SEDIMENT COMPACTION AND ITS INFLUENCE ON BASEMENT SUBSIDENCE

by

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ABSTRACT

Compaction of claystones-shales and limestones penetrated by well TT-1 and TT-2 in the western margin of the South Makassar Basin (SMB) has been evaluated. Each type of lithology exhibits specific porosity-depth relationship which is characterized by an exponential curve. In the study area the relationships are : $\phi = 69.e^{-0.00039z}$ for claystones-shales and $\phi = 59.e^{-0.00073z}$ for limestones, where ϕ is the porosity (%) and z is the depth below the top of the sediments.

Those relationships facilitate decompaction of the sediments and hence restoration of their original thicknesses. This study indicates that the thicknesses of the sediments have been significantly reduced by compaction. It is evident that basement subsidence during Miocene times should be increased by 100 to 308 m if corrected for compaction.

Understanding the (basement) subsidence is an important aspect of basin analysis as it facilitates the calculation of the amount of extension from which the formation of sedimentary basin can be modelled.

I. INTRODUCTION

One of the diagenetic processes that affected sedimentary rocks during their deposition is compaction, which can be defined as the reduction of pore volume in the sediments due to loading (Perrier & Quiblier, 1974). Indeed, it is resulted by physical processes associated with increasing pressure and chemical cementation of the matrix of the sediments. Several factors which affecting compaction during diagenetic processes are the type of sedimentary rocks, age, rates of sedimentation and burial, abnormal pressure, mineral transformation and cementation.

Each type of sedimentary rocks is deposited with an initial porosity and will exhibit different response to compaction. For example, clays and coals will show the greatest compaction value as they have the highest initial porosity. On the other hand, sandstones, chalks and clays display similar compaction trend with increasing depth, however, compaction for each of them is somewhat different due to physical and chemical differences of the matrix of the rocks. Recent study by Schmoker and Halley (1982) also reveals that like other sedimentary rocks, decrease of carbonate porosity with depth can be characterized by an exponential curve.

Since it is closely related with porosity decrease, compaction is an important parameter in estimating the maximum burial depth of stratigraphic units. Hence, it can be used to calculate the thickness of stratigraphic sections which has been removed by erosion (Magara, 1976 a). During the process of burial the load of the overburden will cause an expulsion of the pore water. This in turn would cause hydrocarbons to migrate from source rocks to reservoirs (Magara, 1968; Magara, 1976 b). In the analysis of basin formation by stretching mechanism and in geohistory analysis, the effect of compaction is also one important factor that has to be accounted for (McKenzie, 1978; Situmorang, 1982; van Hinte, 1978; Widiastuti et.al., 1985).

In this paper, one of the effect of compaction i.e. porosity decrease due to vertical pressure exerted by the load of the overburden is discussed. Its influence in the analysis of basement subsidence is also presented with an example from exploration wells situated in the western margin of the South Makassar Basin.

