave low recoveries and high acid consumption, up to 5 times the theoretical. It was supposed that the fine copper might in fact be incorporated in the mica flakes, and thus shielded from attack by acid or chloridizing gases.

(d) The ore contained negligible precious metal content.

Company Test Work

The initial drilling of the Ukaparinga leases (Plates 61-62) in 1969 by Crane Enfield Metals (under the author's supervision) indicated a possible reserve of 3 million tonnes of 0.7% copper at 0.2% cut-off, which suggested that the deposit could be of economic interest if additional reserves could be found close by. This latter probability was high, so the next stage was to examine the potential recovery of copper from the ore, particularly as the previous work by AMDEL on low-grade ore showed that economic recovery would be difficult. Accordingly, the author first repeated the AMDEL agitation acid leach tests in the company's laboratory at Elizabeth and confirmed their poor results (see Appendix 6).

A pilot leach plant at Somerton Park was made available by F.J. Wadhams Pty. Ltd., and the author ran a bulk test using 500 tons of ore averaging 0.9% copper freshly mined from the open cut (Plate 59). This extensive test carried out continuously over a period of two weeks suggested that a maximum yield of cathode copper by electrowinning leach liquor would be about 30%, despite experiments in which the crushing size, leach time, acid strength and current applied were maximised. The major problem was traced to the inability of the acid to attack the ore sufficiently.

Thus, the next step appeared to be an investigation of the mineralogy of the ore in detail in an endeavour to discover the nature of the copper and suggest a way in which it might be recovered. This investigation was carried out by the author in conjunction with Dr. Keith Henley of AMDEL.

MINERALOGICAL INVESTIGATIONS

Seventy samples of the Ukaparinga Shist were examined by the author, and their descriptions are given in Appendix 7. Most specimens were from relatively to completely unoxidized drill core, but 12 were of oxidized material from the surface or the adits in the Ukaparinga Mine. All samples were investigated in thin section, and thirty were also examined under reflected light on polished sections. Ten samples were examined using the electron probe.

UNWEATHERED SAMPLES

In hand specimen all samples of material examined from below the base of oxidation are schistose, with a more or less well developed schistosity defined by the subparallel orientation of mica/chlorite flakes. Quartz segregations and lenses in the schist are common. The colour of the schist ranges from silvery-grey in the muscovite-rich varieties to dark greenish black in the mica/chlorite-or tourmaline-rich varieties. Grains of chalcopyrite and pyrite (more rarely), are disseminated throughout the rocks and locally form massive cross-cutting veins; these latter, however, are not common. In most samples the sulphides are fresh, supergene enrichment is absent, and copper carbonates, such as are present at and near the surface, are also absent.

In thin section the schist typically shows sub-parallel oriented flakes of biotite, chalorite and muscovite in a matrix of strained quartz and opaques. Certain samples contain aggregates of sericite rather than flakes of muscovite. Minor minerals which may or may not be present in different specimens include tourmaline, plagioclase, rutile, sphene, clay apatite, carbonate and epidote. Photomicrographs of the mineral textures are shown in Plates 71-78. Semi-quantitative spectrographic analyses of representative samples are shown in Table 9.

Biotite occurs in all samples, the proportion varying from less than 1% to 45%. It forms sub-parallel flakes, generally from 0.2 to 2 mm in length, although in a small number of samples a foxy brown

TABLE 9

UKAPARINGA SCHIST-SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES

(analyses done by AMDEL)

Results in ppm unless otherwise stated. Detection limits in brackets.

Element	Sample Numbers 1486	4445	4439
Barium (50)	50	300	15
Beryllium (1)	2	2	1
Bismuth (5)	5	bld	bld
Chromium (20)	100	80	bld
Cobalt (5)	10	10	bld
Copper (0.5)	2.40%	2000	700
Gallium (1)	bld	5	bld
Gold (3)	bld	bld	bld
Lanthanum (100)	bld	100	bld
Lead (1)	15	1	8
Lithium (1)	3	20	20
Manganese (10)	1000	bld	bld
Nickel (5)	5	25	bld
Phosphorous (100)	3000	bld	bld
Potassium (5)	1000	3000	bld
Rubidium (10)	30	10	bld
Silver (0.1)	8	bld	0.8
Sodium (50)	300	300	bld
Strontium (10)	50	bld	bld
Tin (1)	bld	1	3
Tintanium (100)	300	3500	bld
Vanadium (10)	10	100	25
Yttrium (10)	10	80	bld
Zinc (20)	80	bld	20

bld = below level of detection

variety is present, intergrown with the dark brown variety. It is not certain whether the two varieties are co-existing in equilibrium or whether one is replacing the other, but the latter seems more likely. The biotite flakes show all stages of alteration to chlorite, from slight marginal replacement to complete pseudomorphing by the chlorite. It seems probable that most, if not all, of the chlorite in the samples is secondary after biotite.

Muscovite is present to varying extents in the samples, from less than 5% to 30%. It occurs in two forms, sub-parallel flakes in the size range 0.2 to 3 mm, and aggregates of very fine ($<$ 0.01 - 0.1mm) flakes ('sericite'). The origin of the latter variety is uncertain but some possibly represents pseudomorphously replaced ?andalusite or ?feldspar (Plates 72-75).

Chlorite is a ubiquitous component ranging from trace amounts to 70% in different samples. It occurs as sub-parallel flakes in the size range 0.1 to 2 mm, generally intergrown with, and forming from, biotite. The chlorite is pleochroic, from pale green to almost colourless, shows low order, anomalous, yellow-brown interference colours, and is length fast.

Quartz occurs in all samples examined, the proportion varying between 5 and 70%. It forms anhedral grains, mainly in the size range 0.2 - 2 mm, which are generally elongate parallel to the schistosity and which show well developed strain extinction. The quartz grains mould on the mica flakes and are themselves moulded on by chalcopyrite.

Feldspar is present in certain samples as anhedral untwinned grains in the size range 0.2 to 1.0mm. It is frequently intergrown with or rimming sulphides (Plates 71(d), 74(d), and 75(a)).

Tourmaline is present in three of the samples examined. In one sample (Plate 71) it constitutes 30% of the minerals present and occurs as large (1-5mm) euhedral porphyroblasts which grow across the schistosity and around which the schistosity is bent (indicating some post-porphyroblastesis deformation). These porphyroblasts contain parallel oriented inclusions of titano-hematite and, rarely, staurolite inherited from the overgrown schistosity. In other samples the tourmaline forms small (0.2-1.0mm) euhedral porphyroblasts, often oriented parallel to the schistosity. The tourmaline is highly pleochroic from blue-green to colourless or pale pink but in some crystals irregular brown areas are present.

Of the other minor minerals staurolite is of most significance as it indicates the metamorphic grade of the deposit. Several grains enclosed in tourmaline were observed (Plate 71); however, all were small and although the optical properties are consistent with staurolite, the identification must be considered probable rather than certain. The presence of staurolite suggests that the rocks have undergone lower amphibolite facies metamorphism. The absence of other indicator minerals may be due to their subsequent replacement under retrogressive conditions (e.g. andalusite replaced by sericite).

The opaque mineralogy of the samples is somewhat variable (see Plates 76-78). The content of opaques varies from trace to about 15% by volume and chalcopyrite is nearly always present to the extent of between 30 and 100% of the total opaques. Only in samples from 125.5m, 131.5m, and 132.7 m was no chalcopyrite observed. Pyrite is the only other sulphide present, generally to the extent of less than 20% of the total opaques but constituting up to 65% in the sample from 125m. These sulphides form anhedral grains (subhedral-euhedral in the case of pyrite) intergrown with the silicate minerals. Their grain size is mainly in the range 0.03 to 2 mm and thus there is likely to be little difficulty in liberating them during beneficiation.

The chalcopyrite tends to form anhedral irregular grains which mould around the micas and quartz and which are often elongate parallel to the schistosity (Plates 76(b), 77(d), and 78(b)). A minor proportion occurs as very narrow intergranular veins and stringers between the silicate minerals (Plates 76(a), 78(d)). Pyrite is generally subhedral or euhedral and in certain samples is veined by the chalcopyrite (Plate 78(c)). Chalcopyrite was observed as veins in the fractured tourmaline porphyroblasts in the samples from 105m. (Plate 77(b,c)) and also, rarely, as small inclusions in magnetite crystals in the same sample (Plate 77(a)). A curious feature observed in some samples is the development of lobate margins to the quartz where it abuts the chalcopyrite (Plates 76(a), 77(d) and 78(d)). This possibly indicates marginal replacement of quartz by chalcopyrite.

No clear microscopic evidence of the relative date of emplacement of sulphides is apparent but in view of the localisation of the copper to a particular stratigraphic horizon and the virtual absence of cross-cutting veins with associated alteration, it seems most likely that the sulphides were deposited with the original sediments and subsequently recrystallised during the ?lower amphibolite facies metamorphism. Certainly cross-cutting replacement textures indicative of epigenetic mineralisation are absent, although minor replacement of pyrite and quartz by chalcopyrite has possibly taken place.

Ilmenite, almost always partially altered to rutile, and rutile are common minor constituents of the samples. The ilmenite crystals are lath-shaped and generally oriented sub-parallel to the schistosity (Plate 71(c)).

Magnetite was observed in a few samples, where it constitutes between 5% and 98% of the total opaques. It occurs as anhedral and subhedral grains up to 1.5mm in size, often intergrown with chalcopyrite (Plates 73(d), 76(c), 77(a)).

One sample was observed to contain lath-shaped crystals of titaniferous hematite (Plates 71(c), 77(a,b)). These crystals are between 0.1 and 0.5mm long and contain exsolution lamellae of ilmenite.

WEATHERED SAMPLES

In hand specimen these are similar to the unweathered samples, except that no sulphides are present. In thin section (Plate 75) the mineralogy and textures are also similar to the unweathered samples. Sub-parallel biotite flakes, often partially chloritised, are intergrown with elongate, strained quartz crystals and define the schistosity. In two of the samples there are two varieties of biotite present, the normal moderate-brown variety and the rarer foxy-brown variety; both show partial to complete alteration to pale green chlorite and it is not clear whether they are co-existing in equilibrium or whether one is replacing the other. Chlorite is a common constituent of the rocks and optically is indistinguishable from that in the drill-core samples; it generally appears to have formed by retrogressive alteration of biotite and is often intergrown with fine-grained rutile formed as a result of the release of TiO_2 during the alteration. Muscovite occurs as well-defined flakes, which generally lie parallel to the biotite flakes but locally appear to grow across them, and as fine-grained felted aggregates ('sericite'), possibly representing pseudomorphed aluminosilicate crystals. In one of the samples prismatic tourmaline crystals, similar in pleochroism to those in the drill-core samples, lie sub-parallel to the schistosity.

The main difference between the weathered samples and the unweathered samples is in the opaque mineralogy. Whereas the unweathered samples commonly contain chalcopyrite and/or pyrite, these minerals are absent in the weathered samples. The main opaque mineral present in the weathered samples is martite (hematite after magnetite), which forms abundant, irregularly distributed, euhedral crystals, mainly in the size range 0.08 to 0.4mm. The crystals retain the euhedral outline of the original magnetite but are now completely replaced by hematite which shows the characteristic Widmanstatten texture.

MINERALOGY OF LEACH TEST SAMPLES

The +200 μm size samples of ground oxidised ore and leached residue from one pilot plant test (designated 7009), in which recovery was extraordinarily low, were used to prepare polished thin section grain mounts, with a view to searching for opaque minerals such as native copper which may resist attack by dilute sulphuric acid.

