THE ORIGIN OF DOLOMITE IN EARLY CAMBRIANCARBONATES OF YORKE PENINSULA, WESTERN MARGIN OF STANSBURY BASIN, SOUTH AUSTRALIA

by

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ABSTRACT

The Early Cambrian carbonate sequence in Yorke Peninsula consists of tidal flat lithologies in the lower part (Kulpara Fomation) and lagoonal lithologies with sporadic bioherms (Koolywurtie Member) in the upper part. Dolomitization have been recorded in those carbonates mainly of replacive nature, only small amounts are void – fill cement.

Petrographic and stable isotopic analysis have supported the conclusion that dolomitization of the Early Cambrian carbonates in Yorke Peninsula was an on-going process by hypersaline water followed by a mayor episode of recrystallization during shallow burial diagenesis, where enormous quantity of magnesium required for regional dolomitization is supplied by sea water. The geochemical and tectural modification of the dolomites are the result of a later stage recrystallization event, in shallow burial diagenetic environment by surfacederived meteoric water.

I. INTRODUCTION

Dolomite and the problem of its origin were first addressed in 1871 by a French naturalist (Deodat de Dolomieu) when he described the rock in the southern Alps, Italy. In sedimentary milieux, dolomite is essentially a product of the transformation of a metastable carbonate to a more stable one. A variety of dolomite types exists in nature and they are distinguished by differing crystal forms, chemistries, and times of formation. Subsequent diagenetic modification (stabilization or recrystallization) may alter the initial physical and chemical characteristics of dolomites (Land, 1980; Banner et al., 1988; Cander et al., 1988). Such modification may have occurred in an environment different from the one where the dolomite initially formed, and this complicates evaluation of the origin of ancient dolomites.

More than 40% of petroleum production in Indonesia is found from in the carbonate reservoir rocks. Most of carbonate rocks have experienced diagenetic process at some degree. Dolomitization is a common diagenetic process and it creates pores in carbonate rocks. Therefore understanding dolomitization process is one of the essential points to oil exploration, especially in Indonesia.

Many studies have suggested that dolomite can form from a wide variety of fluids, including hypersaline (Mc Kenzie, 1981); mixed-water (Badiozamani, 1973; Dunham and Olson, 1980), deep burial brines (Mattes and Mountjoy, 1980) and normal sea water (Saller, 1984; Baker & Bums, 1985). Land (1985) emphasizes two major requirements for the formation of massive dolomite in ancient sequences. First, there must be a source of Mg ions and a process whereby the dolomitizing fluid is effectively pumped through the carbonate sediments. Second, a metastable (Ca-rich or partly disordered) carbonate must revert to a more stable phase.

Stable isotopic analysis has become an increasingly popular tool in the study of carbonate rocks. The oxygen isotopic composition of dolomite reflects the temperature of precipitation of the dolomitizing fluids, whereas the carbon isotopic composition of dolomite is generally dependent on the composition of its limestone precursors. Carbon isotopes are more resistant to diagenetic alteration than oxygen isotopes, as commonly observed in dolomites. A progressive depletion of ^{18}O of carbonates of increasing age has been recorded by Veizer and Hoefs (1976). The early Phanerozoic carbonates usually have more negative ä ^{18}O values than those of later Phanerozoic age (Tucker 1989) and this may reflect seawater depleted in ^{18}O and/ or hotter temperatures (Karhu and Epstein, 1986); diagenetic alteration (Land 1980, 1985; Banner et al. 1988; Cander et al. 1988; Whittaker et al. in press.); or organic matter decomposition in the sulphate-reducing zone (Sass et al. 1991).

Major and trace elements have been used to obtain information on the nature of dolomitizing fluids. The compositional variation of major elements reflects the degree of stoichiometry of dolomite and also reflects the degree of dolomite ordering (Lumsden and Chimahusky 1980). Trace elements, on the other hand, can be incorporated into the carbonate lattice, mainly by substituting for Ca^{2+}. The amount of trace element incorporated during precipitation depends on its partition or distribution coefficient. The values of these coefficients are not precisely known and seem quite variable for each element, being particularly dependent on temperature, rate of precipitation and other kinetic factors (Land, 1980). Therefore, it is suggested that trace element data should not be used in isolation to provide solutions to the problem of carbonate diagenesis. They are best used to complement other analytical tools like petrography and stable isotope studies. A good outline of the basic principles of trace element analysis and examples of its application to carbonate diagenesis can be found in Veizer (1983).

Strontium isotope ratios have been used in many studies to determine temporal variations in the chemistry of oceans and marine carbonate rocks (Veizer et al. 1983; Burke et al. 1982). It was initially believed that the $^{87}Sr/^{86}Sr$ ratio increased with the age of the carbonate (Wickman, 1948). Later studies have recorded major fluctuations in this ratio through geologic time (e.g. Burke et al. 1982). In more than 700 m of Early Cambrian carbonates occupying an area greater than 1800 km^2 on Yorke Peninsula, South Australia, a total of 200 m thick carbonates have been dolomitized. Dolomitization is very intensive in the lower part (Kulpara Formation) but scattered and patchy in the upper part (Parara Limestone). This study documents the petrographic and geochemical characteristics of the Yorke Peninsula dolomites, from which the origin and diagenetic modification of the dolomite can be inferred.

II. GEOLOGICAL SETTING

A 700 m-thick sequence of Early Cambrian shallow shelf carbonate occurs along the eastern side of Yorke Peninsula. It forms the western margin of the Stansbury Basin which is bordered by the Gawler Craton on the west and the Adelaide Fold Belt on the east (Figure 1). Much of the basin is offshore under Gulf St. Vincent. Its Cambrian sequence is poorly exposed, but has been penetrated by at least 12 drill holes.

The carbonates consist of peritidal to lagoonal lithologies with patches of carbonate reef buildups in the upper part, and are of Atdabanian to Botomian age (SADME 1989). They have been termed (in ascending order) the Kulpara Formation, the Parara Limestone and the Koolywurtie Member, and are laterally equivalent to the contrasting facies of the Normanville Group on Fleurieu Peninsula, where the eastern part of the Stansbury Basin is exposed (Figure 2) (Daily 1956; Abele & McGowran 1959; Alexander & Gravestock 1989). Relict depositional textures, structures and fossils in the Yorke Peninsula sequence suggest that its carbonates were deposited in tidal flat and lagoonal settings as illustrated in the composite stratigraphic column (Figure 3).

The Early Cambrian carbonates of the Yorke Peninsula found an upward deepening sequence in which most of the lower part, comprising the supratidal and intertidal lithologies of the Kulpara formation, has been intensely dolomitized. In the upper part of the section, the predominantly subtidal lagoonal lithologies of the Parara Limestone, and its shallow water fenestral bioherm facies (Koolywurtie Member), display only patchy dolomitization. Features of the peritidal sediments in the lower part of the sequence include a creamy coloration; mudcracks; fenestral fabrics; flat pebble breccias; and finely laminated, peloidal, oolitic and stromatolitic carbonates. Lagoonal lithologies present high in the sequence are characterized by grey colours; the absence of laminated textures; the presence of trilobites and abundant burrow structures which commonly appear as mottled carbonate; and bioherm facies which consist of boundstones, with evidence of sub aerial exposure (fenestrae), and bioclastic wackstone.

III. METHODS

Petrographic analysis was carried out on more than 200 thin sections partly stained with alizarin red-S and potassium ferricyanide (Dickson 1966).

Thirty seven samples were selected for stable isotope analysis. Individual diagenetic phases (dolomite and calcite cements) were separated and sampled using a dental drill. Representative portions (~15 mg) were treated with 100% phosphoric acid at 25 °C for calcite and 50 °C for dolomite and the collected $C0_2$ analyzed in Micromass VG 602D ratio mass spectrometer. The measured isotope ratios are corrected for 170 as described by Craig (1957) and Mook and Grootes (1973), and are reported in the usual delta notation relative to the PDB standard. Precision was determined by analy-