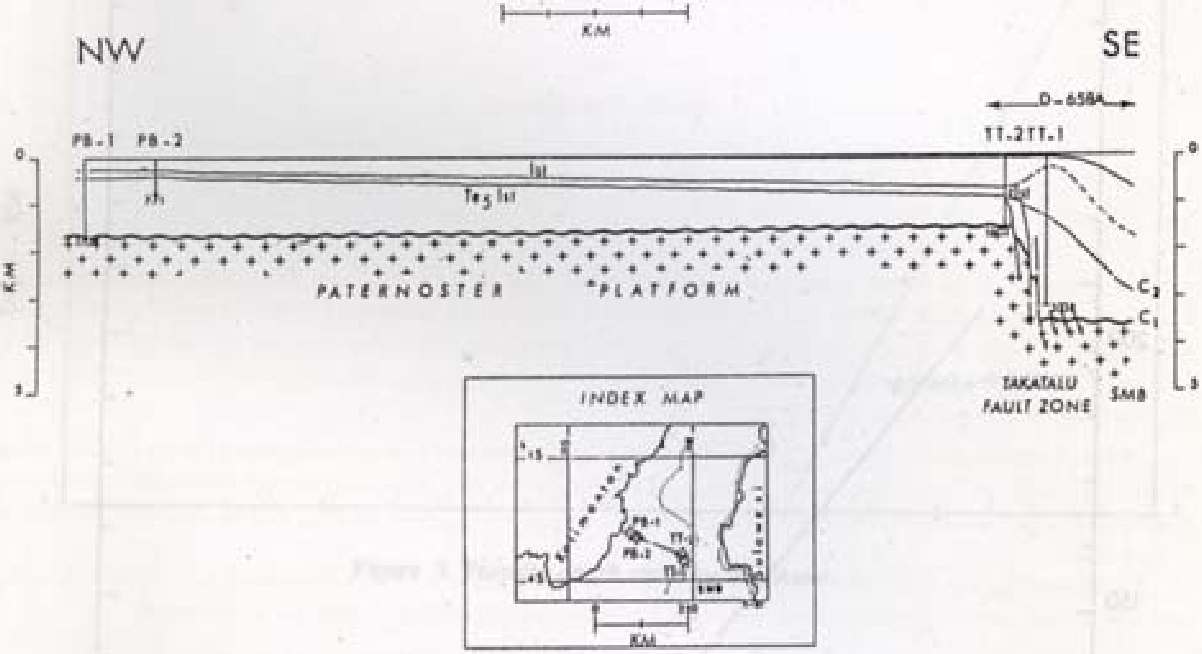

Figure 1 Simplified NW–SE cross section, PB.1 - PB.2 - TT.1 - TT.2, offshore Southeast Kalimantan.

II. POROSITY-DEPTH RELATIONSHIP

Much has been written about compaction of the shaly strata (e.g. clays, shales), therefore, characteristic relationship between their porosity and their depth of burial has been well documented (Athy, 1930; Hedberg, 1936). The accounts of nonshaly layers (e.g. sandstones and limestones) are very rare, despite their importance as petroleum reservoir rocks. This is probably due to the fact that other changes such as mineralogical changes can occur during compaction.

The relationship between the porosity and burial depth for sandstones has been proposed by Hardenbol et al. (1981), who also assume that reef limestones and sands display similar compaction trend under load. They further assume that grain carbonates compact like sands containing 30% shales, whereas micrites like shales containing 35% sands.

However, it is generally accepted that the porosity of the sediments exponentially decreases with depth in a relationship :

$$\phi = \phi_s e^{-cz} \qquad \text{......................... (1)}$$

where, ϕ is the porosity value at depth Z, ϕ_s is the surface porosity value ($z = 0$), C is a constant of dimension (length^{-1}) and Z is the depth below the top of the sediments; ϕ_s and C are determined empirically.

Compaction is manifested by reduction of the thickness of the sediments at the time of deposition to its present thickness. Thus, the present thickness will be somewhat less than the initial thickness. In the analysis of subsidence, it is necessary to restore the original thickness of the sediments. To do this we have first to establish the porosity-depth relationship for each type of lithology. Once the porosity-depth curve has been set up, decompaction is carried out simply by removal of the younger sedi-