The opaque components constitute about 3% of the total unleached ore, and in approximate order of abundance comprised goethite (and various limonites), hematite (some variety martite), and magnetite, pyrite, rutile, and traces of chalcocite and malachite. The amount of copper mineral visible was quite incompatible with the assay of 1.35% Cu. The limonite and goethite occurred in various forms, some with typical boxwork-like vesicular form and others as encrustations on haematite, magnetite and pyrite. Pyrite was present only as very rare fine discrete grains, not usually associated with any other minerals except an oxidized envelope of limonite. The rutile occurred as needle-like inclusions in the main rock component, biotite, which also contained minor quantities of very fine unidentifiable material.

The leached ore samples from this particular pilot plant run were also examined in polished section with a view to determine if the residual copper was present in an opaque form. The very low recovery is emphasised by the residue assay of 1.32% copper versus 1.35% for the unleached ore.

The leached ore was found to be essentially similar, with the exception of a distinct depletion of hydrated limonites and goethites as would be expected after dilute acid attack. Haematite, magnetite, some goethites, rutile and rare traces of pyrite were still evident. No opaque copper minerals were seen, and all traces of malachite had vanished.

Although no definite information concerning the non-leachable copper mineralisation was obtained, the following inferences could be drawn:

(i) Copper in the form of carbonate films, or adsorbed with limonitic crusts or boxworks was being dissolved by the acid leach used.

(ii) The principal gangue mineral, biotite, contained abundant inclusions of very fine, perhaps colloidal sized, opaque particles between the mica foliae.

(iii) Biotite is not notably attacked by dilute, cold sulphuric acid as used in the leaching process; it is however readily decomposed by the types of hot acids used in assay procedures.

(iv) No other location for the non-extractable copper could be suggested from optical observations.

On the evidence of these samples it would appear that the non-leachable copper was probably contained among the interlamellar inclusions in the biotite. As such it would be inert to dilute sulphuric acid as used in the leach, but would be dissolved by strong sulphuric or other oxidizing acids which are capable of attacking biotite.

Further evidence for the above conclusion was obtained by an investigation of a complete series of size fractions obtained by screen sizing and cyclosizing the leach residue from the same pilot plant test run. The analytical results are set out in Table 10.

Two features of the date in Table 10 are of particular significance:

1. Extraction of copper varies from 0 to 12.7% in different size fractions and shows no correlation with decreasing grain size.

2. In both the leached and unleached material there is a marked enrichment of copper in the coarsest fractions (approximately twice the copper content of the head) and a marked depletion in the -74 +23 μm fraction.

TABLE 10 RESULTS OF ACID LEACHING EXPERIMENT ON ORE SAMPLE 7009

Size Fraction (μm)	Weight %		Cu Assay %		Cu Disb^n%		Approximate % of copper in size fraction leached
	Ground Ore	Leach Residue	Ground Ore	Leach Residue	Ground Ore	Leach Residue	
+208	3.7	3.4	1.35	1.32	8.2	7.8	2.2
-208 +147	6.2	6.4	1.25	1.22	12.6	13.6	2.4
-147 +104	7.8	7.7	0.93	0.85	11.8	11.4	8.6
-104 + 74	9.3	8.5	0.63	0.55	9.6	8.1	12.7
- 74 + 43	8.0	8.0	0.10	0.10	1.3	1.4	0
- 43 + 33	8.2	7.9	0.18	0.18	2.4	2.5	0
- 33 + 23	9.2	9.0	0.36	0.34	5.4	5.3	5.6
- 23 + 15	10.2	10.0	0.53	0.50	8.8	8.7	5.7
- 15 + 10	5.7	5.5	0.62	0.59	5.8	5.6	4.8
- 10	31.7	33.6	0.66	0.61	34.1	35.6	7.6
Total	100.0	100.0	(0.61)	(0.58)	100.0	100.0	(4.9)

The remaining size fractions of the leached and unleached material were examined microscopically in an attempt to relate the mineralogy to the copper content. All fractions were found to consist mainly of biotite and quartz in various proportions and there was a clear correlation between biotite content and copper content, biotite being a major component of the coarsest fraction and a minor component of the -74 +23 μm fraction. These results suggest that the copper is closely associated with the biotite, either substituting for Fe^{2+} in the lattice or as very fine inclusions of copper mineral(s) between the micaceous foliae.

It was concluded that the only means of establishing the location of the copper conclusively would be by using electron-probe microanalysis.

ELECTRON PROBE MICROANALYSIS

OXIDISED ORE

Polished thin sections of the +208µm fractions (leached and unleached) from pilot plant run 7009 were submitted to AMDEL for examination using an electron probe microanalyser, operated under the supervision of Dr. Keith Henley.

The instrument was operated at an accelerating voltage of 15 kV, a beam current of 0.1µA and a beam diameter of 2µm. Pure copper was used as a standard and the results were corrected for atomic number and mass absorption effects.

The mineral grains were scanned for copper and point analyses obtained at three locations on each of eight grains of biotite. The results are given in Table 11 and photomicrographs showing the copper distribution in randomly selected biotite grains are shown in Plates 69-70.

The following conclusions may be drawn from Table 11 and Plates 69-70:

1. In the unleached fraction individual biotite grains contain between 0.6 and 2.3% Cu in solid solution (or as fairly homogeneously distributed submicron inclusions): the mean copper content of the eight grains is 1.39% Cu.

2. In the leached fraction individual biotite grains contain between 0.8 and 1.5% Cu in solid solution (or as fairly homogeneously distributed submicron inclusions): the mean copper content of the eight grains is 1.09%.

3. Individual biotite grains vary in their degree of homogeneity. In both the leached and unleached material half the grains analysed give three point analyses which vary by less the 0.15% Cu from their average, whereas the remaining half gives three point analyses which vary by between 0.15% and 0.9% Cu from their average.

It is clear from these results that the source of the copper in both the leached and unleached samples is the biotite. This confirms the microscopic results which suggested a correlation between biotite content and copper content in the size fractions, and explains the poor recoveries obtained during leaching. However, in view of the limited number of grains analysed and their variability in copper content, it

TABLE 11

ACCURATE ELECTRON-PROBE ANALYSES OF Cu IN BIOTITE FLAKES (from Henley, 1973)

Grain	Cu%			
	Point 1	Point 2	Point 3	Average
	Ground Ore			
1	0.56	0.60	0.64	(0.60)
2	0.64	0.65	0.80	(0.70)
3	0.87	0.99	1.07	(0.98)
4	0.76	1.24	1.41	(1.14)
5	1.47	1.81	2.06	(1.78)
6	1.70	1.75	1.97	(1.81)
7	1.39	2.02	2.06	(1.82)
8	1.65	2.11	3.17	(2.31)
			Average	1.39
	Leach Residue			
1	0.78	0.85	0.85	(0.83)
2	0.75	0.86	0.89	(0.83)
3	0.84	0.93	0.95	(0.91)
4	0.73	0.89	1.23	(0.95)
5	0.98	1.09	1.15	(1.07)
6	0.98	1.03	1.40	(1.14)
7	1.17	1.24	1.93	(1.45)
8	1.30	1.52	1.72	(1.51)
			Average	1.09

cannot be concluded that the difference between the average values of 1.39% and 1.09% Cu is significant.

As far as can be ascertained from the probe results, the copper is distributed throughout the biotite, either in solid solution (probably substituting for Fe^{2+}) or as submicron sized inclusions of discrete copper minerals.

The high concentration of copper in this biotite is remarkable. Biotites containing from several thousand ppm to over 1% Cu have been recorded previously from the vicinity of copper orebodies (Al-Hashimi and Brownlow, 1970; Lovering et al, 1970; Parry and Nackowski, 1963) and it has been suggested that analysis of biotites could be used as a prospecting tool, giving enhanced geochemical contrast over that obtainable from whole-rock analyses.

Values up to 3% Cu in biotite (ground ore point 3, grain 8 in Table 11) have not previously been recorded and it was felt that the biotite in sample 7009 was worthy of further study to determine the exact location of the copper (Henley, 1972).

Subsequently, the author had access to AMDEL electron probe equipment through a reciprocal arrangement with the South Australian Institute of Technology, and was able to carry out further tests on these samples.

Two samples were selected for detailed examination by normal optical and microprobe techniques. These were both from the ground ore samples 7009/110/1 (assay 1.35% Cu, nominal size +208 microns) and 7009/110/2 (assay 1.25% Cu, nominal size -208 +147 microns). Representative portions of these were mounted in polished blocks so that the biotite flakes could be examined in two orientations - parallel to and perpendicular to the basal (001) cleavage.

The initial microprobe work involved scanning of the biotite flakes in each mount to observe the distribution of the following elements: Cu, Si, Fe, Al and Mg. This ensured that the grains scanned were in fact biotite. The distribution of all elements was found to be essentially uniform (Plates 67-68). The grains were also observed optically at high magnification (1500x) but no opaque inclusions were seen which could account for the distribution of copper, e.g. Al-Hashimi and Brownlow (1970) note sulphide inclusions down to one micron in size in biotites they analyzed for copper.

Following these observations approximately 100 biotite flakes in each sample were probed for their copper content (Table 12). The average counts ranged from 140-157 above background.

One biotite flake from each sample was analyzed in detail for the following elements: Cu, Fe, Mn, Ti, K, Si, Al, Mg. The copper contents of these flakes were 0.50% (7009/110/1) and 0.81% (7009/110/2) with a possible variation of ± 0.05%. Fig. 30 is a plot of the uncorrected count ratio

$$\frac{(\text{Cu count in biotite - background})}{\text{Cu count in standard}}$$

against the corrected copper content. The two analyzed biotites lie on a straight line passing through the origin. Assuming therefore that this straight line relationship is true for biotites with Cu contents in the range 0-1%, the averaged count ratios for approximately 100 flakes in each sample were plotted and their copper content determined. The results are shown below:

	Electron Probe	Assay
7009/110/1)	.95 ± .05%	1.35%
)		
)	.93 ± .05%	
7009/110/2	.99 ± .05%	1.25%

These results are in close agreement with the chemical assays given for the two samples and it is concluded that most of the copper is present within the biotite structure.

All samples were analyzed by XRD techniques to determine their mineral constituents and to indicate the order of abundance of the minerals. Examination of the traces indicates that a biotite, a chlorite and quartz are the predominant constituents. It has not been possible so far to determine whether the biotite and chlorite are present as separate grains or are constituents of mixed layer grains.

Biotite and chlorite predominate in the +74 μm fractions and the -23 μm portion of both the ground and leached ore. Quartz predominates in the -74 to +23 μm material. These abundances correlate with the copper assays giving further proof that the copper content is associated with the micaceous minerals.

TABLE 12

COPPER CONTENT OF BIOTITES

Count Range	7009/110/1		7009/110/2
	A	B	
0 - 50	3	3	5
50 - 100	4	5	20
100 - 150	14	16	18
150 - 200	12	16	20
200 - 250	8	7	12
250 - 300	4	1	4
300 - 350	2	5	5
350 - 400	-	2	4
400 - 450	-		2
Average Counts	181	183	197
Background	41	35	39
Count Ratio $\left(\frac{Av - Bk}{Std}\right)$	.0789	.0773	.0822

UNOXIDIZED ORE

Five drill core samples taken below the base of oxidation were submitted to AMDEL for examination using the electron probe to determine whether their biotites contained a significant proportion of copper. The samples were selected to give as representative a range as possible of opaque mineralogy so that the possible effects of variations in oxygen and sulphur fugacity during metamorphism on entry of copper into biotite could be ascertained. The samples selected were as follows:

Depth M	Opaque Mineralogy
97.5	Chalcopyrite (95%), pyrite (5%)
107	Chalcopyrite (50%), titano-hematite (45%), magnetite (5%)
116	Chalcopyrite (70%), pyrite (2%), ilmenite and rutile (2%), magnetite (25%)
124	Chalcopyrite (30%), pyrite (65%), ilmenite and rutile (4%)
126	Ilmenite and rutile (2%), magnetite (98%)

Numerous grains of biotite in each of these five rocks were analysed using the electron-probe. However, in all cases the copper content was found to be below the limit of detection (ca. 0.03%) and it appears that virtually all the copper present in these samples is in the chalcopyrite (Henley, 1972). Thus, the copper in the biotite is of secondary origin, and probably originated during weathering of the Ukaparinga Schist when copper ions released by oxidation of chalcopyrite could react with hydrobiotite derived from primary biotite.