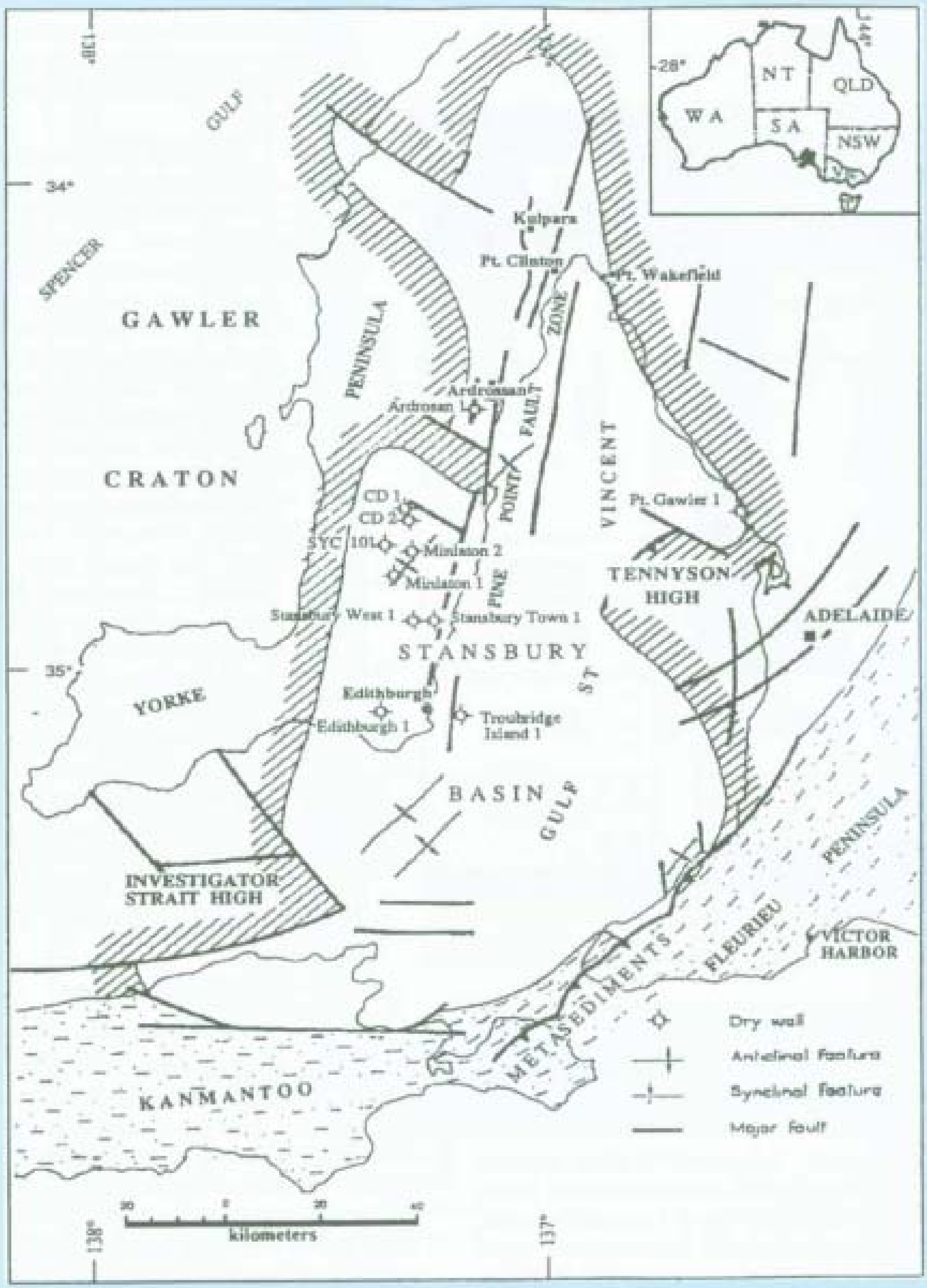


Figure 1
Stansbury - Basin Location Map (After Sadme 1989)

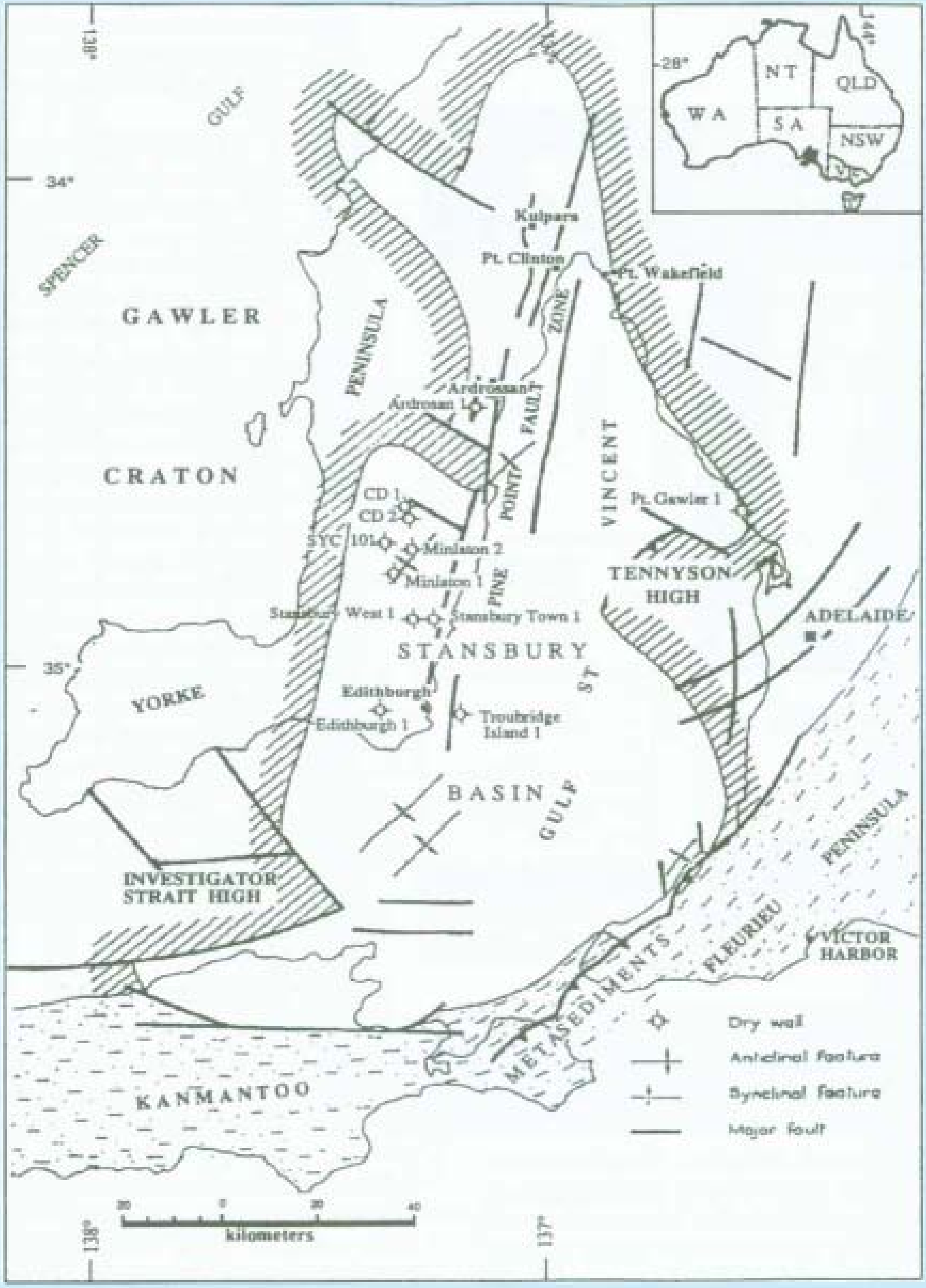
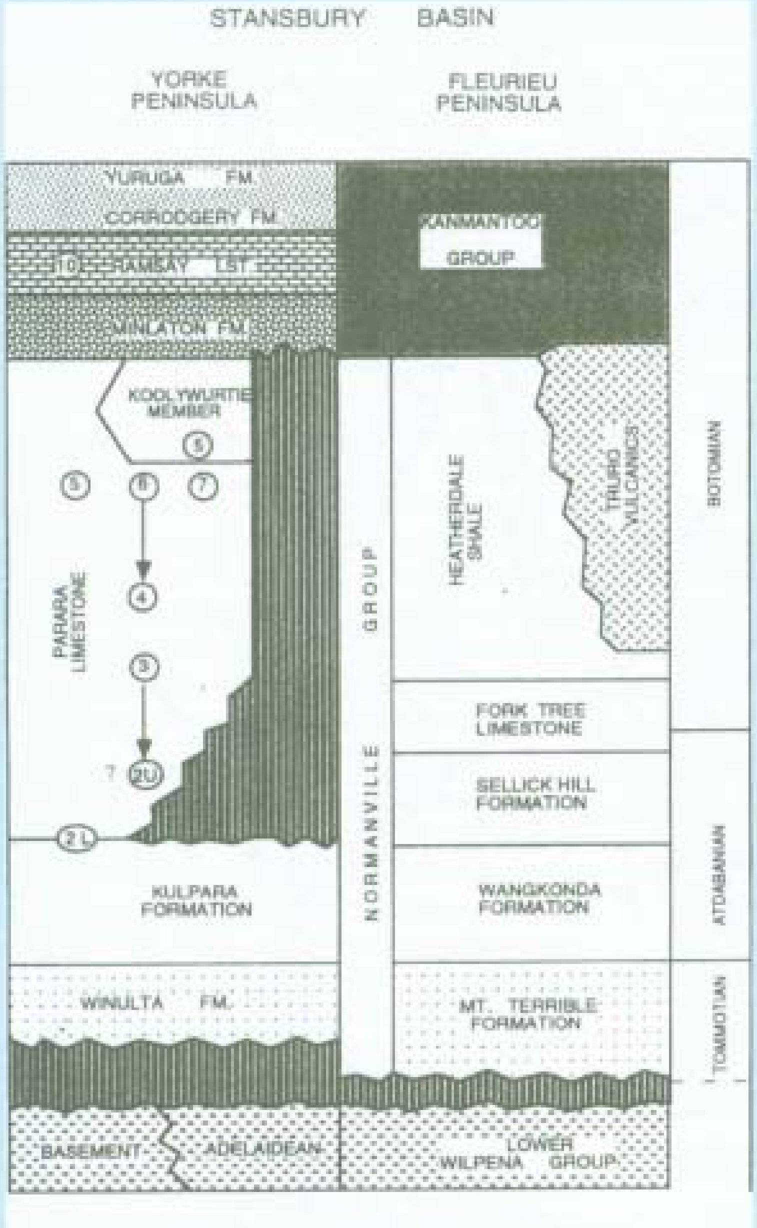


Figure 1
Stansbury - Basin Location Map (After Sadme 1989)



Note numbers refer to Faunal Assemblages of Daily (1956).