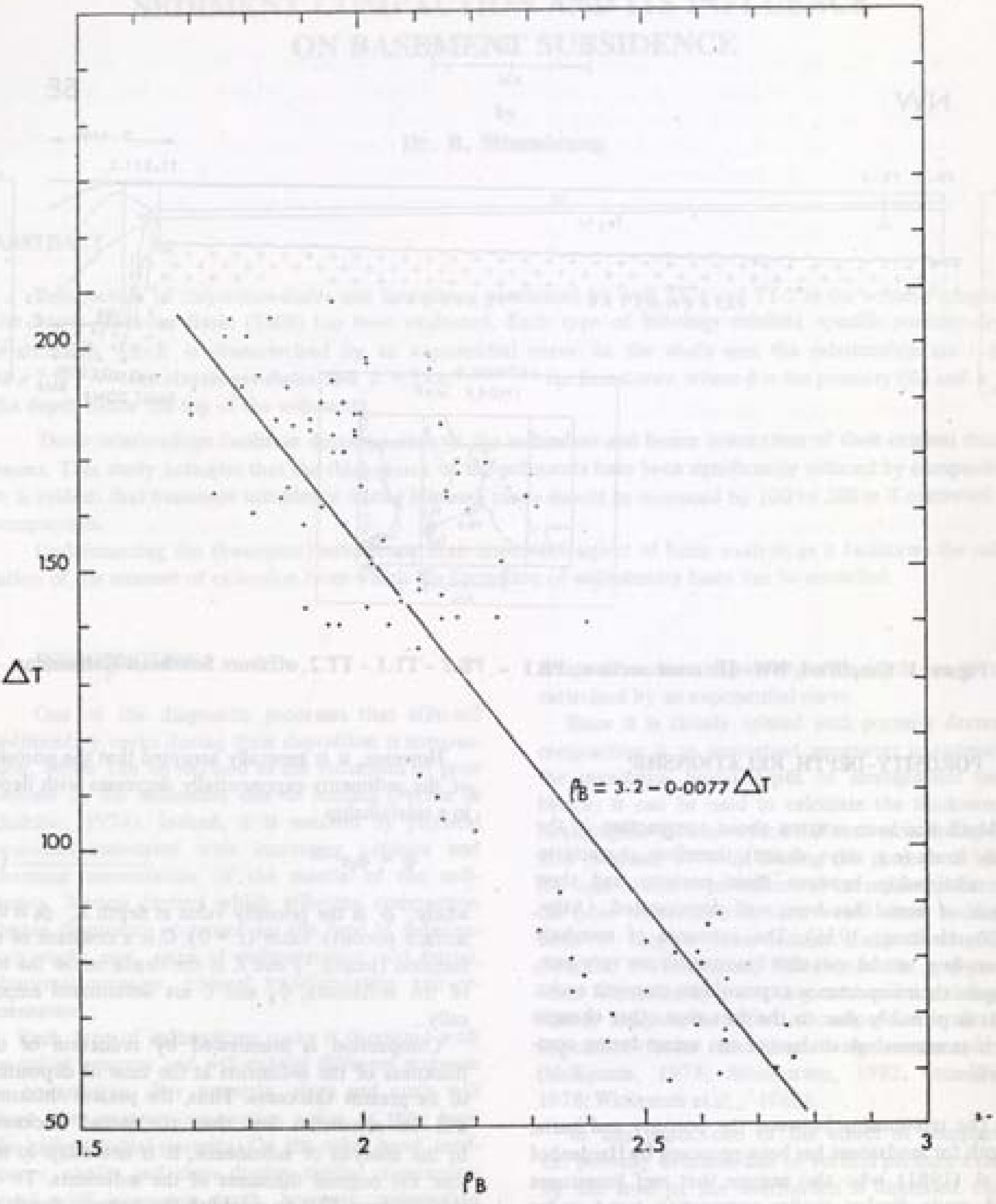

Figure 2 Plot of bulk density against transit time for claystone of well TT.1 and TT.2.