OTHER TEST WORK

Subsequent work on the ore in 1973 (Henley and Brown, in press) indicated that the biotite had in fact been altered to hydrobiotite above the oxidized zone, although whether the introduction of copper preceded or post-dated the formation of hydrobiotite from biotite is unknown. In addition, X-ray diffraction analysis showed that the hydrobiotite in the oxidized zone was a randomly interstratified $10A^{o}$ to $14A^{o}$ combination of biotite--vermiculite containing approximately 25-35% vermiculite layers by weight.

The extreme difficulty in extracting the copper from the hydrobiotite lattice is exemplified by the results of experiments carried out by the CSIRO in 1970-71 (Woodcock, pers. comm.). Extractions of less than 15% were obtained when leaching with sulphuric acid at pH 1.7 and 20°C even after agitation for 3 days. Increase in acid strength to 120 g/litre (pH about 0) was only slightly beneficial at 20°C but addition to manganese dioxide, ferric sulphate, ferrous sulphate plus manganese dioxide, or sodium chlorate, did not yield an appreciable improvement in extraction. Increase in temperature gave significant improvements in extraction but grind-time had only a marginal effect; even after 20 minutes grinding and leaching at pH 1.1 and 80°C for 6 hours, the copper extraction was only 75%. In addition to acid leaching, various other reagents were tried by Mr. Woodcock in an attempt to extract the copper from the hydrobiotite. Hot, 1.5% potassium cyanide solution and hot 10 molar caustic soda solution were both ineffective in extracting the copper, and ammonia leaching gave poorer extractions than acid leaching. Treatment with hot 2 molar caustic soda solution followed by acid leaching of the alkali-treated residue showed no improvement in extraction over direct acid leaching. Reduction roasting followed by acid leaching gave little improvement in copper extraction. Oxidizing roasting followed by acid leaching showed that a marked decrease in copper extraction took place with increasing temperature, the percentage extraction with no treatment and after roasting for one hour at 250°C, 500°C and 1000°C being 49, 53, 15 and 5 respectively (leaching 1 hour at 20°C and 5 hours at 80°C at pH 5). The refractory behaviour evidence by these extraction experiments suggests that the copper is very firmly held in the hydrobiotite lattice. The decrease in extraction after oxidizing roasting may be connected with the exfoliation and collapse of the basal spacing to 10Å on heating, particularly if the copper was originally present in the interstratified vermiculite layers and became locked in the collapsed structure.

The possibility of extracting the copper from the mica schist by using hydrothermal fluids was then investigated by the CSIRO (Hesp and Osetzky, 1973). Over 120 experiments were carried out using 20 per cent by weight solutions of NaCl, KCl, NH_4Cl, NH_4F, $MgCl_2$ and $CaCl_2$

at different temperatures (100-500°C), pH values (3.8, 6.8, 10.0) and durations (3-6 days).

In general the yield of copper extraction increased with the temperature of treatment between 100-400°C. With two of the solutions ($NaCl$ and NH_4F) very high (80-84%) extraction yields were obtained at 400°C. No definite trends were observed so far concerning the effect of pH of the solutions and the duration of the treatment.

Information on the original samples and extraction residues obtained in X-ray diffraction studies suggests that the copper may have been tied up in a "mixed-layer" structure which was destroyed to a varying extent by the different solutions and the copper was released. The solutions which were most effective in the extraction of copper (i.e., $NaCl$ and NH_4F) attacked the chlorite and mixed-layer components, while those which caused the destruction of the biotite-component (i.e., $MgCl_2$ and $CaCl_2$) gave relatively poor extraction yields.

The conclusion that the copper is tied up in the vermiculite is inescapable. Whether the copper is substituting for (Fe^{++}, Mg^{++}) in the octahedral sites of the vermiculite lattice or is substituting for K^+ or Mg^{++} in the interlayer sites is not known. Both substitutions are possible up to a maximum theoretical Cu^{++} content in vermiculite of 4-6% Cu (Henley & Brown, 1973), and both may in fact occur at once. Some important observations can be made from the hydrothermal leaching work, and the following are of interest:

1. Among the hydrothermal solutions which commonly occur in nature $NaCl$ is the most effective in releasing the transporting of copper while KCl, $MgCl_2$ and $CaCl_2$ are less effective.
2. The extraction of copper is reasonably fast at 400°C (complete in less than 3 days) but also takes place at lower temperatures (100-300°C) although more slowly.
3. The pH of solutions does not appear to influence extraction yields greatly but Eh (oxidation-reduction potential) has a strong effect.

ORIGIN OF THE COPPER MINERALIZATION

Detailed geochemical test work, both rock and soil, carried out by the author for Crane Enfield Metals between 1969 and 1971 show conclusively that the copper is localized entirely within the Ukaparinga Schist, with a mean content of over 2,000 rock samples of 0.34% copper. The maximum copper content of adjacent beds is 50 ppm, and background of all beds in the area mapped (excluding the Ukaparinga Schist) is a very low 35 ppm. In view of this fact, and the virtual absence of cross-cutting veins with associated alteration, it seems most likely that the sulphides were deposited with the original sediments and subsequently recrystallized during prograde metamorphism. Subsequently slightly saline groundwater percolating through the primary ore under oxidizing conditions extracted some of the copper ions and allowed their migration and incorporation into vermiculite formed by normal weathering of primary biotite, giving rise to the refractory copper ore which forms the major part of the orebody above the base of oxidation.

The source of the copper which formed within the original host sediment which became the Ukaparinga Schist is unknown at this stage, primarily because the nature of that original sediment is unknown. It is likely to have been a mud, laid down quietly in a closed marine basin, but much further work beyond the scope of this study needs to be done to determine the nature and conditions of sedimentation.

CONCLUSION

The Ukaparinga Schist is clearly a mappable formation, probably lying stratigraphically within the basal portion of metamorphosed Skillogalee Dolomite of Lower Torrensian age, overlying an older Pre-Cambrian inlier formed by the Warren Schist. Recent work by Oakes (1974) has demonstrated that the Ukaparinga Schist represents a minor regressive sequence within an overall transgressive phase. The original sediment (probably a carbonaceous feldspathic wacke) is thought to have been "deposited under an arid climate in a deltaic environment within a lagoon sheltered from the open sea by a stromatolitic algal reef over a basement palaeohigh. Stagnating bottom waters provided the euxinic conditions under which synsedimentary deposition of copper sulphides occurred" (Oakes, 1974).

Oakes' stratigraphic and geochemical study supports the mineralogical and petrological evidence cited in this thesis, proving fairly conclusively that the copper within the unweathered Ukaparinga Schist was deposited and incorporated within the original sediment, probably as discrete chalcopyrite grains. Metamorphism may have remobilized the sulphides to a small extent, and by lateral secretion formed the richer (+1% Cu) portions of the Schist.

Later, during a deep and prolonged weathering cycle extending from the Ordovician to the Tertiary, copper was released as ions which became incorporated within the weathered biotite (hydrobiotite) lattice, such incorporation tightly "locking in" the copper and inhibiting its removal by all but the most severe physico-chemical conditions. However, since this metallurgical difficulty exists only in weathered Ukaparinga Schist, the Schist is still considered to be of considerable economic interest, and exploration for further occurrences of the Schist could prove most productive.

APPENDICES

APPENDIX I

RAINFALL

About 75% of the rain falls in the seven months April to October inclusive (Table 1). Rain falls on only one third or less of the total days each year, and even in the wettest months (June to August) less than half the total number of days are wet (Commonwealth Bureau of Meteorology, pers. comm.). Because of the high evaporation rate in summer (over 230 mm. per month) the summer rain is largely ineffective (i.e., evaporation exceeds precipitation). Approximately one year in five is a drought year, when the season of continuously effective rainfall is less than five months. However, in general the rainfall is moderately reliable and has a moderate overall variability from year to year and in the same months in different years.

In hilly areas, where run-off is facilitated by sloping ground, the nature and the intensity of the rainfall are of comparable importance to the annual total. Heavy rains (exceeding 50 mm.) of short duration (less than 24 hours) occur about once every five years in summer and autumn, when the soil is in a vulnerable condition and liable to erosion, hence erosion rates in the area can be high (Commonwealth Bureau of Meteorology, pers. comm.).

Mean temperatures, maximum and minimum, are about 21°C to 10°C, with the maximum daily temperature variation rarely exceeding 17°C. Frosts are common in the winter months. Hot spells with temperatures over 38°C are a feature of the summer weather. Sudden cold changes with a fall of 5-10°C in almost as many minutes can occur after a hot spell. Hailstorms may occur at any time of the year, but the most severe are usually associated with summer thunderstorms.

APPENDIX II

INDUSTRY

Primary industries of various types are established within the mapped area, and to a considerable extent the industry is related to the geology and soil development. The poorest soils, overlying the Barossa Complex on the west and the Warren Schist on the east, are almost entirely undeveloped apart from some failed experimental pine plantations. The natural vegetation remains, and these areas have been retained as national parks.

As described previously, the best soils close to Williamstown support extensive horticultural development, and there is a limited scope for expansion south of the South Para River on the flats overlying the Burra (Western) soil association. Much of the land, however, is undeveloped apart from clearing for stock grazing. Pasture improvement has proceeded slowly, probably since the quality of the pastures tried has been fairly low. The majority are composed solely of annual species of which subterranean clover and grasses of low productivity are invariably constituents. Lucerne has not been grown extensively, although some isolated patches have proved particularly valuable for the upper echelons of stock production such as stud farms. There is a distinct lack of perenial grasses, although these would be a valuable fodder, especially after summer rains.

A major industrial development for the area could occur with the expansion of the existing forest plantations. The Mount Crawford forest has not proved entirely successful in the growth of Pinus radiata, the principal softwood grown commercially in South Australia, although it does support two timber mills in Williamstown. A substantial proportion of the town's income is derived from the forest.

Timber has always been of importance to Williamstown, where the best red gum in South Australia had its home. The red gum sleepers for the first railway (Adelaide to the Port) were cut there; the timber for the first ship built in South Australia, the "R. Helen Marquies" grew there, as well as the first piles used in the Port; also the first telegraph poles in Adelaide (Hammat, 1934).

Pinus radiata was first planted in the Mount Crawford forest reserve in 1914. Most early plantings were on poor argillaceous soils, and these trees have grown very slowly and in some places proved a complete failure. Superphosphate addition has assisted to some extent in promoting growth.

Growth rate of Pinus radiata is measured by an index known as the site quality (S.Q.) which is defined as the productivity of a site in terms of cubic volume of wood produced at a certain age (Woods, 1962). The best is S.Q. I which is equivalent to a mean annual increment (M.A.I.) of about 35 cubic metres per hectare. The lowest healthy growth is S.Q. VII which is equivalent to an M.A.I. of about 10 cubic metres per hectare. Plus and minus signs mean better or lower than average, while F. or N.F. means a crop has failed to produce significant wood. The diagram (Fig. 6) shows the relationship of site quality to geology and native vegetation, although other factors such as topography, aspect and the extent of Tertiary weathering also play large parts.