Figure 2
Regional stratigraphy of the stansbury Basin
(After Gravestock, in press)

sis of calcite standards. Dolomite ä ^{18}O values have not been corrected for phosphoric acid fractionation factor (Sharma and Clayton, 1965). This is because the precise value of this factor for dolomite has not yet been precisely determined, and Land (1980) has recommended that dolomite analyses should not be corrected.

Trace and major elements were analyzed from 27 representative samples using a JEOL 733 micro analyzer wavelength dispersive system (WDS) by inserting carbon-coated polished thin sections into the specimen chamber of an electron microprobe. WDS analysis conditions were 15 kv accelerating voltage and 30 nA electron beam current

Strontium isotope analysis was conducted on only four samples, carefully selected to be representative of the main dolomite types. The analysis was performed by Jo Maw by (Department of Geology and Geophysics, University of Adelaide). The procedure used is as follows: powdered samples were washed three times in 0.2 N ammonium acetate (AR grade) and then rinsed in distilled water three times to eliminate exchangeable Sr from clays. Previous experience suggests that this cleaning procedure can remove as much as 40 % of the Sr from clays. The cleaned samples were dissolved in 1.4 N acetic acid. Insoluble residues were removed by centrifugation and were usually less than 5% by weight. Sample solutions were poured into teflon beakers and evaporated on a hot plate. The dried samples were redissolved in distilled water, centrifuged, and then transferred to cation exchange columns, where strontium fraction was collected and then evaporated to dryness. The sample was then loaded onto Ta filaments and run as a metal on Finnigan MAT 261 mass spectrometer.

IV. PETROGRAPHY

A. *Description of Dolomite*

In the study area dolomitization is not restricted to carbonates of a specific depositional environment. Nevertheless, close facies and stratigraphic control on the distribution of dolomite is evident from the general decrease of dolomite content up section, from tidal flat carbonates in the lower part to the deeper lagoonal facies in the upper part of the sequence. This suggests that the dolomitization process was a function of both palaeogeography and the permeability of the precursor limestones.

Differences in dolomite texture, crystal size and

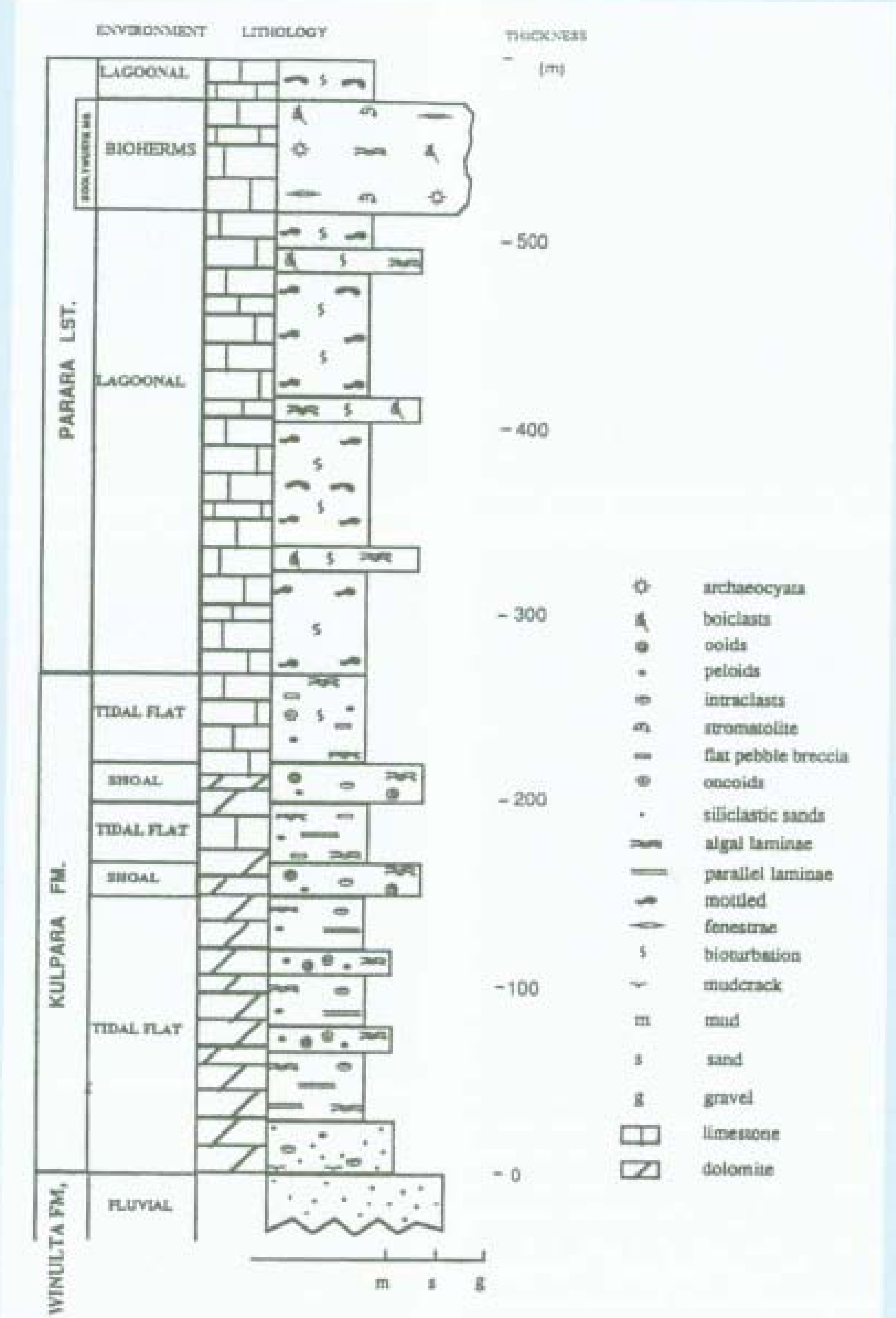


Figure 3
The composite sections of Early Cambrian carbonate sequence in Yorke Peninsula based on drillholes (Minlaton no. 1, Syc. 101, CD. 1, CD 2 and Ardrossan No. 1)

shape facilitated the recognition of three distinct types of replacement dolomite and a void-fill dolomite. These dolomite types reflect differences in the time and mode of formation and the nature of the precursor limestone. The replacement dolomites (in paragenetic sequence) are: 1. finely crystalline non-planar dolomite; 2. medium to coarsely crystalline non-planar dolomite; and 3. coarsely to very coarsely crystalline dolomite. Void-fill dolomite is mostly limpid, but volumetric ally is insignificant and comprises less than 2% of the total dolomite. The dolomite terminology employed here is that of Sibley and Gregg (1987).

Type 1 replacement dolomite : fine anhedral dolomite with crystals up to 30 ìm in size, mostly forming a non planar mosaic. It appears dirty and dark in color, due to abundant inter and intracrystalline organic matter and scattered pyrite. Both dolomite and pyrite are probably products of anoxic diagenesis involving sulphate-reducing bacteria (Friedman and Sanders 1967; Berner 1984).

Type 1 dolomite is common at several stratigraphic levels in the Kulpara Formation, probably reflecting cyclicity of sedimentation. Preserved fenestrae and mudcracks are associated with this dolomite, indicating early lithification and in a near-surface environment. The fact that its find crystal size and its association with preserved fine laminae (Figure 4) is further evidence that Type 1 dolomite was of early diagenetic and supratidal origin.

Scattered carbonate clasts consisting of Type 1 dolomite are also found floating in lime matrices, or in a more coarsely crystalline mosaic of Type 2 dolomite, in the middle and upper parts of Kulpara Formation. These dolomite clasts were probably transported from nearby supratidal and intertidal channels or ponds in a semi-consolidated form as suggested by the diffuse contact between the edges of clasts and the surrounding matrix. Often Type 1 dolomite grades upward in size to merge with or be replaced by other, more coarsely crystalline fabric. The lack of preserved evaporite minerals associated with Type 1 dolomite is suggestive of a prevailing seasonally humid climatic regime, similar to that of the Recent Coorong area of South Australia (Muir et. al. 1980; Warren 1988).