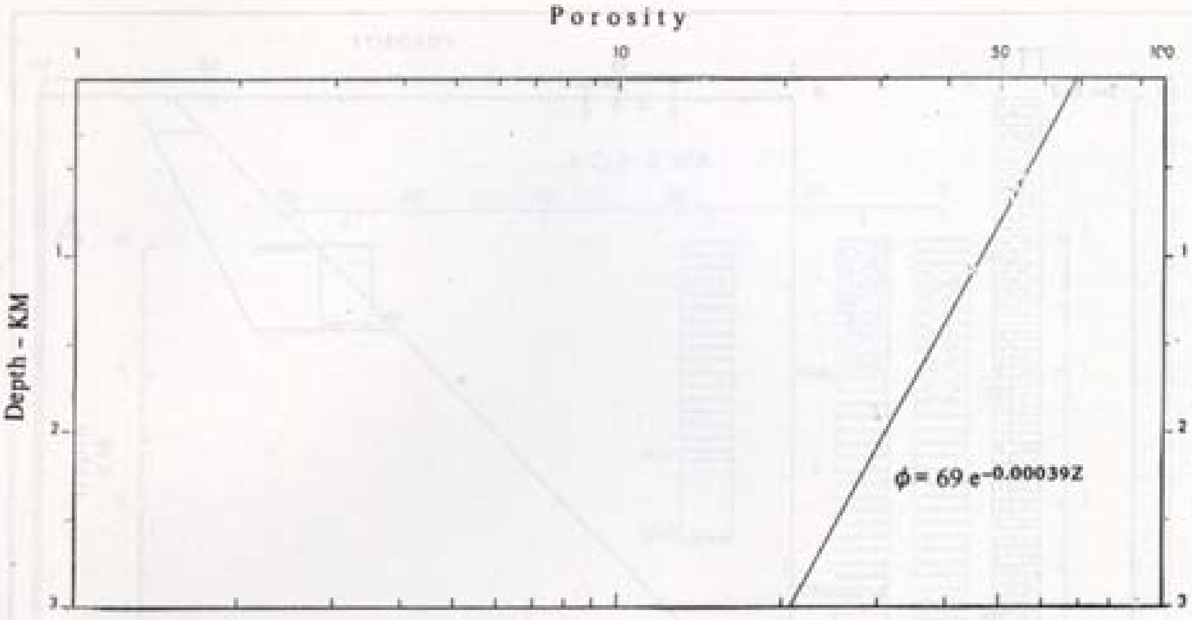

Figure 3 Porosity-depth curve for claystone.

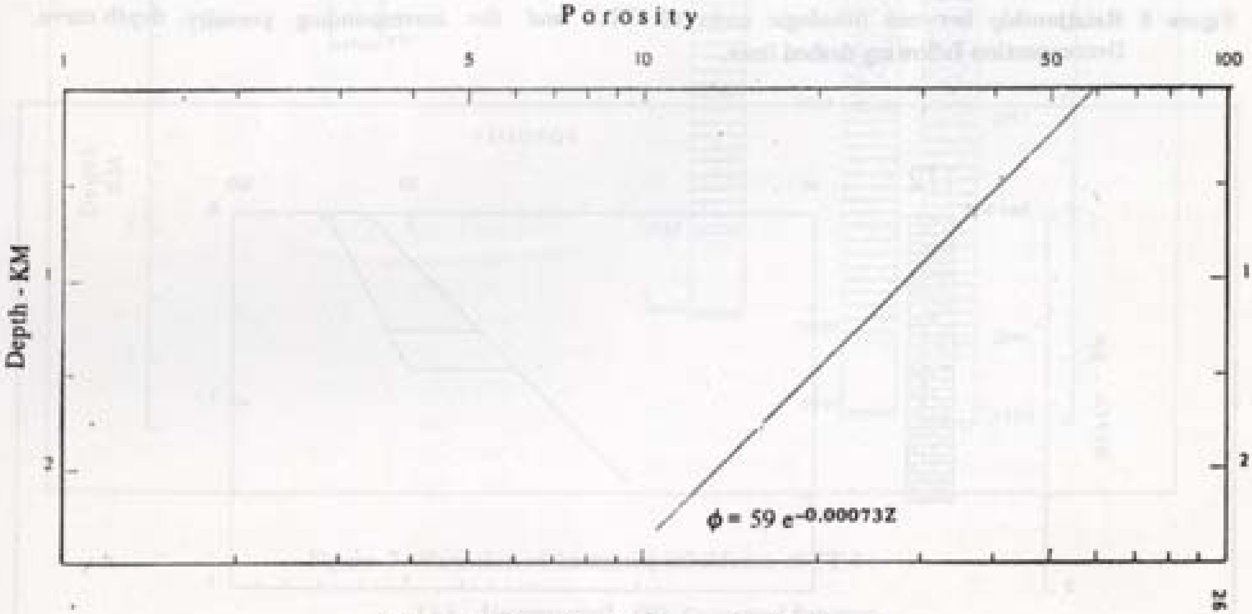

Figure 4 Porosity-depth curve for limestone.