It can be seen that the Burra Group rocks provide the most fertile soil for plantation development, and extensive areas of suitable cleared land at present used for pasture are available south of the South Para River and to a lesser extent between Williamstown and the river. The development of this land for Pinus radiata would not only be justified on economic grounds but also for extending the pollution buffer zone around the reservoir (assuming that the Department of Woods and Forests can be dissuaded from their policy of placing cattle on agistment in the plantation in the reservoir environs).

The mining industry is discussed in the body of the thesis in the chapter on economic geology.

APPENDIX III

EARLY SETTLEMENT

Williamstown lies at the southern end of the Lyndoch Valley, which was discovered in December 1837 by Colonel Light, first Surveyor-General of South Australia. He named the valley in honour of General Thomas Graham, Lord Lynedoch, who took his title from his property named Lynedoch near Balgowan, Scotland. Lord Lynedoch was a general in the Peninsular War under Wellington and won the Heights of Bar-rosa; time has altered both the spelling and pronunciation of Lynedoch and Bar-rosa.

In 1839 Joseph Gilbert, David Randall, Robert Tankine, John Warren and a Mr. Giles lodged ₤16,000 (about $1,230,000 in 1973 dollars) with the Government. It was the days of selection before survey, and ₤1 an acre had to be put down. When the survey was nearing completion, they divided the land in proportion to the money they invested; John Warren selected and named Springfield, Giles took a block at Tasker Vale to the south along the river, Rankine settled on the Para east of Giles, Randall at Corryton Park and Gilbert at Pewsey Vale (Hammat, 1934), adjoining Warren to the north. About the same time Dr. Browne settled at Wongalere and planted the first vineyard in the district. In 1840 John Warren planted an orchard of mixed fruit trees and also made a nursery of vine cuttings obtained from Mr. Reynell's vineyard at Reynella. The Pewsey Vale orchards and vineyards were planted at the same time, the wine from the latter providing succour for a thirsty A.R.C. Selwyn during the first geological examination of South Australia in 1859. Selwyn claimed that Gilbert's wine was "equivalent to the highest class of continental wine" but his joy may have been influenced by the long dusty ride from Cape Jervis.

APPENDIX IV

MOVEMENT ON THE KITCHENER FAULT

MODEL TEST

An experiment was devised to examine the movement necessary on the Kitchener Fault to cause the anomalous off-set of metamorphic zones in the Williamstown area.

It was assumed that metamorphism was due to heat flow from a central core. The highest grade was the migmatite (Rathjen Gneiss) zone and metamorphism decreased uniformly away from this core in three dimensions.

Using Fig. 6 of Offler and Fleming (1968) showing the distribution of metamorphic zones in the Mt. Lofty Ranges as a base, three-dimensional scale model was constructed by building up progressive layers of different coloured plasticine, each colour representing a particular zone. The model took the form of portion of an ellipsoid (Plate 58).

A slice was made in such a way as to duplicate the Kitchener Fault, and the western section removed. A horizontal slice was made through the eastern section simulating erosion to the present level, the top being removed to show a plan view of the metamorphic zones as shown in Offler and Fleming's diagram. The maximum permissible paring of the surface of the western portion was then carried out, such that the biotite zone was still the only zone exposed by this simulated erosion.

The western and eastern halves were then rejoined so that their surfaces were equiplanar and the amount by which the eastern section had to be thrust upwards to achieve this was measured. The distance was 6000 metres.

Attempts to minimise this throw by combining it with varying amounts of transverse movement made little differences to the result. Various types of fault movement were then tried, including semi-circular and semi-spherical motion, but the throw in all cases was larger than the simple thrust movement tried initially. The semi-spherical motion, however, produced a plan surface most similar to the one depicted on geological maps (e.g., Thomson, 1969) and suggests a mechanism of movement for the Kitchener Fault.

GRAVITY SURVEY

Since a throw of 6000 metres is difficult to imagine, particularly as the total thickness of sediment measured in the area is only 3000 metres, further experimental evidence was sought. It was decided to conduct a reconnaissance regional gravity traverse across the fault, to see if a profile would show plateau regions on either side of the fault which could be correlated and hence give some idea of throw.

The Lands Department bench marks installed in 1973, which run from Gawler southeast through Williamstown to Springton, were used as stations. These gave a station interval of approximately 1000 metres with precise information on elevation and location, accurate to 1.5mm, and latitudes to the nearest second.

Gravity measurements were taken with a World Wide Geodetic gravity meter (Plate 57), and the profile was drawn from the values obtained, using an elevation correction factor of 0.2 mgals/metre (corresponding to a density of 2.67 gm./cc.). The probable error in the gravity values is ± 0.4 mgals. Measurements were taken for a distance of 8 kilometres west and east of the fault, comprising 19 stations in all.

The profile shows a sharp negative anomaly in the vicinity of the scarp, proving the existence of the Kitchener Fault in the northern part of the area where it does not outcrop. The approximate position of the fault, obtained from the maximum gradient on the profile, corresponds to the scarp. It also shows the location of the Murray Vale thrust fault, suggesting that this may be of comparable magnitude to the Kitchener Fault.

A difference of 7 mgal. was determined between the two blocks on either side of the faults, the eastern side being a gravity low with respect to the western. From the formula

$$g = 2\rho G h, \quad \text{where}$$

$$h = \frac{7}{0.01276}$$

G = gravitational constant
g = gravity difference
ρ = rock density
h = elevation difference

i.e., 1 gm/cc difference in density represents a throw of 16,800 metres. Specific gravity measurements on either side of the faults of 15 specimens from seven different rock units suggest an overall difference of about 0.1 gm/cc, corresponding to a throw of about 2000 metres, but this data is crude and very inconclusive.

TABLE 8

GRAVITY METER SURVEY: FIELD SHEET

Station Reference Number	Time	Dial Reading	Drift	Drift Corrected Reading	Station Height Feet	Density	E.C.F. (0.05908)	Latitude Measure 34°41'39"		Rdg. x Cal.	A+B+C
8309	12.15	62483	62483	0	0	267		0		0	
8307	12.45	62138	2486	-3.48	+63.32	267	+3.74	+51"	-1.20	-3.09	-0.55
8309	1.25	62490	2490	0	0	267	0	0"	0	0	
8306	1.55	62646	2505	+1.41	+1.44	267	+0.03	+40"	-0.94	+1.25	+0.34
8302	1.25	63585	2520	+10.65	-132.98	267	-7.86	+29"	-0.68	+9.45	+0.91
8301	2.40	63264	2527	+7.37	-68.61	267	-4.05	+23"	-0.54	+6.54	+1.95
8300	2.55	63317	2535	+7.82	-56.64	267	-3.35	-9"	+0.21	+6.94	+3.80
8376	3.00	63224	2537	+7.87	-33.17	267	-1.96	-28"	+0.66	+6.98	+5.68
8375	3.10	63332	2542	+7.90	-44.59	267	-2.63	-63"	+1.48	+7.01	+5.86
8374	3.20	63700	2547	+11.53	-104.91	267	-6.20	-75"	+1.76	+10.23	+5.79
8304	3.40	62558	2558	0	0	267	0	0	0	0	
8311	3.55	59933	2554	-26.21	+362.52	267	+21.42	+61"	-1.43	-23.26	-3.27
8313	11.05	60575	2550	-19.75	+284.63	267	+16.82	+91"	-2.13	-17.52	-2.83
8314	11.20	0955	2548	-15.93	+281.85	267	+16.65	+119"	-2.79	-14.13	-0.27
8315	11.30	0798	1546	-17.48	+324.26	267	+19.16	+140"	-3.28	-15.51	+0.37
8316	11.40	0169	2543	-23.74	+392.13	267	+23.17	+125"	-2.93	-21.06	-0.82
8317	11.55	0602	2539	-19.37	+318.22	267	+18.80	+81"	-1.90	-17.19	-0.29
8318	5.05	59280	2536	-32.56	+494.68	267	+29.23	+46"	-1.08	-28.89	-0.74
8309	5.15	62534	2534	0	0		0	0	0	0	0

Examination of the shape of the western part of the profile suggests a low-angle fault dipping 50^{o}-60^{o} to the east for the Kitchener Fault. The shape of the Murray Vale fault profile is more difficult to interpret, as the data is insufficient. However, the overall picture is one of two large, faulted blocks, separated by a narrow block with basement at a greater depth than the adjacent blocks.

APPENDIX V

PETROLOGY OF THE LODE IN DDH 3, DELORAINE GOLD MINE

There is a sharp hanging-wall contact where sulphide and magnetite-bearing lode is separated from the host rock by a clearly defined quartz zone about one centimetre wide. This zone consists of strongly stressed quartz subhedra in parallel growth at right angles to the host rock contact. Thin veinlets of siderite with which some magnetite is associated cut transgressively across the parallel quartz growths, thinning towards the lode zone and thickening towards the hanging wall. Oxidation of the sulphides has produced intergranular limonite films among the components of the host dolomitic shale where the siderite veins enter it.

The lode abutting the quartz zone consists of irregular granular strongly stressed quartz in a fine-grained sericite-chlorite-muscovite matrix, while some coarse-grained titaniferous hematite occurs in the micas.

Twenty centimetres from the contact the lode consists of major euhedral magnetite with abundant chalcopyrite and minor hematite in a quartz-calcite gangue. This grain size of the magnetite varies up to a maximum of 3mm, and it was clearly the first ore mineral to form. Subsequently, chalcopyrite and hematite formed in the spaces between the magnetite grains, and in shrinkage fractures within the larger magnetites. Small amounts of bornite with exsolved chalcopyrite lamellae, and clusters of euhedral specularite, formed separately in the quartz-calcite gangue.

About 60cm in from the hanging wall contact fragments of country rock are contained in the lode. These fragments consist of a quartz-rich phyllite composed of numerous relatively large quartz grains dispersed through a very fine-grained sericitic medium in which there are magnetite, sulphides, zircon and epidote. The enclosing lode quartz is typically highly strained and shows characteristic parallel growth. Rows of well crystallised magnetite euhedra divide adjacent parallel quartz clusters, and also exist in individual intergranular quartz boundaries. There is widespread fine-grained sericite in all the intergranular boundaries within the lode quartz aggregate.

Although magnetite is the major ore mineral here, there are also small amounts of chalcopyrite and specularite, as well as traces of bornite. The chalcopyrite is contained as minute inclusions within the magnetite and it also exists separately as small grains in the quartz. Most of the specularite exists as clusters of minute flakes at random sites with the quartz.

Just over one metre in from the contact there is a strong development of bornite with subordinate chalcopyrite and specularite. These minerals occur in a gangue assemblage of quartz and abundant tourmaline. To a large degree the parallel growth structure of the tourmaline prisms determines the configuration of the biotite-chalcopyrite masses, hence the latter formed as complex, net-like structures in the grain boundary junctions between the tourmalines. Coarser-grained intergrowths of bornite and chalcopyrite were formed only within the areas of purely quartz gangue.

The exsolution intergrowths between bornite and chalcopyrite indicate a minimum temperature of formation for these two minerals of 475°C. Specularite formed earlier, and at a higher temperature.

About 1½ metres from the hanging-wall contact the lode gangue consists of highly irregular granular, strongly stressed quartz with abundant intergranular and locally clustered sericite, sparsely distributed tourmaline and apatite. Extensively replaced fragments of the country rock, now converted to quartz-sericite schist, are contained within the lode. The ore assemblage is a granular intergrowth of magnetite and bornite with subordinate and finer-grained chalcopyrite and specularite.