Type 2 replacement dolomite : medium to coarsely non-planar dolomite which is characterized by a cloudy appearance with crystal sizes ranging from 30 to 150 µm. It displays a variety of fabrics and crystal forms and occurs in tidal flat and lagoonal lithologies. The crystals are generally anhedral to subhedral, with weakly to moderately undulose extinction. The frequency distribution of crystal size in Type 2 dolomite is bimodal (Figure 5), a medium crystalline phase (averaging 50 µm) coexists with a more coarsely crystalline phase (averaging 120 µm). This bimodality probably reflects the sediment precursors, that is micrite and microspar. Type 2 dolomite can be differentiated into two subtypes, based on its host lithofacies: peritidal related (PR) and lagoonal related (LR). In the peritidal facies the medium crystalline phase usually has only a few planar crystal faces with the remainder being bounded by irregular, interpenetrating faces. The coarsely crystalline PR-dolomite has more planar crystal faces with interlocking grain margins. Dolomites in the lagoonal facies, however, are medium crystalline and with organic matter commonly found in their crystal interstices. Thus, LR-dolomite has a characteristically dirty appearance. In the uppermost part of the section, in the bioherm facies of the Koolywurtie Limestone Member, sporadic Type 2-dolomite occurs in association with evaporite minerals (gypsum and anhydrite), (Figure 6). A high salinity and arid climatic conditions (Mc Kenzie 1981) are indicated.

Type 2 dolomites form at least 90 % of the dolomite in the Stansbury Basin, replacing large volumes of precursor limestones and early Type 1 dolomite (Figure 7). Note that the fine depositional textures are still well preserved in Type 1 but not Type 2 dolomite, suggesting pervasive dolomitization in the latter case. Dolomitization is very intense in the peritidal lithologies of the lower section, but there are only sporadic patches of dolomite in the overlying lagoonal carbonates. These patches appear to have been burrowed and suggest that permeability was a primary control.

Type 3 replacement dolomite : is characterized by coarse to very coarse crystalline (300-600µm). The crystal is euhedral to subhedral with planar boundaries, replacing mainly the pre-existing interparticle cements of relatively high energy peritidal lithofacies (grainstone and packstone). This type of dolomite fabric has been termed "xenotopic mosaic" which reflects formation above the critical roughening temperature (CRT) of 50° C (Gregg and Sibley 1984). The relationship between Type 3 dolomite and the other types of dolomite is not clear. Distorted ooid grains (probably due to mechanical compaction) are transected by Type 3 dolomite (Figure 7) suggestive of a late diagenetic event and in turn this dolomite was posdated by stylolites (Figure 8). Its xenotopic texture and coarse crystal size, although not necessarily late diagenetic features are consistent with higher tem

Figure 4
Type 1 dolomite replacing fine laminae mudstone of supratidal carbonates. Note that fine laminations are well preserved

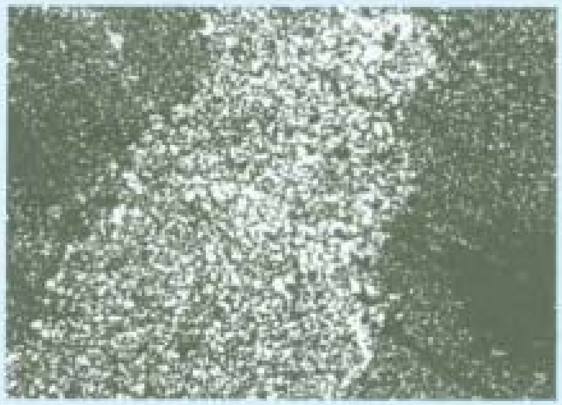


Figure 6
Type 1 dolomite transected by Type 2 dolomite. Note that laminations is well preserved in Type 1 butnot in Type 2

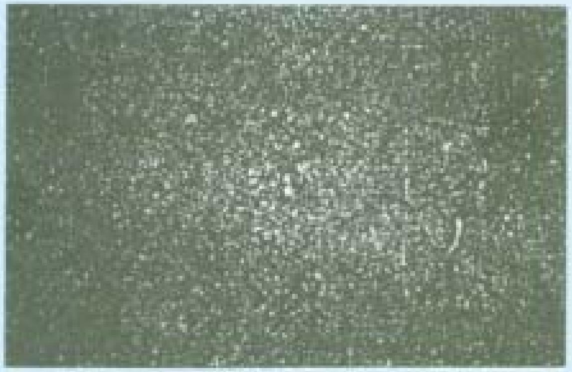


Figure 5
Type 2 dolomite slowing bimodality in crystal size

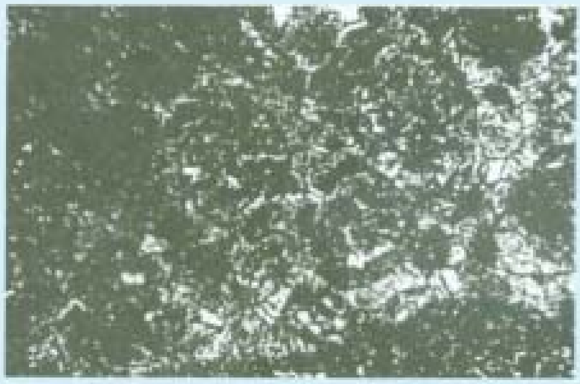


Figure 7
Type 3 dolomite mainly replacing intergrain sparry cements. Note that ooid rims were transected by this dolomite

peratures (Zenger 1983). A schematic diagram showing an interpretation of dolomitization process for Type 3 dolomite is shown in Figure 9.

Dolomite cement **:** It is characterized by clear euhedral rhombs with planar crystal faces and sharp terminations, showing no sign of corrosion and resembling schizohaline (limpid) type dolomite of Folk and Land (1975). The limpid dolomite cements have been found to grow on Type 1, 2 and 3 replacement dolomites filling fractures and molds (Figure 10). It suggests that precipitation of these cements followed dissolution event and in turn the limpid dolomite was overlain by thin ferroan calcite around their edges (Figure 11). Volumetrically, the dolomite cements are insignificant, comprising less than 2 % of the total dolomite. Although the limpid dolomite cements have been observed to overgrown on the eroded surface of late stage Type 3 dolomite, but the precipitation of these cements is also predated stylolites (Figure 12).

B. *Petrographic Summary*

1. A syndepositional or early diagenetic and supratidal origin of Type 1 dolomite is suggested by its rela-

tively fine crystal size, well preserved depositional textures (e.g. fenestrae, mudcracks, intact laminae) and its occurrence in several sedimentary cycles. The lack of associated evaporite minerals implies that this dolomite formed under a humid climate.

2. Type 2 dolomite forms 90 % of dolomite population, replacing large volume of precursor limestone and the early Type 1 dolomite and destroyed most of depositional textures (Figure 7), suggesting of pervasive dolomitization. The presence of evaporite minerals in associated lagoonal facies suggesting of seasonally arid climatic conditions and the involvement of hypersaline water.

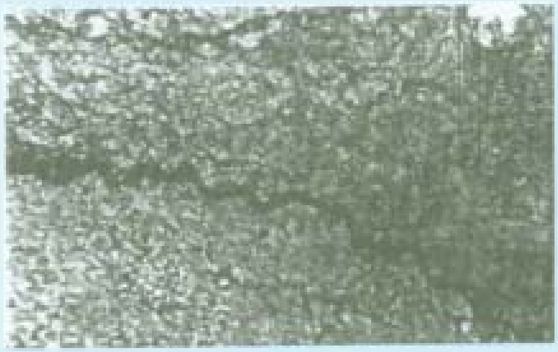


Figure 8
Stylolite posssated Type 3 dolomite

3. Type 3 dolomite is a coarse to very coarse xenotopic mosaic generally replacing the pre- existing spary calcite cement of a relatively high energy peritidal lithofacies. It is difficult to pinpoint the timing of Type 3 dolomite formation, because of its lack of petrographic interaction with other dolomites. Its xenotopic texture and coarse crystal size, although not necessarily late diagenetic features are consistent with higher temperatures (Zenger 1983), possibly above CRT (Gregg and Sibley 1984) and its association with broken ooid grains possibly confirms formation of late diagenetic events.
4. Dolomite cement is of limpid type, usually lining moulds and fractures and is a minor component of the dolostones (less than 2 %). The limpid dolomite has been found overgrowth on either Type 1,2 or 3 replacement dolomite. In turn it is overlain by ferroan calcite (Fig. 10). This suggests that dissolution may have occurred below photic zone in subsurface environment prior to the precipitation of the dolomite cement, but after or during the formation of Type 3 dolomite.
5. Stylolitization postdated all dolomite types, suggesting that dolo