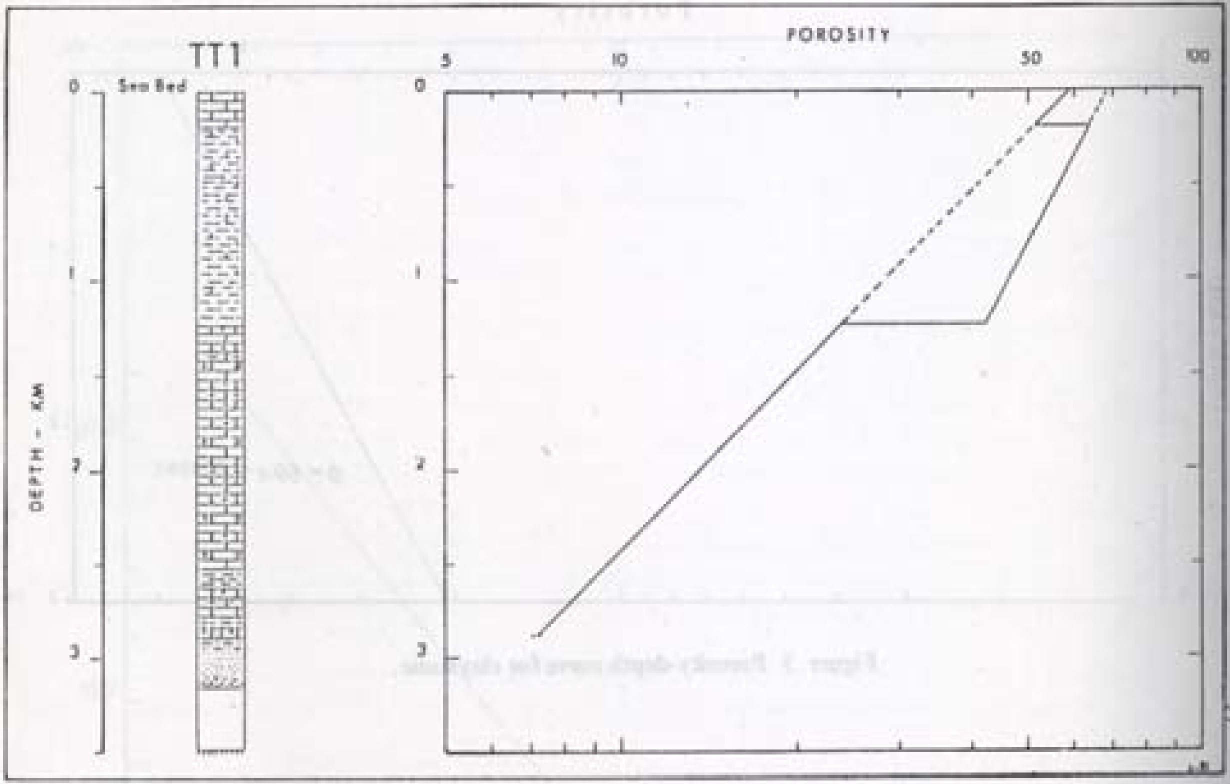

Figure 5 Relationship between lithologic units of TT.1 and the corresponding porosity- depth curve. Decompaction following dashed lines.