Near the foot wall contact of this two-metre wide (true thickness) section of lode there is a transition from irregular granular stress quartz aggregate to a parallel quartz aggregate growth, forming perpendicular to the footwall contact. The inner zone of irregularly granular quartz contains sericite and epidote, as well as sparse tourmaline, pyrite, hematite and limonite. There is little sulphide apart from pyrite and secondary marcasite which line open backed cavities. Very little ore except fine granular material associated with thin carbonate veinlets, occurs in the zone of parallel quartz growth against the footwall. There is a sharp footwall contact with the phyllitic host rock.

APPENDIX VI

AGITATION LEACH EXPERIMENTS

PROCEDURE

About 8 kgm of crushed ore from the Wadhams bulk sample was thoroughly mixed and a sample split out for assay and sizing. Two more samples were split out and leached with sulphuric acid under the conditions set out below:

The head sample assayed 0.925% copper. The sizing analysis was as follows:

Mesh (B.S.S.)			Nominal Size (μm)			Weight %
	+	7			1850	2.5
- 7	+	14	- 1850	+	925	5.5
-14	+	25	- 925	+	580	11.6
-25	+	36	- 580	+	353	9.3
-36	+	52	- 353	+	244	9.6
-52	+	100	- 244	+	147	23.4
-100	+	200	- 147	+	104	19.1
-200				-	104	19.0
						100.0

TEST I

One kilogram of ore and one litre of water were added to a two litre beaker and agitated using a laboratory propellor type stirrer. 64% sulphuric acid solution was added from a burette to the agitated pulp maintaining the pH at 2.0. The pH was measured continuously using a pH meter. At ½, 1, 2 and 4 hours about 30 mls of slurry were extracted as a sample. The samples were immediately filtered in a vacuum filter and the residue washed by repulping with water and filtering three times. The residue was then dried and assayed. After 6 hours the remaining slurry was filtered and washed using the same techniques as for the smaller samples. A sample was split out from the final residue for assay and the primary filtrate collected and assayed for copper and iron.

The residue was checked for sulphides by floating in a Wemco Fagergren laboratory cell at pH of 8.5 adjusted with lime, 115 gm/tonne of sodium sulphide and 450 gm/tonne of potassium hexyl xanthate. The concentrate was assayed for copper and sulphur and the tail for copper only. The sodium sulphide was added to promote tarnished sulphides and at the dosage used it would not be expected to promote non-sulphide copper minerals.

TEST II

The slurry was agitated under vortexing conditions (i.e., aerated) and acid was added at the rate of 2 mls/15 minutes following an initial addition of 4 mls at time zero. The slurry was sampled after 1, 2, 4½ and 6 hours. All other procedures were as for test 1.

TEST I

LEACH RESULTS

Time (hours)	%Copper in residue	%Copper dissolved
0	.925	0
½	.865	6.5
1	.850	8.2
2	.785	15.3
4	.750	19.0
6	.720	22.3

Total acid consumed was 8.0 kgm/tonne of ore.

The final liquor contained 1.96 g/l of copper and .7 g/l of iron.

FLOTATION RESULTS

Product	Weight%	%Copper	%Dis. of Cu	%S
Conc.	10.9	3.2	49.0	1.7
Tail	89.1	0.4	51.0	
Feed	100.0	0.72	100.0	

Microscopic examination of the flotation concentrate revealed the presence of copper/iron sulphide minerals - possibly Bornite. Microscopic examination of the leach residue indicated that the incidence of composite grains was quite small.

TEST II

LEACH RESULTS

Time (hours)	%Cu in residue	%Copper recovered
0	.925	0
1	.57	38.4
2	.70	24.3
4½	.57	38.4
6	.49	47.0

Final pH was 0.4.

Total acid consumption was 48 kgm/tonne of ore.

The final leach liquor contained 3.57 g/l of copper.

DISCUSSION

With acid consumption as high as 48 kgm/tonne only 47% of the copper is recovered after 6 hours of agitation leaching yielding a residue assaying 0.49% copper. These results are in agreement with those obtained by AMDEL (Report No. 553) on a sample of similar head grade. Other work by AMDEL on higher grade head samples gave higher recoveries however the average residue grade ranged from 0.4 to 0.6% copper indicating that the tailing figure obtained in this testwork is close to the limit for acid leaching of this ore. Microscopic examination indicated liberation was complete and that finer grinds would not substantially increase recovery.

The flotation results show conclusively that there are sulphide minerals in the ore. These minerals are not acid soluble and if half the copper reporting in the float concentrate is in the sulphide form (justified on the basis of the sulphur assay of this product) they would account for 19 per cent of the copper in the head sample. The remaining 34% of the copper left in the residue would be predominantly in the form of refractory minerals.

APPENDIX VII

PETROLOGICAL DESCRIPTIONS OF ROCKS

A total of 340 thin and polished sections were described in the course of this study. On the advice of Dr. Kleeman, complete descriptions of only those specimens referred to in the text of this thesis are given here. However, an index to the rocks is given, and a complete set of descriptions is lodged with the Geology Department at the University of Adelaide. All specimens, together with copies of complete descriptions, are lodged at the School of Applied Geology, South Australian Institute of Technology, and may be examined there.

ROCKS WEST OF KITCHENER FAULT

Barossa Complex

4642-46, 4651-2, 4654, 4660-63, 4676-89, 4708, 4710

Rhynie Sandstone

4664-72, 4711

Skillogalee Dolomite

4690-93, 4712-15

Woolshed Flat Shale

4694-95, 4716-17

Undalya Quartzite

4657, 4696-4705, 4718-4724

Saddleworth Formation

4653, 4656, 4659, 4706-07

ROCKS EAST OF KITCHENER FAULT

Warren Schist

4516, 4590, 4650

Rhynie Sandstone

4148, 4222, 4336-37, 4426, 4430, 4438, 4497, 4553, 4563-64, 4566, 4641, 4655, 4711

Springfield Sub-group

4591-4603, 4649

Mt. Crawford Granite-Gneiss

4616-4626, 4647

Kyanite-Damourite Schist

4581, 4634-35

Ukaparinga Schist

4008, 4015, 4032, 4037, 4047, 4049, 4096, 4102, 4107, 4109, 4148, 4163, 4167, 4175, 4198-99, 4201, 4206, 4212, 4219, 4222, 4226, 4236, 4238, 4254, 4335, 4354-4380, 4390-91, 4410, 4420-22, 4431-32, 4434-35, 4440, 4445, 4451-52, 4456, 4458, 4489, 4559

Victoria Creek Marble

1678, 1681-82, 1686, 4313-4334, 4346-4353, 4400-4406, 4450, 4455, 4460, 4468, 4531, 4533-36, 4538-42, 4550, 4554-56, 4560-62, 4530, 4532, 4604-05

Pipeline Schist

4262, 4264, 4300-4313, 4338-45, 4436-37, 4441-44, 4446, 4461, 4464, 4483, 4490, 4494-96, 4603, 4606-4611, 4636

Pewsey Vale Formation

4532, 4537, 4540, 4543-45, 4547, 4549, 4552, 4557-58, 4565, 4567-74, 4576-78, 4612-15, 4658

Pegmatites

4411-12, 4433, 4439, 4548, 4551

Amphibolites

4484, 4546, 4575, 4627-32, 4637, 4648

4137 - Crenulated quartz-muscovite schist.

Components:	Quartz	25-30%
	Muscovite	50%
	Chlorite	5-10%
	Biotite	10%
	Sericite	3-5%
	Opaques	2-3%

A metamorphosed strongly foliated schist with a coarse semi-regular crenulation due to an oblique shearing stress at about 45° to the foliation. It consists principally of aligned muscovite flakes interspersed with biotite in various degrees of chloritisation and lenticular layers of granoblastic quartz. Sparse lenses or bands of fine sericite mesh probably represent former felspars hydrolytically altered.

Opaques scattered irregularly throughout appear to be prismatic or tabular iron oxides, which are slightly encrusted with a surface alteration of limonite.

4262 - Feldspar-quartz-mica schist.

Section is taken at contact between quartzite marker and typical Pipeline Schist.

Components: Quartzite marker:

Microcline	50%
Quartz	30%
Plagioclase (oligoclase)	20%
Chlorite	accessory
Rutile	accessory

Pipeline Schist:

Plagioclase	40%
Microcline	30%
Quartz	22%
Biotite	6%
Chlorite	1%
Tourmaline	1%
Muscovite	accessory
Rutile	accessory
Pyrite	accessory
Apatite	accessory

Quartzite is a medium-grained (0.5 mm.), structureless, granular - probably originally an arkose. Schist is fine-grained (0.1 - 0.2 mm.), granular to weakly schistose, probably originally a fine-grained feldspathic sandstone.

4301 - Felspar-quartz-mica gneiss, with light hydrolytic alteration and mineralisation.

Components:		
	Quartz	30-40%
	Felspars	15-20%
	Biotite	5-10%
	Chlorite	10-15%
	Sericite (argillaceous)	20%
	Sphene	3-5%
	Pyrite	5-7%
	Chalcopyrite	trace
	Rutile	trace

A banded rock with layers composed principally of granoblastic quartz and felspars with included flakes of variously altered muscovite biotite. Granular clusters of sphene occur preferentially oriented along the banding, and coarser infilling masses of sulphide which occur preferentially in the coarser gneissose bands.

Hydrothermal alteration has affected principally the micas which are chloritised and argillised along margins, and the cores of the biotites are bleached and partly argillised as well.

The sulphide is identified in polished section as almost exclusively pyrite. It occurs as irregular anhedral grains measuring up to 3 mm. acrss. These are more-or-less distributed along the banding. The grain size of the pyrite is consistent with the grain size of the silicate minerals in the host bands, indicating that it developed during the metamorphic reconstitution of the rock.

Minute grains (0.02 mm.) of chalcopyrite are randomly distributed in trace abundance, and many of the pyrite grains carry chalcopyrite inclusions of this size. Accessory very fine rutile is scattered along some bands.

4306 - Sheared folded felspar-mica-quartz gneiss.

Components:		
	Quartz	40%
	Felspars (argillised)	20-30%
	Biotite	20%
	Chlorite	5%
	Muscovite	5-8%
	Sphene and leucoxene	1%
	Opaques (iron oxides)	2-3%

A medium to fine grained schistose gneiss composed of broad folds of alternating micaceous and quartzo-felspathic granoblastic mosaic. Random shears traverse the rock containing chlorite and comminuted and argillised components. Minor attendant dragfolding distorts the immediately adjacent layers.

The rock consists of isolated but generally aligned biotite flakes set in polygonal quartz xenoblasts and extensively argillised remnants of felspars. Iron oxide grains are scattered around some layers with minor grains of sphene and earthy clusters of leucoxene. Some formation of fine ochreous haematite has taken place.

Alteration has been principally of the hydrolytic type probably associated with the cycle of major folding rather the later shearing.

4309 - Quartz-mica-felspar schist.

Components:	Quartz	20-30%
	Felspars	30-40%
	Biotite	20-25%
	Muscovite	5%
	Chlorite	10%
	Pyrite	1%
	Accessory minerals - Tourmaline,	Zircon
	Chalcopyrite	rare trace

A fine to medium grained schistose rock composed of aligned biotite and rare muscovite flakes set among a granoblastic mosaic of quartz and felspar polygonal crystals. Both potassic and soda-lime felspars are present in probably similar proportion. Traces of tourmaline prisms and zircon grains are scattered throughout most often in association with the biotite.

Chlorite has formed along minor subparallel shear fissures with traces of argillisation and formation of angular grains of sulphide (pyrite ?).

Mineragraphic:

In polished section, subhedral pyrite grains, average size 0.2 mm. are seen sparsely and randomly scattered through the rock. Rare, smaller (0.01 mm) grains of chalcopyrite are also randomly scattered.

4312 - Quartz-felspar-biotite schist.