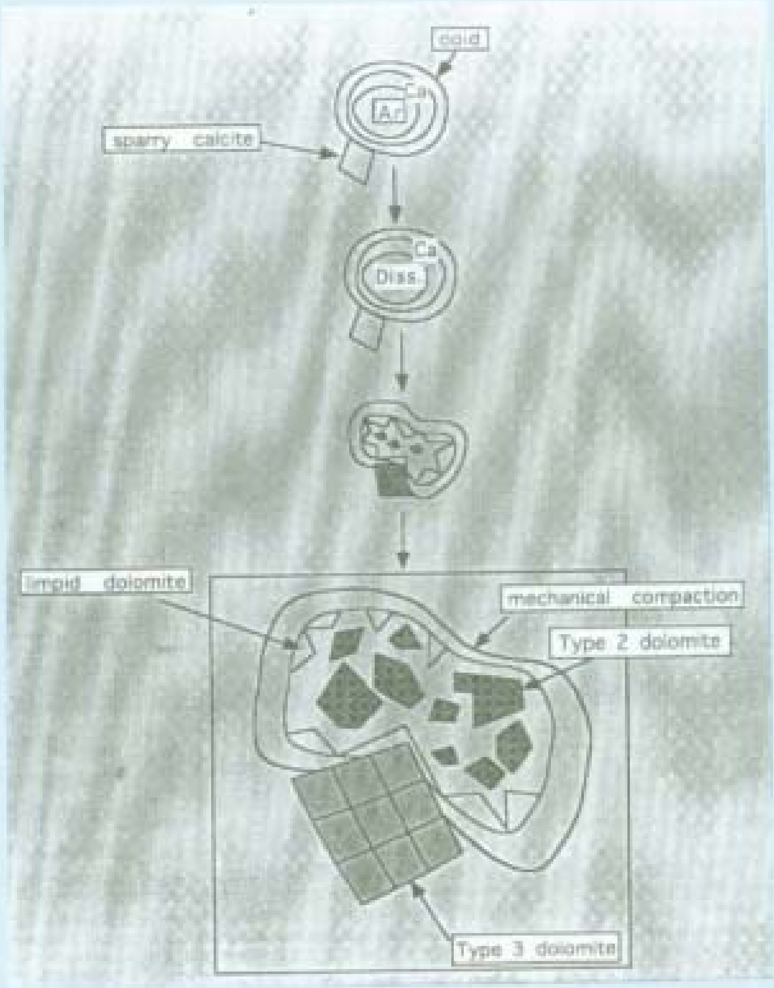


Figure 9
Schematic diagram of the dolomitization process for Type 3 dolomite

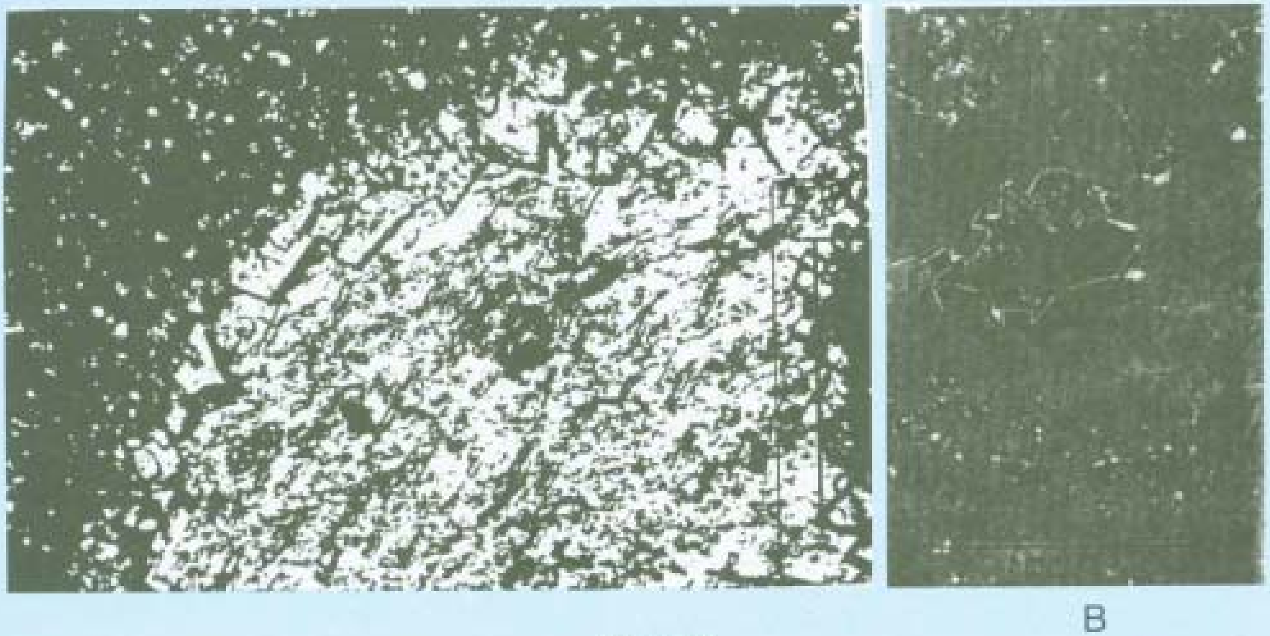


Figure 10
Limpid dolomite cements filling cavities. Note in these pothographs the substrates are Type 1 (A) and Type 3 (B), and also note the erosional surface on Type 3 dolomite (arrow)
Stylolite posssated Type 3 dolomite

Figure 11
Limpid dolomite cements filling ooid molds. Note the blue stains of Fe calcite around their edges

mitization ceased at depth where stylolites began to form.

V. ISOTOPIC AND TRACE ELEMENT GEOCHEMISTRY

Analytical data on representative samples Early Cambrian carbonates from the Yorke Peninsula are presented in Table 1.

A. *$CaCO_3$ Concentration*

The compositional variation of major elements in dolomite reflects its degree of stoichiometry, commonly expressed as mole percent of $CaCO_3$. Dolomite stoichiometry is controlled partly by the Mg/Ca ratio of the precipitating fluids (Morrow 1978; and Lumsden and Chimahusky 1980). CaCO3 concentration in the dolomites of Yorke Peninsula ranges from 46 to 54 mole percent (Figure 13), nearly 60% of the samples analyzed fall into the near stoichiometric (49 to 51 mole percent) category, most of which are peritidal related PR Type 2 dolomites.

Near stoichiometric dolomites like the PR Type 2 dolomite are interpreted by Lumsden and Chimahusky (1980) and Morrow (1982) to have precipitated from very dilute waters, possibly at elevated temperatures in a subsurface environment. A general trend of a declining Ca concentration with later stages of dolomitization is apparent in the other dolomite types (Table 1). This trend implies a progressive diagenetic change (Fuchtbauer 1972) which is consistent with the interpretation of dolomite paragenesis based on petrographic evidence.

B. *Sr Isotopes*

The Sr isotopic ratios of ancient seawater are best recorded from fibrous calcite cements of coeval limestones, because these early cements usually have the lowest $^{87}Sr/^{86}Sr$ ratios. Later cements have a greater radiogenic ^{87}Sr content. Early Cambrian seawater has been suggested to have $^{87}Sr/^{86}Sr$ ratios ranging from 0.7082 in the lower Tommotian to 0.7096 in the upper Botomian (Whittaker et al. 1993).

Figure 12
Stylolite croscuts ooid dolograinstone, including limpid dolomite as part of intergranular cements

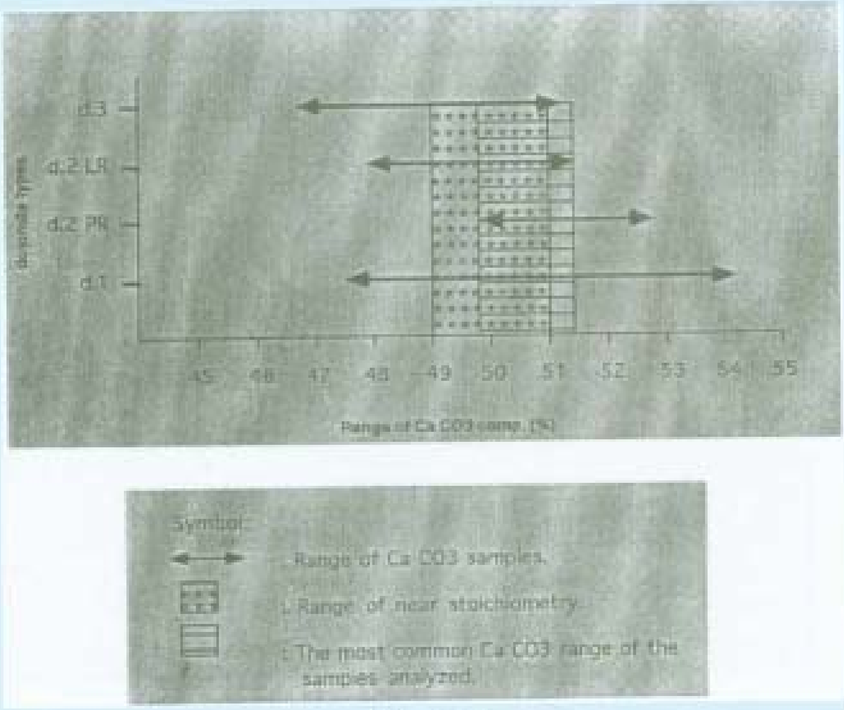


Figure 13
Range of $CaCO_3$ composition for dolomite types

A ratio of 0.7085 was obtained from one limestone sample of Atdabanian in the study area, confirming the suggested Sr isotopic composition of Atdabanian seawater. Most of the samples analysed were collected from Atdabanian lithologies, except for the LR Type 2 dolomite which was taken from a Botomian sample. The ^{87}Sr/^{86}Sr ratios of Yorke Peninsula dolomite range from 0.7089 to 0.7140, which are higher than the ratios of corresponding seawaters (Table 2), suggesting that dolomites were formed by modified seawater. The Sr content of Yorke Peninsula carbonates is more radiogenic up section, except for one sample of PR Type 2 replacement dolomite with a high clastic content (Figure14), this further supports of progressive diagenetic change. The enrichment of ^{87}Sr in later carbonate cements and dolomites has been attributed by Banner et al. (1988) and Whittaker et al., (1993) to diagenetic fluids of basinal origin.