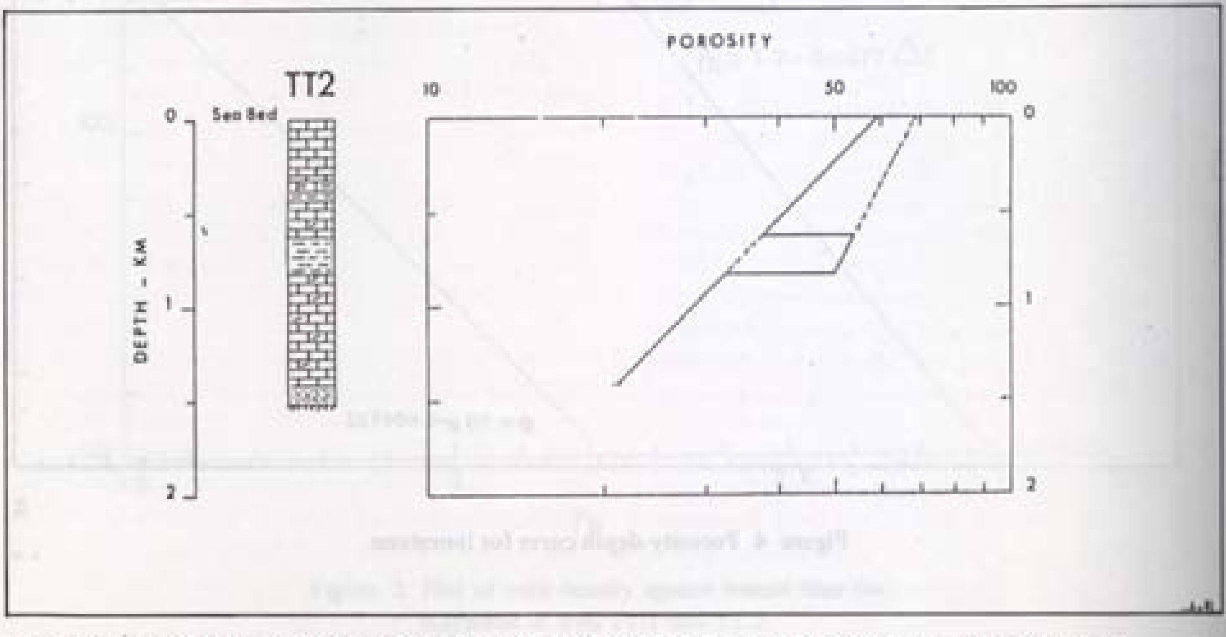

Figure 6 Relationship between lithologic units of TT.2 and the corresponding porosity-depth curve. Decompaction following dashed lines.