Components:		
	Quartz	20%
	Felspars	30-40%
	Muscovite	1-2%
	Biotite	40%
	Chlorite	5-10%
	Tourmaline	1-2%
	Chalcopyrite	trace
	Pyrite	trace

A fine grained foliated schist consisting of polygonal xenoblasts of felspars and quartz enclosed among semi-continuous trains of biotite flakes. Minor alteration shows along the margins of the biotite. Subidioblastic prisms of tourmaline are scattered throughout.

Traces of clays and secondary (?) felspars are present along minor fissures generally parallel to the foliation. The rock is very similar to the previous sample 4311.

Mineragraphic:

Minute (0.01 mm) grains of chalcopyrite are randomly scattered as inclusions in quartz. Rare vary fine aggregates of slightly coarser (0.1 mm) chalcopyrite also occur locally.

Independent subhedral grains of pyrite are randomly scattered. There appears to be no specific, significant mode of occurrence of the sulphides.

4314 - Metasomatised quartz-felspar-mica schist.

Components:		
	Quartz	20-30%
	Felspars (argillic)	30-40%
	Biotite	30%
	Tourmaline	1-2%
	Chlorite	3-5%
	Carbonate	2-3%
	Leucoxene (rutile)	2%
	Pyrite	1-2%

A very fine grained gneissic schist consisting of broad bands of granoblastic quartz-felspar mosaic interspersed with abundant parallel aligned flakes of biotite separated by thinner leucocratic layers of quartz-felspar almost devoid of biotite. The rock has been affected by metasomatic-pneumatolytic fluids which have permeated along the leucocratic bands lightly argillising felspars and forming chlorite from marginal biotite. Transverse fissures cross the broad biotitic layers and have been filled with masses of carbonate and clays.

Granular masses of leucoxene (rutile) are scattered along the leucocratic layers with sparse sulphides, also along these layers and in the transgressive veins of alteration products.

The pyrite in this sample appears largely to be genetically related to the alteration, although minor subhedral pyrite is also distributed along the foliation as in the previous samples.

No chalcopyrite occurs in the polished section examined.

4315 - Hydrothermal vein in quartz-biotite-tremolite-felspar schist.

Components:		
	Quartz	7-10%
	Felspars	40-50%
	Biotite	10-15%
	Tremolite-actinolite	15-20%
	Carbonates	3-5%
	Clay minerals	5-10%
	Sphene	3-5%
	Pyrite	3%
	Chalcopyrite	trace
	Specularite	trace

A metamorphic schistose rock of fine to medium grain consisting of alternating aligned biotitic and tremolitic layers set among xenoblastic felspars. The tremolite has the form of coarser poikiloblastic prisms enclosing felspars, principally of the plagioclase variety.

The veining is transgressive to the metamorphic foliation and consists principally of clear anhedral quartz with minor carbonate. Alteration marginal to the veins has resulted in formation of potassic felspars by metasomatism, and some hydrolytic formation of clay minerals along solution channels. Fine subhedral crystals of pyrite occur through the rock and relatively massive pyrite occupies part of the vein at one end of the hand specimen. Crystals of sphene pseudomorphous (?) after titanian iron oxides occur randomly.

Most pyrite appears to be directly related to the areas of alteration. Minute (0.02 mm) blebs of chalcopyrite and traces of specularite are enclosed in quartz near the pyrite and also within the altered zones.

4316 - Biotite-carbonate-tremolite rock (calc-silicate ?).

Components:		
	Quartz	1%
	Tremolite-actinolite	50%
	Carbonate	15-20%
	Biotite	5-7%
	Talc (?)	10-15%
	Clay mineral	10%
	Pyrite	5%
	Chalcopyrite	trace

A very crudely layered rock consisting of coarsely poikiloblastic intergrowths of tremolitic amphibole with irregular masses of anhedral carbonate most commonly having the form of veins. Rare relict grains of quartz are present and sub-parallel trains of partially aligned biotite flakes. Masses of talcose (?) clays are distributed along some of the carbonate veinlets.

The rock appears to have been a felspathic mica schist which has been altered by calcic metasomatism due to introduction of carbonate bearing hydrothermal veins.

Subhedral grains of pyrite are scattered as individuals and in small aggregates. These tend to be coarsest in areas of maximum concentration of metasomatic mineralisation. Minute (0.02 mm) inclusions of chalcopyrite rarely occur in pyrite grains - otherwise chalcopyrite is absent.

4317 - Talcose marble.

Components:	Quartz	1-2%
	Carbonate	60-70%
	Talc	20-30%
	Chloritic clay mineral	5%
	Pyrite	3%

A saccharoidal mass of carbonate containing subparallel talcose layers enwrapping the coarse polygonal carbonate crystals. Flaky masses of chloritic clay mineral pseudomorphous after former biotite are present as partially aligned inclusions in the carbonate causing a weak lineation. Traces of relict quartz grains are present in the carbonate.

Irregular to subhedral masses of pyrite up to 1 mm. are scattered throughout. Chalcopyrite is absent.

The rock appears to be the product of calcic metasomatic alteration of a biotitic schistose or gneissic rock.

4318 - Talcose marble

Components:	Quartz	1%
	Carbonate	70-80%
	Talc	15-20%
	Chloritic clay (?) mineral	5%

A coarse grained saccharoidal massive carbonate rock enclosing equally coarse masses of finely intermeshed talc flakes. Rare relict grains of corroded quartz and masses of argillised (?) chlorite flakes are also present as random knots.

The rock shows no lineation or texture except a sparse random mesh of intersecting fractures. It is considered likely to be of similar metasomatic derivation as the previous samples 4317 and 4316. Opaques are entirely absent.

4319 - Talcose marble.

Components:	Quartz	trace
	Carbonate	70%
	Talc	20-30%
	Chlorite (and clays ?)	5-7%

A coarse grained saccharoidal massive carbonate rock similar to the samples 4318 and 4317. Irregular masses and broad veins of fine intermeshed talc flakes are included among the carbonate. Traces only of quartz are discernible. Partially aligned flakes of chlorite and chloritic clays are slightly more abundant in this sample suggesting a relict banding. No opaques are present.

The rock is considered to be of similar metasomatic origin as for the previous sample.

4320 - Quartz-felspar-talc schist.

Components:		
	Quartz	5-10%
	Felspar	30-40%
	Talc	40-50%
	Muscovite)) Biotite)	10-15%
	Opaques (sulphide)	1-2%

A weakly foliated and banded schist composed of polygonal felspar and quatz xenoblasts enveloped in very finely intermeshed flakes of talc which are partly aligned parallel to the banding. The banding is due to relict aligned lenses and layers of quartz-felspar alternating with micaceous remnants (biotite ?) in various stages of alteration to talc.

Isometric crystals of sulphide up to 0.5 mm. diameter are scattered randomly with a slight tendency to be aligned along the banding.

4324 - Talcose marble.

Components:	Carbonate	70-80%
	Talc	15%
	Felspar	3-5%
	Opaques (sulphide)	2-3%

A medium grained granoblastic aggregate of polygonal carbonate with fine intergranular veinlets of intermeshed talc flakes broadening into veinlets up to 0.5 mm. wide in a few places.

Random subidioblastic plagioclase felspars occur as fine inclusions among the talc and carbonate, with fine pyritohedral crystals of sulphide (pyrite ?). The rock is classified as a talcose marble of metamorphic-metasomatic origin.

4325 - Talcose marble.

Components:	Carbonate	90%
	Talc	7-10%
	Felspar	1-2%
	Opaques	1-2%

A medium grained granoblastic aggregate of polygonal carbonate enclosing finer flakes and aggregates of foliated talc, some tend to form minor veinlets.

Random idioblastic to subidioblastic plagioclase felspars are sparsely scattered with finer pyritohedral crystals of sulphide (pyrite). The sample is very similar to number 4324 and is of similar origin.

4326 - Talcose marble.

Components:		
	Carbonate	70-80%
	Talc	20-30%
	Felspar	trace
	Chlorite	1%
	Limonite	1%

A medium grained granoblastic aggregate of polygonal carbonate interspersed with finer layers and lenticles of intermeshed talc flakes and a few foliae of chlorite. A few very rare felspars are enclosed among the carbonate and the whole is weakly layered.

The rock is stained yellow in hand specimen, and is spotted with microscopic grains of limonite pseudomorphs after sulphide. Most staining is intergranular to the carbonate or lining scattered voids produced by supergene (?) leaching.

The rock is a metamorphic-metasomatic talcose marble leached and oxidised by surface waters probably extending down a fault zone below the normal water table.

<u>4327</u> - <u>Talcose marble</u>.

Components:		
	Carbonate	70-80%
	Talc	20%
	Felspar	1%
	Chlorite	trace
	Limonite	1-2%

A very similar rock to number 4326 in that it consists principally of a medium grained granoblastic polygonal carbonate mosaic interspersed with layers and minor lenticular masses of talc and traces of chlorite. A few felspars are included among the carbonate.

The rock has been leached and oxidised similarly to sample 4326 so that former sulphides are now represented by pseudomorphous goethite masses. Limonite staining has however only permeated the immediately adjacent intergranular fissures.

4328 - Talc-carbonate schistose marble.

Components:	Carbonate	60%
	Talc	30-40%
	Chlorite	trace
	Pyrite	2%

A partially foliated mass of talc flakes generally up to 1 mm. diameter and considerable intermeshed finer material intercalated with granoblastic carbonate bands and fine veinlets. The banding is irregular and much disturbed by shearing. The talc tends to be greenish in hand specimen which may be due in part to traces of chlorite.

Irregularly dispersed subhedral crystals of pyrite are present, principally within the talc. Chalcopyrite is absent.

4329 - Chlorite-talc-carbonate schist.

Components:		
	Carbonate	50-60%
	Talc	30%
	Chlorite	10%
	Tremolite	3-5%
	Quartz	trace
	Pyrite	1-2%

A mass of contorted and sheared schistose laminae of granoblastic carbonate of medium to fine grain size interspersed with foliated talcose bands containing broad flakes of chlorite and relict altered prisms of tremolite. Rare masses of quartz are present intermittently.

Individual subhedral grains and very small groups of these are scattered, generally within the talc-chlorite areas in the carbonate.

4426 - Heavy mineral fraction of Rhynie Sandstone Equivalent.

A polished section of the mineral grains in the sample was prepared.

The principal component (the opaque black mineral) was found to be -

TITANIFEROUS HAEMATITE - Fe_2O_3 with TiO_2.

Grains are relatively pure haematite with common occurrence of lamellar twinning and under adequate magnification every grain is seen to contain plentiful exsolution lamellae of ilmenite oriented within the grains along rhombohedral directions.

The proportion of ilmenite present within the haematite would be in the interval 5-10% and the total TiO_2 assay would probably be about 5%.

Other mineral grains present in order of abundance are quartz, goethite, magnetite, topaz, tourmaline, zircon and green grains which appear to be amphibole.

4433 - Pegmatite.

Components:	Quartz	50%
	Altered Feldspar	25%
	Sericite	10%
	Muscovite	15%
	Magnetite	accessory
	Sphene	accessory
	Zircon	accessory
	Apatite	accessory
	Tourmaline	accessory
	Almandine garnet	accessory

The rock is coarse and irregularly grained consisting of large phenocrysts of quartz, containing ubiquitous tourmaline, zircon and rare apatite inclusions, and large randomly oriented segregations of sericite. Rare sphene microphenocrysts are found in association with the quartz. The feldspars have been largely altered to saussurite, and in parts weathered to kaolinite. However, a few extinction angles could be recorded from some laths and these gave the composition as the Na rich plagioclase albite (approximately An_{10}). Relatively large "books" of mica are present. Each of these "books" has been subjected to intense weathering by percolating solutions and each lath or flake has been stained a bright green by precipitated malachite. The solutions have percolated through the weakest zones in the rock and deposited malachite on the muscovite flakes. Where cavities have been formed in the rock, by the complete removal of weathered material, finely disseminated iron oxides (? limonite) have been precipitated.