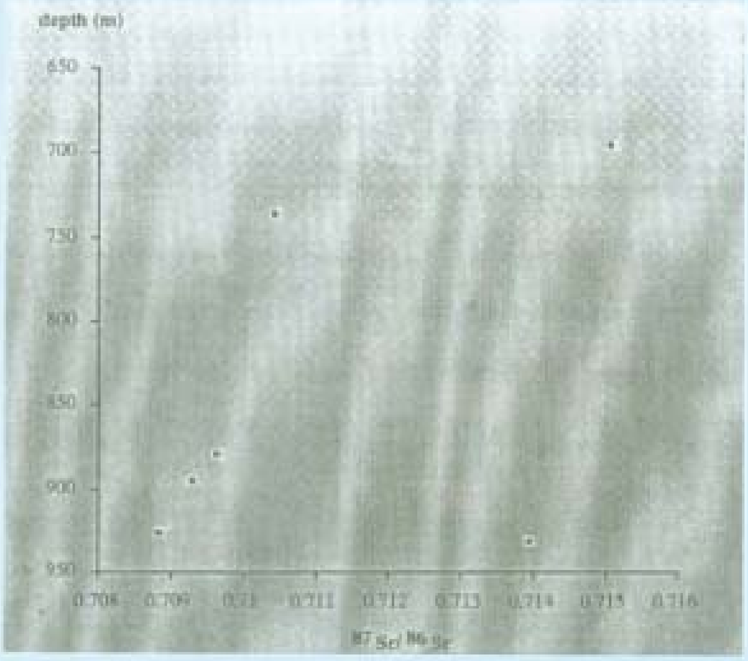


Figure 14
Sr isotope ratios of carbonaater versus depth

C. *Stable Isotopes*

The average ä ^{13}C values of the various Yorke Peninsula dolomites (-1.3 to 0.7 %ł; Table 3) are well within the range of normal marine carbonates. The narrow spread of ä ^{13}C values indicates that the precursor carbonate was affected by only minor alteration during diagenesis, (cf. Degens and Epstein 1964; Land et al. 1975). In contrast, these dolomites are very depleted in ^{18}O (mean ä ^{18}O= -14.7 to -6.8 %0; Table 3). Although ä ^{18}O of the Type 1 dolomite shows an average enrichment of 2.8 %0 over fibrous calcite (Table 3), but it is unlikely that this difference reflects any true equilibrium fractionation factor. The ä ^{18}O values of Early Cambrian fibrous calcites in South Australia have been strongly affected by multistage diagenesis and cannot be considered representative of their original composition (Whit taker et al. 1993). The oxygen composition of dolomite is dependent upon precursor carbonate, temperature and composition of the reactive flu-

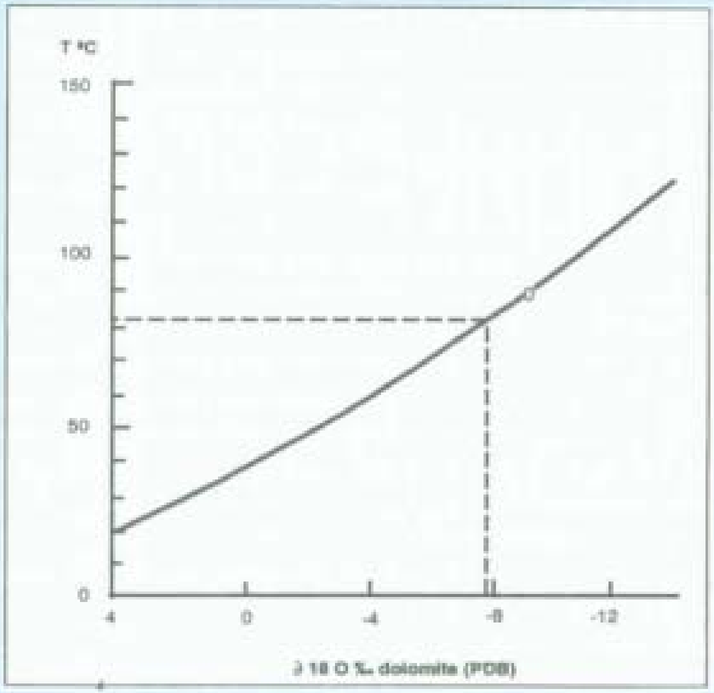


Figure 15
∂ 18 O dolomite versus temperature for Type 1 and 2 replacement dolomite of Yorke Peninsula (using Sheppard and Schwarcz's curve, 11970)

Table 1
Isotopic and trace element data of the carbonate sequence on York Penonsula, Stansbury Basin, South Australia

UA		(m)	‰PDB			p	p		m					m	o		1%				
Sample No	Well/se*	Depth	d 18 O	d 13 C	ca	Mg	Sr	Mn		Fe	Na	Sr/Mg	Ca	Mg		Sr		Fe	Mn	Na	Mg/Ca
prefix 760																					
fibrous calcite cement																					
760-1454	M1	443	-8.3	0.4																	
1464	M1	446.2	-9.4	-0.4	440382	2399	107	196		192	93	0.045	99.1	0.9		0.01		0.00	0.00	0.00	0.01
Y.11	ss	-	-11.4	-0.5																	
1388	M1	423.1	-		440386	1898	0	219		171	199	0.000	99.3	0.7		0.0		0.00	0.00	0.00	0.01
avr			**-9.7**	**-0.2**	**440384**	**2149**	**54**	**208**		**181**	**146**	**0.025**	**99.2**	**1**		**0**		**0**	**0**	**0**	**0.1**
blocky calcite cement																					
1454	M1	443	-16.7	-1.9																	
1547	M1	471.5	-15.9	-1.4																	
2416	M1	736.4	-16.2	-1.7	447754	1875	165	4404		4475	40	0.088	98.6	0.7		0.02		0.71	0.01	0.00	0.01
832	M1	832			403276	3670	147	5205		6170	38	0.040	97.8	1.3		0.01		0.94	0.01	0.00	0.01
2508	M1	895.5			394670	1930	274	1475		1500	188	0.413	89.9	0.8		0.03		0.28	0.00	0.00	0.01
392	SYC 101	392			444129	6413	239	779		730	0	0.037	97.6	2.3		0.02		0.11	0.00	0.00	0.02
avr			**-16.3**	**-1.7**	**434208**	**3469**	**206**	**2966**		**3219**	**67**	**0.099**	**96.2**	**1.3**		**0.02**		**0.51**	**0.01**	**0.00**	**0.01**
Type 1 dolomite																					
2279	M1	694.1			248154	131115	0	112		2220	336	0.000	53.3	46.4		0.00		0.34	0.00	0.00	0.01
2617	M1	797.7	-7	-1.1																	
2834	M1	866.5	-7.6	-2.2																	
2508	M1	895.5	-7.2	-2.7	201344	112428	196	906		13641	295	0.002	50.8	46.7		0.02		2.50	0.00	0.00	0.92
2942	M1	896.7	-6.6	-2.2																	
3042	M1	927.2	-6.4	-0.9																	
3055	M1	931.2			247086	147032	0	456		3819	128	0.000	50.2	49.2		0.0		0.56	0.00	0.00	0.98
3092	M1	939.4	-7.2	-2.4	248824	162344	44	1019		7348	216	0.000	47.5	51.5		0.0		1.01	0.00	0.00	1.08
224	CD-2	68.3	-7	0.4																	
213	CD-1	64.9	-6	0.4																	
392	SYC 101	392			222596	112657	77	516		2404	2207	0.001	54.3	45.3		0.01		0.42	0.00	0.01	0.83
22	A1	22			209523	121306	85	326		2111	146	0.001	50.6	49.0		0.01		0.37	0.00	0.00	0.97
avr			**-6.9**	**-1.3**	**228824**	**131140**	**67**	**556**		**5290**	**554**	**0.001**	**51.1**	**48**		**0**		**1**	**0**	**0**	**0.94**
type 2 peritidal related dolomite																					
3055	M1	931.2	-6.4	-2.4	248049	149017	0	698		5976	74	0.000	49.6	49.4		0.0		0.85	0.00	0.00	0.99
832	M1	832			241573	140496	146	252		1473	148	0.001	50.9	48.8		0.01		0.22	0.00	0.00	0.96
2416	M1	736.4	-6.7	0.1	237599	126499	150	1431		5120	54	0.001	52.8	46.4		0.02		0.82	0.00	0.00	0.88
3857	ST.1	1175.6	-6.1	-0.9																	
242	CD-2	73.8	-6.8	0.6																	
225	CD-2	68.6	-7.7	0.8																	
46	SYC 101	46.2	-6.7	-0.6																	
16	A1	16	-5	-0.2																	
22	A1	22			209653	118451	73	277		1317	116	0.001	51.3	48.5		0.01		0.23	0.00	0.00	0.95
136	A1	136	-7.6	-1.5																	
143	A1	143	-6.1	-1.7	233736	133403	136	306		1589	144	0.001	51.4	48.4		0.01		0.25	0.00	0.00	0.94
avr			**-6.6**	**-1.2**	**233522**	**133634**	**101**	**593**		**3068**	**107**	**0**	**51**	**48**		**0**		**0**	**0**	**0**	**1**
type 2 lagoonal related dolomite																					
1388	M1	423.1	-8.8	-0.8																	
1391	M1	424	-6.5	-0.6	264096	170034	0	1810		9244	38	0.000	47.9	50.9		0.00		1.20	0.00	0.00	1.06
2026	M1	617.5	-9.4	0	256723	152153	0	3274		9825	48	0.000	50.1	48.6		0.00		1.36	0.00	0.00	0.97
2126	M1	648	-8.3	-0.2																	
2283	M1	885.9	-10.9	-0.8	271143	154934	0	239		905	62	0.000	51.4	48.4		0.00		0.12	0.00	0.00	0.94
92	SYC 101	92.3	-9.2	-0.3																	
290	SYC 101	290	-11.9	0																	
HG7	ss	-	-8.3	-0.8																	
775	M1	775	-7	-0.6																	
avr			**-8.9**	**-0.1**	**263644**	**159040**	**0**	**1941**		**6658**	**49**	**0.000**	**49.8**	**49.3**		**0.00**		**0.89**	**0.00**	**0.00**	**0.99**
type 3 coarse to very coarse dolomite																					
366	SYC 10				241229	147543	0	931		4407	243	0.000	49.5	49.9		0.00		0.65	0.00	0.00	1.01
3017	SW1	1011	-14.7	-0.1																	
143	A1	143			236570	130562	113	2385		12501	62	0.001	51.2	46.8		0.01		1.95	0.00	0.00	0.91
2886	M1	880	-14.9	-0.9	258640	178485	25	568		1850	703	0.000	46.7	52.7		0.00		0.34	0.00	0.00	1.13
avr			**-14.7**	**-0.1**	**244480**	**152177**	**46**	**1298**		**6253**	**336**	**0.000**	**49.1**	**50**		**0**		**1**	**0.00**	**0.00**	**1.01**
dolomite cements																					
2279	M1	694.6	-6.8	0	216981	139828	0	791		5056	507	0.000	48.1	51.1		0.0		0.80	0.00	0.00	1.06
2508	M1	895.5			215646	122147	211	175		739	253	0.002	51.7	48.2		0.02		0.13	0.00	0.00	0.93
832	M1	836	-8.3	-0.2	240274	134206	143	1446		7878	106	0.001	51.4	47.4		0.01		1.21	0.00	0.00	0.92
3055	M1	931.2			245809	156417	0	6956		33484	46	0.000	46.6	48.9		0.0		4.55	0.01	0.01	1.05
avr			**-8.8**	**0**	**229747**	**138150**	**89**	**2342**		**11789**	**228**	**0.001**	**48.5**	**48**		**0**		**2**	**0.00**	**0.00**	**0.99**