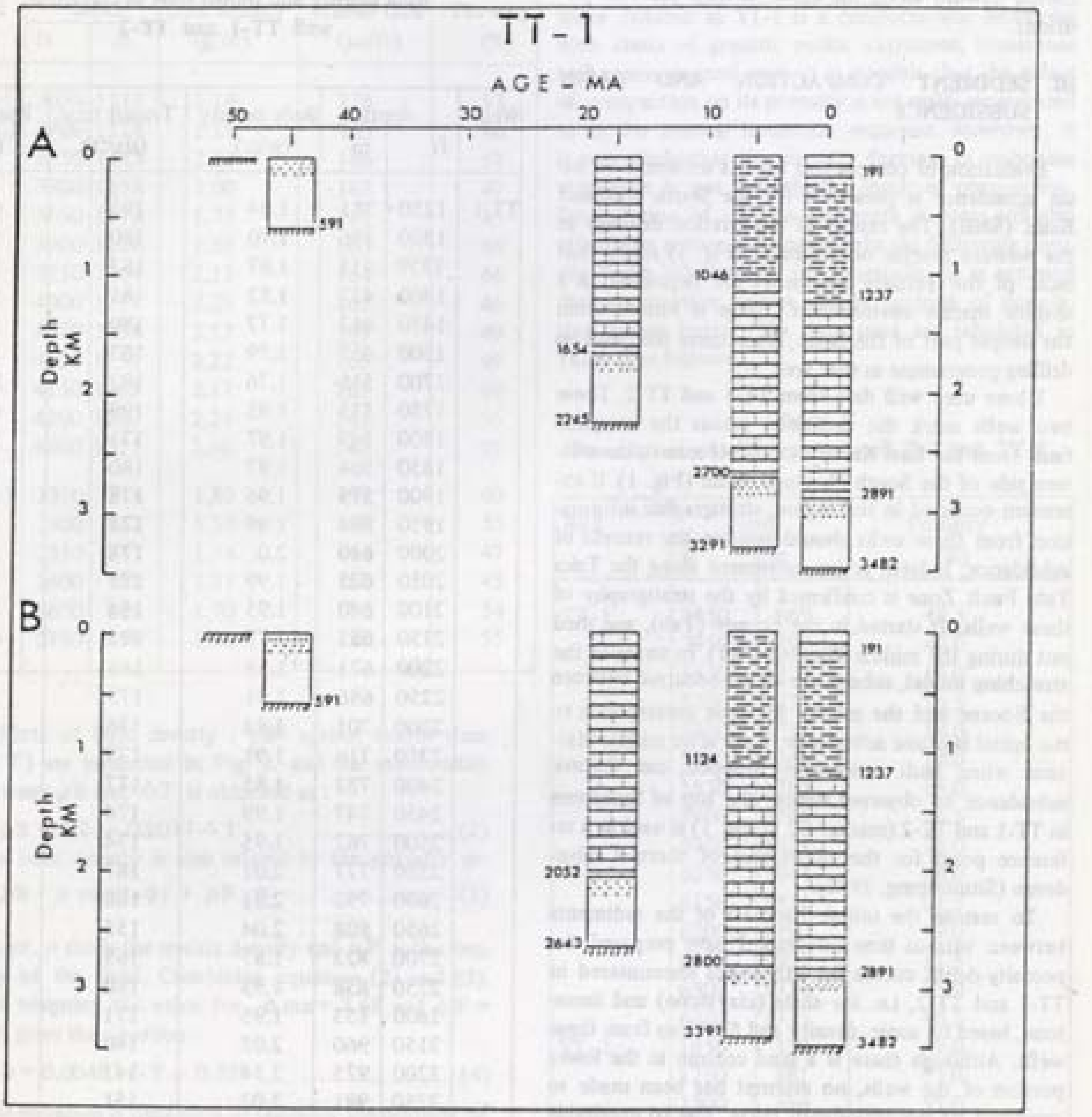

Figure 7 Variation of basement subsidence at TT.1 :

(A) Uncorrected, (B) Corrected for compaction. The stratigraphic section has been simplified.

ments, so that the underlying sediments can be removed upward along the curve to their previous positions.

III. SEDIMENT COMPACTION AND BASIN SUBSIDENCE

Evaluation of compaction and its influence on basin subsidence is presented for the South Makassar Basin (SMB). The results of exploration drillings in the western margin of the basin (Fig. 1) reveal that most of the Tertiary sediments are deposited in a shallow marine environment. Little is known from the deeper part of the basin, since there has been no drilling programme in that area.

I have used well data from TT-1 and TT-2. These two wells mark the transition across the marginal fault from the East Kalimantan Shelf area to the western side of the South Makassar Basin (Fig. 1). If extension occurred in this region, stratigraphic information from these wells should contain the records of subsidence. Indeed, active movement along the Taka Talu Fault Zone is confirmed by the stratigraphy of these wells. It started in the Eocene (Tab), and died out during the middle Miocene (Tf1). In terms of the stretching model, subsidence which occurred between the Eocene and the middle Miocene corresponds to the initial isostatic subsidence. Only after middle Miocene when fault movements stopped, can thermal subsidence be observed.Hence, the top of limestone in TT-1 and TT-2 (marker C2 in Fig. 1) is used as a reference point for the calculation of thermal subsidence (Situmorang, 1982).

To restore the initial thickness of the sediments between various time intervals, I have prepared the porosity-depth curves for lithologies encountered in TT-1 and TT-2, i.e. for shale (claystone) and limestone, based on sonic, density and SNP logs from these wells. Although there is a sand column in the lower portion of the wells, no attempt has been made to construct its porosity-depth curve, due to unreliable information from the logs.