The severely weathered nature of this sample makes further observations difficult. Several possibilities present themselves as to the origin of the secondary minerals, malachite and Fe oxides. It is possible that the Fe oxides are a weathering product of some primary Fe rich mineral.

This cannot be verified in this sample as the cavities have been leached and no crystal shapes can be determined from them. The second possibility is that the Fe oxides are secondary. The relationship of the malachite to the muscovite indicates, beyond doubt, that it has a secondary origin. It is possible that both the Fe and Cu rich precipitates have been derived from the chemical weathering by solutions, of a mineral such as chalcopyrite and have been preferentially deposited in the cavities and on the muscovite flakes respectively. Alternatively the Fe and Cu may have been derived from two independent sources and deposited independently in the pegmatite.

4489 - Biotite-muscovite-quartz schist.

Components:		
	Quartz	30-40%
	Felspars	15-20%
	Biotite	15-20%
	Muscovite	25-30%
	Opaques (iron oxide)	1-2%

A medium to coarse grained rock with a moderate foliation due to partial parallel alignment of coarse muscovite and biotite flakes set among xenoblastic quartz and minor felspars. Traces of chloritisation occur among the biotite. Scattered irregular masses of iron oxide opaques are scattered sparsely throughout.

Slight shearing stresses have induced minor crumpling of the foliation and strain recrystallisation of quartz grain margins.

4516 - Biotite-quartz-muscovite schist.

Components:	Quartz	30%
	Muscovite	50-60%
	Biotite	10-20%
	Opaques	1%

A metamorphosed strongly foliated schist with a broad folded crenulation with axial crumpling of micaceous layers. It consists principally of aligned muscovite flakes with rare interspersed biotite and layers of granoblastic quartz, which also occur as sparse individuals through the micas. Very rare irregular crystals of iron oxide opaques are also present intermittently.

This rock differs from several similar samples (e.g. 4107) in that there is no chloritisation or other evidence of hydrolytic alteration.

4591 - Tremolite marble.

Components:	Tremolite	100%

A crystalloblastic rock made up entirely of a fine matted mosaic of fibrous tremolite grains of varying size.

4592 - Quartz-chlorite-muscovite schist.

Components:	Quartz	50%
	Chlorite	30%
	Muscovite	10%
	Sericite	10%
	Magnetite	1-2%
	Sillimanite	rare
	Zircon	rare

A crystalloblastic rock composed of a mosaic of interlocking transparent unstrained quartz grains (1.0 mm.) with elongate, oriented coarse-grained (6 mm.) chlorite flakes giving the rock a marked schistosity. The chlorite is pleochroic pale green to green and contains minute rounded zircon inclusions. The quartz contains small spindles of unaltered sillimanite as inclusions. Elsewhere sillimanite has altered to sericite, which in turn is altering to muscovite.

4593 - Quartz-sericite-chlorite schist.

Components:	Quartz	65%
	Sericite	25%
	Chlorite	5%
	Muscovite	3%
	Biotite	2%
	Limonite (after pyrite)	1%
	Zircon	accessory

A crystalloblastic schistose rock made up of a mosaic of transparent unstrained quartz grains (0.5 mm.) and sericite after mica. The biotite is pleochroic light to dark brown and often shows alteration to chlorite. The chlorite is pleochroic from pale yellow to green and contains minute inclusions of rounded zircon.

4594 - Quartz-feldspar-mica gneiss.

Components:	Quartz	50%
	Plagioclase (andesine)	30%
	Sericite	10%
	Biotite	10%
	Muscovite	2%
	Chlorite	accessory
	Magnetite	accessory

A crystalloblastic, gneissic rock composed chiefly of transparent, strongly strained quartz (0.8 mm) and plagioclase. Sericite, possibly retrogressed from sillimanite, occurs as fibrous knots often intimately mixed with chlorite, the latter being a product of alteration of biotite.

4597 - Sericite-muscovite-quartz schist.

Components:	Sericite	70%
	Muscovite	20%
	Quartz	5%
	Chlorite	5%
	Ilmenite	2%
	Limonite (after pyrite)	1%

A crystalloblastic, schistose rock composed mainly of knots of sericite possibly pseudomorphing kyanite, together with well oriented muscovite and pleochroic chlorite after biotite. The quartz is unstrained.

4604 - Tremolite marble.

Components:		
	Tremolite	80%
	Chalcedony	20%
	Muscovite	accessory

A slightly schistose rock composed of weakly aligned elongate tremolite grains which have been replaced by chalcedony along fractures and cleavages.

4605 - Tremolite marble.

Components:		
	Tremolite	70%
	Chalcedony	30%
	Hematite	accessory

A fine-grained granoblastic rock composed of an interlocking matrix of transparent tremolite grains set in a cement of opaline chalcedony.

4611 - Sericite-biotite-quartz schist.

Components:	Sericite	45%
	Biotite	20%
	Quartz	20%
	Feldspar	15%
	Limonite (after pyrite)	1-2%
	Zircon	accessory
	Apatite	accessory

Fine-grained (0.05 mm.) crystalloblastic schistose rock composed of sericite as aligned knots of flakes, some of which appear to be alterations from kyanite, together with pleochroic biotite and well-distributed quartz and feldspar.

4627 - Amphibolite

Components:		
	Hornblende	65%
	Plagioclase (An_{55})	25%
	Quartz	10%
	Sphene	4%
	Magnetite	1%
	Apatite	rare

A strongly schistose fine-grained rock composed of pleochroic (pale yellowish-green to dark green) elongate hornblende grains (0.4 mm.) with abundant quartz and feldspar inclusions. The quartz and feldspar have uniform grain size (0.4 mm.) and are equigranular. Sphene and magnetite occur as elongate, oval clusters.

4628 - Amphibolite

Components:		
	Hornblende	70%
	Plagioclase (labradorite)	20%
	Quartz	10%
	Ilmenite	1%
	Sphene	1%
	Apatite	accessory
	Limonite (after pyrite)	accessory

Similar in texture to 4627.

4629 - Amphibolite.

Components:	Hornblende	70%
	Plagioclase (An_{50})	20%
	Quartz	10%
	Diopside	1%
	Pyrite	accessory
	Zircon	rare

A granoblastic rock composed of a mosaic of irregular and intergrown crystals of strongly pleochroic hornblende (0.2 mm.). Many grains contain inclusions of iron oxide as exsolved grains, suggesting the hornblende was an alteration from original pyroxene.

4630 - Amphibolite.

Components:	Hornblende	70%
	Plagioclase (labradorite)	20%
	Quartz	10%
	Iron Oxide	1%
	Diopside	accessory
	Sphene	rare

A massive granoblastic rock composed of a mosaic of hornblende, quartz and feldspar as in 4629. Sphene tends to collect along directions not related to the present hornblende cleavages but mirroring the probable original pyroxene cleavages.

4650 - Banded gneiss.

Components:	Plagioclase (Ab_{90})	32%
	Quartz	25%
	Sericite	20%
	Biotite	18%
	Limonite	4%
	Opaque	1%

The biotite is strongly oriented and ranges from deep green to dark brown in colour, the usual grain size being 1mm. The sericite bands contain fine grained elongate grains of quartz and plagioclase. The quartz and plagioclase more commonly has its grain size approaching 3 mm. to 5 mm. The opaque is associated with the biotite.

4660 - Feldspar Quartz Sericite Gneiss.

Components:		
	Sericite	40%
	Quartz	30%
	Microcline	25%
	Opaque	5%

Quartz grains (up to 2 mm.) are often fractured and display undulose extinction. Feldspar grains are extremely fractured with fine sericite often filling the fractures and showing a preferred orientation. Opaque grains up to 0.5 mm; often brecciated with "tails" of finer opaque, few euhedral grains.

4662 - Quartz Sericite Gneiss.

Components:	Quartz	50%
	Sericite	40%
	Opaque	5%
	Muscovite	accessory

Quartz grains up to 2 mm; fractured and display undulose extinction. Rare "Porphyroblasts" of quartz up to 1 cm. in size. Fine sericite flakes show a preferred orientation. Opaque grains up to 0.5 mm., occur as fractured disseminated grains, often surrounded by ferruginous stains. Muscovite flakes up to 0.5 mm. Distinct lack of feldspar.

4663 - Biotite Feldspar Quartz Gneiss.

Components:	Quartz	50%
	Plagioclase	25%
	Biotite	10%
	Sericite	10%
	Muscovite	accessory
	Opaque	accessory

The rock displays a mosaic texture of interlocking quartz, feldspar and biotite grains. Quartz grain size between 0.1 mm. and 2 mm; grains show undulose extinction but no fracturing. Plagioclase is multiple twinned and grains unfractured. The majority of the plagioclase is unsericitized. Biotite flakes up to 1 mm. and have a preferred orientation and inclusions of zircon. The flakes are often intergrown with muscovite and concentrated in thin bands. Euhedral opaque grains up to 0.5 mm. in size are common. Fine sericite is unevenly disseminated through the rock and shows no preferred orientation.

4665 - Graphitic Sericitic Phyllite.

Components:	Sericite	50%
	Opaque (Graphite ?)	45%
	Quartz	5%

Fine and coarse lenses of sericite oriented parallel to the cleavage with rare lenses of recrystallized quartz displaying a similar orientation to the sericite lenses. Rare brecciated quartz grains. Rock displays a sheared texture. Fine opaque grains are often parallel to cleavage.

4669 - Feldspathic Silty Sandstone.

Components:	Quartz	70%
	Microcline	15%
	Sericite	10%
	Muscovite	5%
	Biotite	accessory
	Tourmaline	accessory
	Plagioclase	accessory
	Titaniferous hematite	accessory

Grains are angular to subrounded and display some degree of sorting. Quartz grains show undulose extinction and are less than 0.1 mm. Microcline shows only slight sericitization, though extremely fine sericite occurs between grains of feldspar and quartz. Biotite and muscovite flakes up to 0.5 mm. are concentrated in the silt layers within the sandstone. Tourmaline is the blue-green variety.

4670 - Feldspathic Silty Sandstone.

Components:	Quartz	55%
	Microcline	20%
	Sericite	10%
	Muscovite	5%
	Calcite	5%
	Titaniferous hematite	accessory
	Plagioclase	accessory

Quartz and feldspar grain size is less than 0.25 mm. although flakes of muscovite can be up to 0.5 mm. Grains are angular to subrounded and poorly sorted. Microcline shows only slight alteration to sericite. There is an alignment of sericite flakes and to a lesser extent the coarser muscovite. The muscovite is concentrated in the thin silt layers of the sandstone. A calcite cement is present in portion os the rock.

4671 - (Sericitic) Sandstone.

Components:	Quartz	70%
	Sericite	25%
	Muscovite	5%
	Opaques	accessory
	Tourmaline	accessory

The rock is composed of subrounded, well sorted grains of quartz up to 0.5 mm. There is a slight alignment of sericite flakes, parallel to the fine silt laminatons.

4672 - Recrystallized bedded Chert.

Components:	Quartz	90%
	Opaque	10%

Mosaic of interlocking quartz grains of various sizes but generally less than 0.2 mm. Very fine opaque grains are generally concentrated along bedding planes within the chert. The opaque grains are possibly fine carbonaceous material?