Table 2
Sr isotopic ratio of Yorke Peninsula carbonates

(feet)	(m)	Sr 87 / 886	specimens
1547	471.5	0.71873	blocky calcite
2283	695.9	0.70847	calcite (sed)
2283	695.9	0.71506	type 2 dolomite LRD
2416	736.4	0.71043	type 2 dolomite LRD
2886	879.7	0.70963	type 3 dolomite
2938	895.5	0.70929	type 1 dolomite
3042	927.2	0.70885	type 1 dolomite
3055	931.2	0.71396	type 2 dolomite LRD
MF	ss	0.71561	blocky calcite
905.35	ss	0.70845	marine calcite

ids (Land, 1980; Morrow, 1982). Given that the average ä ^{18}O Type 1 and 2 replacement dolomite is -7.4 %o PDB, using the dolomite-water fractionation curve of Sheppard & Schwarz (1970), this value constraints the formation of the dolomite over 80° C (Figure 15) which is far above the assumed Cambrian seawater temperature (30° C) (Walker et al., 1989). Such low negative ä ^{18}O values and high temperature are irrelevant for early diagenetic and hypersaline origin of Type 1 and 2 replacement dolomite. In fact evaporation of sea water only stimulate the enrichment of oxygen isotopes. The possible explanation to the extreme negative ä ^{18}O values of the Yorke Peninsula dolomites is that geochemically the early form of limestones had suffered multi stages of diagenetic before transformed into dolomite. This conclusion is also supported by ä ^{18}O negative values of fibrous calcite and blocky calcite (Table 3).

Nevertheless, the Yorke Peninsula carbonates display good statistical separation of the petrographically determined dolomite types into three isotopic groupings (Figure 16). The first group comprises the Type 1 and peritidal related (PR) Type 2 dolomites; the second includes lagoonal related (LR) Type 2 dolomite and limpid dolomite cement; and the third is late stage Type 3 dolomite. These groups define an isotopic trend for dolomite paragenesis (Figure 13). The first-formed dolomite is slightly depleted in ^{13}C (ä ^{13}C = -1.3 %0) and moderately depleted in ^{18}O (ä ^{18}O = -6.9 %0). Subsequent dolomitization involved progressive enrichment in 13C and further depletion of ^{18}O, so that the last-formed dolomite has an isotopic signature characteristic of dilute water and elevated temperature (ä ^{13}C = + 0.7 %0; ä ^{18}O = -15.7%0).

D. *Trace Elements*

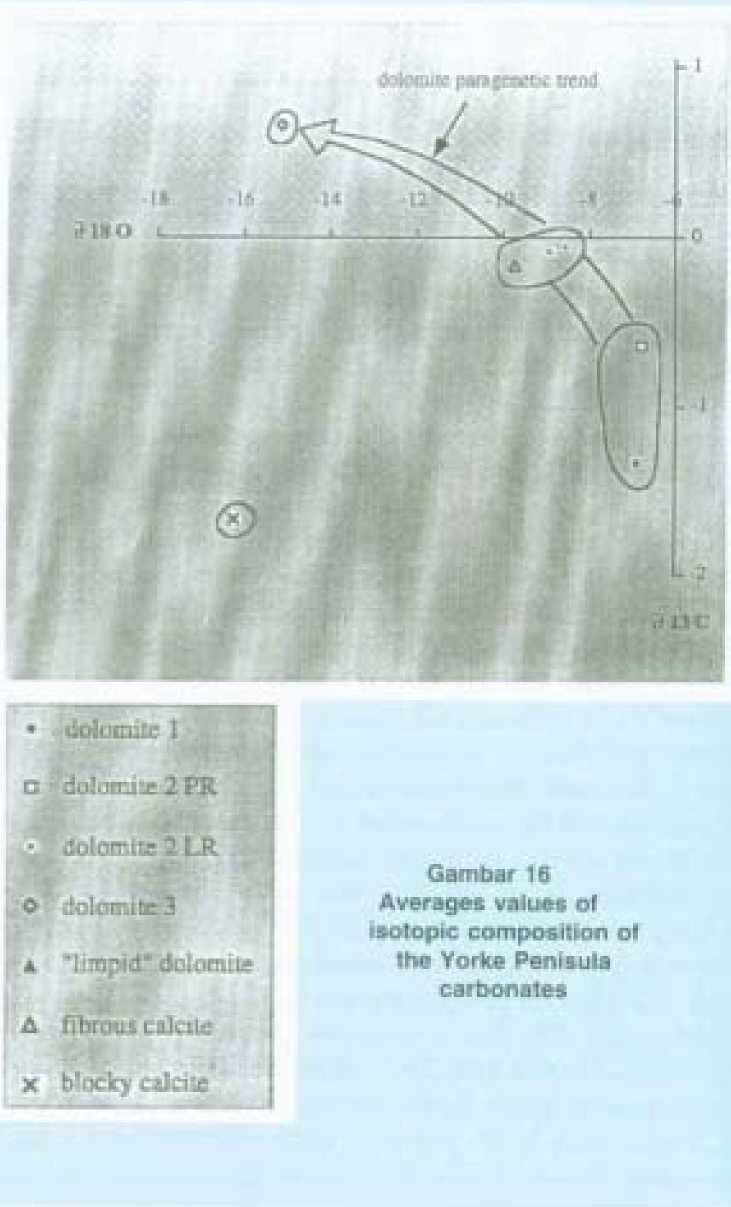
Strontium -The average strontium contents of Yorke Peninsula dolomite range from 0 to 92 ppm (Table 4), which are much lower than the typical values for modem marine dolomite (300 -600 ppm: Katz and Matthews 1977; Veizer 1983; Baker and Bums 1985). This depletion in strontium may reflect dolomitization of a calcite precursor by dilute fluids in a close system (Veizer et al. 1978). However this is unlikely in the case of massive dolomitization which requires relatively high water/rock ratios (Wallace 1990). Therefore the low strontium contents of the Yorke Peninsula dolomites are best explained by dolomitization in a dilute water diagenetic environment, i.e. the mixing zone. The relationship of decreasing *Sr* content with increasing crystal size as suggested by Dunham and Olson (1980) and M'Rabet (1981) is not evident in the Yorke Peninsula dolomites. Table 1 shows that the *Sr* content of the fine crystalline Type 1 dolomite (average 67 ppm) is lower than the medium to coarse crystalline PR Type 2 dolomites (average 92 ppm), whereas the average Sr content of the LR Type 2 dolomite (which has relatively finer crystal size than the PR Type 2 dolomite) is nil.

Sodium -The concentration of sodium in carbonate rocks usually reflects the salinity of fluids during diagenesis (Veizer et al. 1978) and is commonly used to distinguish dolomite types within a formation. Modem marine dolomites have Na contents around 1000 -3000 ppm (Land 1973; Land and Hoops 1973). The low average concentrations of sodium in the Yorke Peninsula dolomites (50 -555 ppm: Table 4), suggest that their environments of dolomitization were less saline than sea water. Dilute dolomitizing fluids are also suggested by the strontium and oxygen isotopicvalues.

Iron and manganese -These two elements are often used as indicators of a reducing diagenetic environment, because the concentrations of Fe and Mn are much higher in anoxic pore fluids than in sea water. Fe and Mn are preferentially taken into dolomite lattice displacing Ca. Therefore dolomites formed by oxidizing fluids usually have low iron and manganese contents. The average concentrations of iron and manganese of Yorke Peninsula dolomite are relatively high (Fe = 3400 -6650 ppm; Mn = 560 - 1950 ppm; Table 4). The greater concentrations of iron and manganese in LR Type 2 and Type 3 dolomites suggests that the final stages of dolomitization occurred in a somewhat more reducing diagenetic environment

E. *Geochemistry Summary*

1. $CaCO_3$ concentrations in the dolomites of Yorke Peninsula vary from 46 to 54 mol. %. Over 60 % of the analyzed samples fall into near stoichiometric catagory (49-51 mol. % $CaCO_3$) and mostly are of Type 2 replacement dolomite. This is inconsistent with the early diagenetic and hypersaline origin characteristics of Type 1 and 2 repacement dolomite. However $CaCO_3$ concentrations plot shows a declining trend toward later stages of dolomitization, which suggests progressive diagenetic change (Fuchtbauer 1972).
2. $^{87}Sr/^{86}Sr$ ratios from selected samples of Yorke Pe insula dolomites range from 0.7089 to 0.7140 (mos of Atdabanian stage). These values are higher th the values proposed by Whittaker etal. (1993) f the Early Cambrian seawater values (0.7082-0.709 This suggests that the dolomites were formed by modified seawater.
3. The average d ^{13}C values of the Yorke Peninsu dolomites (-1.3 to 0.7%0) are within the range normal marine carbonates. In contrast, the d ^{18}O va ues are very depleted and the average d ^{18}O valu of Type 1 and 2 replacement dolomite is -7.4 %



Gambar 16
Averages values of isotopic composition of the Yorke Penisula carbonates

VI.DISCUSSION AND DOLOMITIZATION MODEL

Petrographic evidence for Yorke Peninsula dolomites clearly suggest that dolomitization was an early diagenetic event (pre-stylolite formation). Regarding Type 1 and 2 replacement dolomites which comprise over 90 % of the total dolomites, its petrographic nature strongly suggests that they were originally formed in tidal flat settings with the involvement of hyper saline water at some stages of their diagenetic events.

Other evidence to support the early diagenetic dolomitization include: a massive occurrence of Yorke Penisula dolomite (more than 200 m thick over an area of 1800 square km). Such a massive dolomite body requires a large amount of Mg resources and an efficient transport mechanism. Land (1983) has calculated that to completely dolomitize 1 cubic meter of limestone with 6.3 mol. % MgCO$_3$ and 40% porosity requires: 807 pore volumes of sea water; 8070 pore volumes of 10 times dilute seawater (mixing zone) or 44 pore volumes of hypersaline brine that has percipitated gypsum. The volume of dolomite in Yorke Peninsula is about 360 cubic km (1800 km^2 x 200 m thick). Taking into account 30% estimated impurities and porosity , the estimated volume of Type 1 and 2 replacement dolomite (over 90 % of the total dolomites) would be over 227 cubic km. This amount of volume would have required about 227 x 807 pore volumes of sea water. Therefore such massive dolomitization is more likely to occur

Table 3
Average values (in %o PDB) of carbon and oxygen isotopes for Yorke Penisula carbonates

	$\partial^{18}O$	$\partial^{13}C$
Fibrous calcite	-9.7	-0.2
Blocky calcite	-16.3	-1.7
Type 1 dolomite	-6.9	-1.3
Typy 2 dolomite	-7.9	-0.4
Type 3 dolomite	-14.8	0.5
Dolomite cements	-8.8	0.0

Table 4
Average trace elements concentrations (ppm) in various Dolomites (modified from Mattes and Moutjoy 1980)

Dolomite	Na ppm	Sr ppm	Fe ppm	Mn Ppm
This Study	554	67	5290	556
Type 1	78	51	4865	1270
Type 2	336	46	6250	1300
Type 3	228	89	11790	2340
Limpid				
Recent marine Dolomite	2000	300-400	4-10000	600
Early Diagenetic Dolomite (Pleistocene)	380	1862	-	-
Early Diagenetic Dolomite (Tertiary)	140	150	250	100
Early Diagenetic Dolomite (Paleozoic)	375	120	200-5000	50
Shallow Burial Dolomite	250	98	400-8000	40-4100
Burial Dolomite	368	65	343	63

during early diagenesis, because" Mg rich" seawater can easily be pumped through the"still" semi consolidated sediments, which is essential for water-rock communication. However geochemistry analysis results of the Yorke Peninsula dolomite demonstrate otherwise. CaCO$_3$ concentrations are mostly of near stoichiometric, low negative d ^{18}O values, depleted Sr and Na concentrations and a relatively high Fe and Mn concentrations suggest that the dolomites were formed by dilute water in high temperature of a more reducing environment (i.e. deep burial environment). If heated compaction brines were the dominant diagenetic agent for regional dolomitization of Yorke Peninsula carbonates, then the brines must have been migrated to the shallow burial from a deeper part of the basin in the east (Katmantoo Trough). This seems unlikely scenario because: 1. There is only minor dolomite found in the laterally equivalent carbonate sections in the eastern part of the basin (Fleurieu Peninsula) (Abele and McGowran 1959; and Alexander and Gravestock 1989). 2. If the regional dolomitization was taking place after burial compaction, then it would be inconsistent with the prestylolite occurrence of the dolomites.

The present chemical composition of Yorke Peninsula dolomite strongly suggests that dolomite underwent longlasting meteoric modification. Dolomite with depleted d ^{18}O values, Sr and Na concentrations may be the result of a freshwater component in the fluid that produced dolomite. Mattes and Mountjoy (1980, Table 5) compiled the average concentrations of trace element from various dolomites of different ages and settings. It appears that the average concentrations of Yorke Pennisula dolomite is closely resembled the dolomites from shallow and deep burial settings, and being different to deep burial dolomite is that the Yorke Peninsula dolomite has relatively higher iron and manganese concentrations (Table 4). These and other evidence leed to the conclusion that the regional dolomitization in Yorke Peninsula took place relatively early in diagenetic history replacing the early forms of carbonates in shallow burial environments by surface derived solutions. Dolomite of Hanson Creek Formation (Ordovician - Silurian) from central Nevada (Dunham and Olson 1980), Devonian dolomite in Southeastern New Mexico (Zenger and Dunham, 1988) and Cambrian (Royer) dolomite in Slick Hills, SW Oklahoma, USA (Gao, 1990) have petrographic and geochemistry signatures relatively similar to the Early Cambrian dolomite of Yorke Peninsula, and they have also been interpreted to have formed in shallow burial environment by surface derived solutions.

VI. CONLUSSION

A most likely scenerio for the formation of Yorke Peninsula dolomite is that dolomitization was an ongoing process. It commenced penecontemporaneously during or just after sedimentation when finely crystalline carbonates were preferentially dolomitized, probably in a hypersaline supratidal environment under a seasonally humid climatic condition (Type I replacement dolomite). A temporary change in climatic regime to arid conditions increased seawater salinity and triggered the formation of evaporite minerals and regional dolomitization (Type 2 replacement dolomite), probably in a near surface environment. The final stages of dolomitization (Type 3 replacement dolomite) was marked by mechanical compaction, dissolution and precipitation (dolomite cement) then followed by neomorphism or recrystallization, probably in shallow burial environment by surface derived solutions, resulting in wholesale textural and geochemistry modifications. Dolomitization then ceased at depths where stylolites began to form. Neomorphism or recrystallization of the early dolomite phase involving significant textural and geochemical modification have been suggested by many studies (eg. Land 1980; Wallace 1990; Gao 1990).

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