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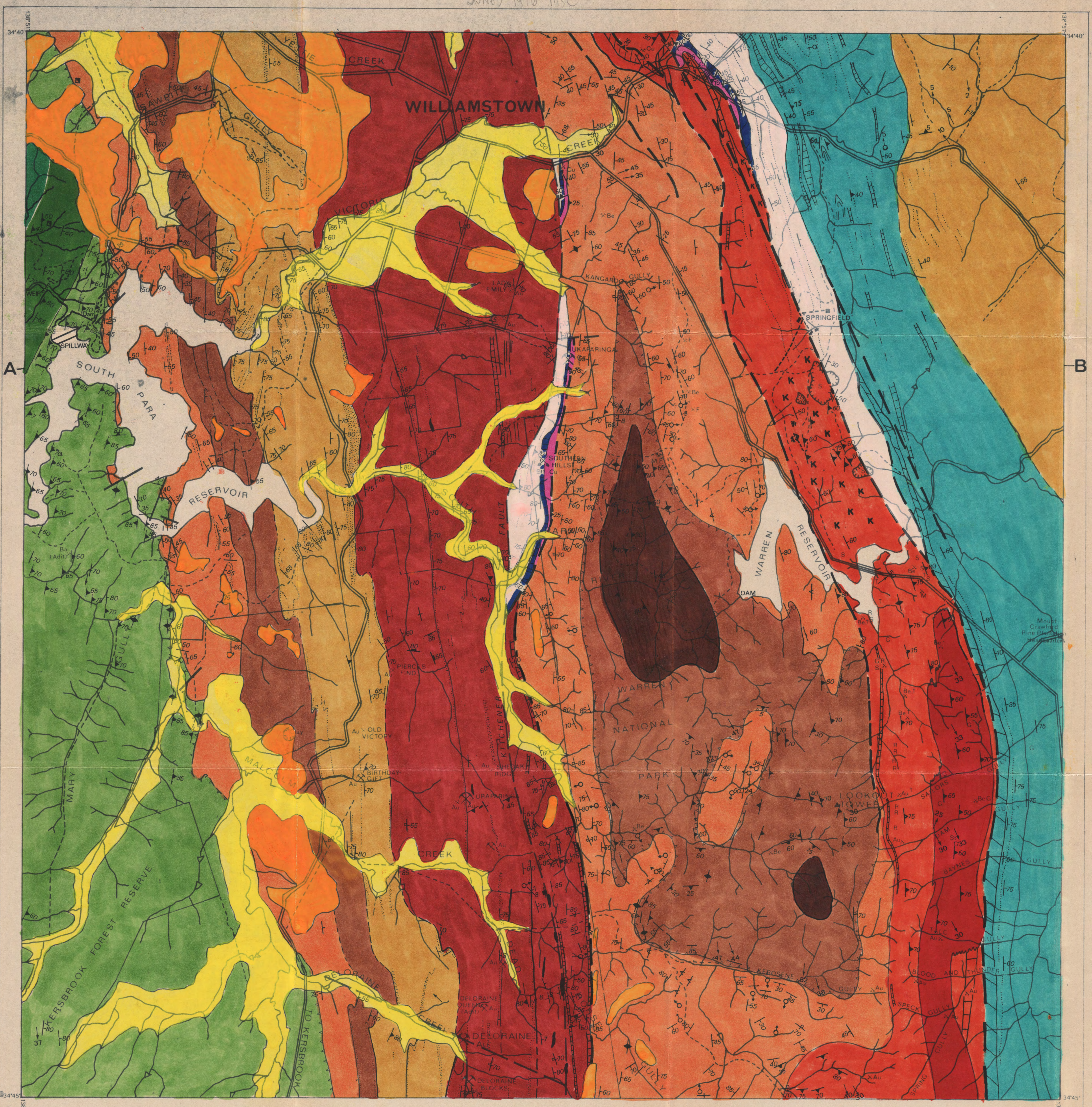
WILLIAMSTOWN

Jones 1976 MsC



REFERENCE

SEQUENCE EAST OF KITCHENER FAULT

PROTEROZOIC — ADELAIDE SYSTEM — TORRENSIAN — BURRA GROUP

UNDALYA QUARTZITE EQUIVALENT
Quartzite; mica-schist; calc-silicate

PEWSEY VALE FORMATION
Calc-silicate

PIPELINE SCHIST

VICTORIA CREEK MARBLE

UKAPARINGA SCHIST

SPRINGFIELD SUB-GROUP:
Micaceous schist, gneiss
KYANITE-DAMOURITE SCHIST
MT CRAWFORD GRANITE GNEISS
Tremolite marble

RHYNIE SANDSTONE EQUIVALENT
Arkosic grit

WILLOURAN — R. WAKEFIELD GP.

WARREN SCHIST
Schist
Gneiss

SEQUENCE WEST OF KITCHENER FAULT

CAINOZOIC — RECENT

Clay; alluvium

CAINOZOIC — TERTIARY

Gravel; grit; sand

PROTEROZOIC — ADELAIDE SYSTEM — TORRENSIAN — BURRA GROUP

SADDLEWORTH FORMATION
Dolomitic phyllite
Quartzite
Phyllite; shale

UNDALYA QUARTZITE
Quartzite; sandstone; phyllite

WOOLSHED FLAT SHALE
Sandy phyllite

SKILLOGALEE DOLOMITE
Dolomite
Phyllite, shale

RHYNIE SANDSTONE
Feldspathic sandstone
Hematite sandstone
Ferruginous conglomerate
Basal conglomerate

PROTEROZOIC — CARPENTARIAN

BAROSSA COMPLEX
Phyllonite
Quartzite
Augen gneiss

Scale 1:20,000

Kilom. 0 0.2 0.4 0.6 0.8 1.0 2 3
Metres 0 200 400 600 800 1000 2000 3000

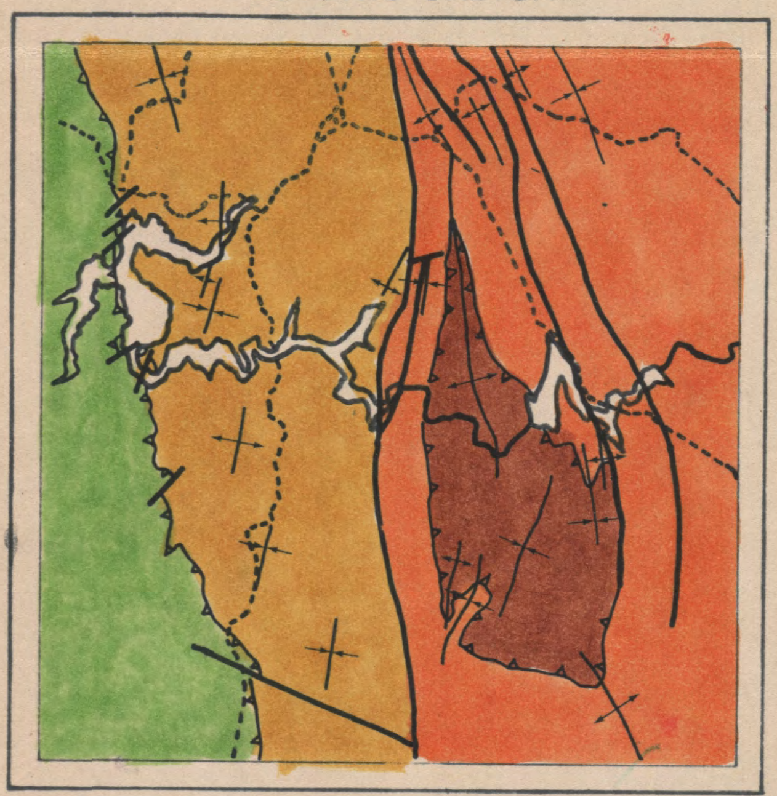
GEOLOGICAL BOUNDARY
  Observed
  Inferred
FAULT
  Observed
  Inferred
BRECCIA
FOLD
  Plunge of minor fold
BEDDING
  Inclined
  Vertical
  Horizontal
  Overturned
  Trend
  Facing
FOLIATION
  Inclined
  Vertical
  Trend
LINEATION
  Inclined
TYPE SECTION

ROAD
TRACK
TRIG.
CREEK
QUARRY
MINE
PROSPECT

MINERAL OCCURRENCE

Barite	Ba	Kyanite	K
Beryl	Be	Mica	M
Copper	Cu	Rutile	R
Feldspar	F	Sillimanite	S
Garnet	G	Staurolite	St
Gold	Au	Tourmaline	T
Iron	Fe		

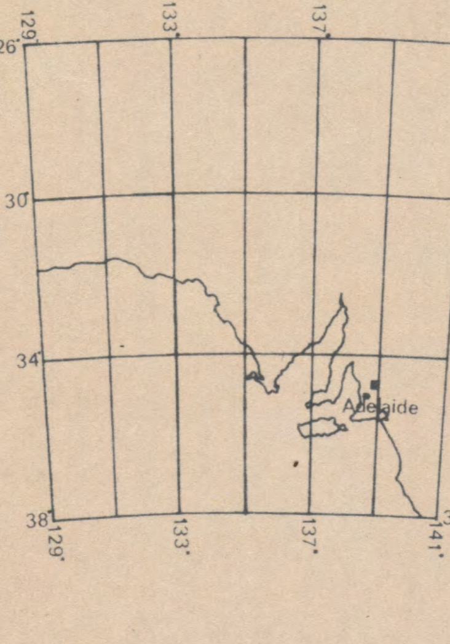
TECTONIC SKETCH



Adelaide System:
Burra Group 🟧
Burra Group (metamorphosed) 🟧
Warren Schist 🟫
Older Precambrian (Barossa Complex) 🟩

Fault
Unconformity
Anticline
Syncline

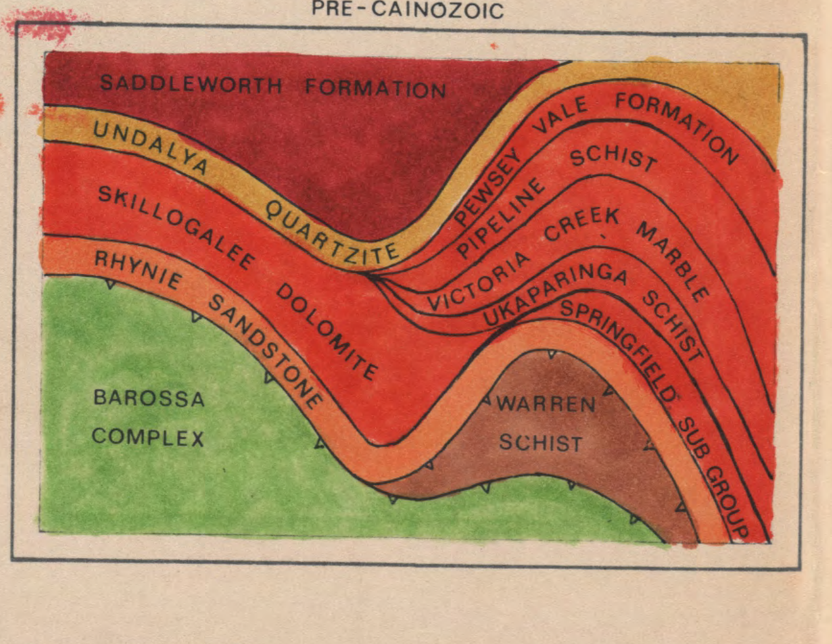
LOCALITY



INDEX TO ADJOINING SHEETS

ROCK RELATION DIAGRAM

PRE-CAINOZOIC



SECTION A-B [natural scale]

Geology by D.G. Jones, B.Sc., 1969-73

Compiled by D.G. Jones in 1973 as part requirement for M.Sc.

Base map prepared from 1:31,680 sheets and 1969 aerial photography provided by the South Aust. Department of Lands.