The porosity values from claystone intervals of TT-2 and TT-1 were used to establish porosity-depth relationships for claystone. To obtain a better estimate of porosity, it is necessary first to establish the relationship between the bulk density and the sonic transit time. The data used is tabulated in Table I as follows :

Table I
Bulk density and transit time of claystone, well TT-1 and TT-2

Well	depth		Bulk density	Transit time	Porosity
	ft	m	(g/cc)	(μs/ft)	(%)
TT-1	1250	381	1.84	195	62
	1300	396	1.70	180	55
	1350	411	1.87	183	56
	1400	427	1.82	185	57
	1450	442	1.77	180	55
	1500	457	1.79	183	56
	1700	518	1.76	192	81
	1750	533	1.95	198	63
	1800	549	1.97	171	50
	1850	564	1.97	180	55
	1900	579	1.96	178	54
	1950	594	1.99	178	54
	2000	610	2.0	178	54
	2050	625	1.99	175	52
	2100	640	1.95	184	57
	2150	655	1.77	195	62
	2200	671	1.58	188	59
	2250	686	1.91	175	52
	2300	701	1.88	176	53
	2350	716	1.91	177	53
	2400	732	1.85	177	53
	2450	747	1.99	174	52
	2500	762	1.95	174	52
	2550	777	2.01	187	58
	2600	792	2.01	188	58
	2650	808	2.04	155	43
	2700	823	1.87	165	47
	2750	838	1.93	180	55
	2800	853	1.95	171	50
	3150	960	2.05	140	35
	3200	975	2.14	141	36
	3250	991	2.02	151	41
	3300	1006	2.07	144	37
	3350	1021	2.10	136	33
	3450	1052	1.90	143	37
	3500	1067	1.90	158	44
	3550	1082	1.93	161	45
	3600	1097	2.25	151	41

Well	depth		Bulk density	Transit time	Porosity
	ft	m	(g/cc)	(μs/ft)	(%)
TT-1 (cont.)	3650	1113	2.14	176	53
	3700	1128	2.15	163	46
	3750	1143	2.12	186	57
	3800	1158	2.00	165	47
	3850	1173	1.73	161	45
	3900	1189	1.86	163	46
	3950	1204	2.15	164	46
	4000	1219	2.29	163	46
	4050	1234	2.17	169	49
	4100	1250	2.22	169	49
	4150	1265	2.17	167	48
	4200	1280	2.24	141	36
	4300	1311	2.40	140	35
TT-2	2350	716	1.80	192	60
	2500	762	1.50	180	55
	2550	777	1.74	164	47
	2600	792	1.81	160	45
	2650	808	1.70	178	54
	2750	838	1.56	180	55

Plots of bulk density (ρB) against transit time (ΔT) are presented in Fig. 2, and the relationship between ρB and ΔT is obtained as :

$$\rho B = 3.2. - 0.0077\,\Delta T \qquad \text{.......................(2)}$$

The bulk density is also related to the porosity as:

$$\rho B = \rho\,\text{ma}\,(1-\phi) + \rho F\,.\,\phi \qquad \text{.......................(3)}$$

where, ρ ma is the matrix density and ρ F is the density of the fluid. Combining equation (2) and (3), and assigning the value for ρ ma = 2.68 and ρ F = 1.1, gives the equation :

$$\phi = 0.00487\,\Delta T - 0.329 \qquad \text{.......................(4)}$$

This equation is then used to calculate the porosity of claystone-shale as presented in the last column of Table I. The porosity-depth curve for claystone-shale can then be constructed, and shown in Fig. 3, with equation :

$$\phi = 69\,e^{-0.00039z} \qquad \text{.......................(5)}$$

Similar procedures have been carried out to construct the porosity-depth curve for limestone. The porosity values are taken from the limestone sections in both well. However, as the lower limestone column in TT-1 is a conglomeratic limestone with clasts of granitic rocks, extrusives, limestones and coarse grained sand, it is possible that the effect of compaction on its porosity is not really represented as in the normal limestone sequence. Moreover, it is very likely that the porosity decrease in carbonate sequences is not entirely the result of compaction. Precipitation of calcium carbonate in pores will also effectively reduce the porosity. In the following porosity-depth relationship for limestone, it is assumed that compaction occurs simply because of dewatering during burial. The data used are tabulated in Table II as follows :

Table II

Porosity values of limestone, well T-1 and TT-2

Well	depth		Porosity
	ft	m	(%)
TT-1	2850	869	48.5
	2950	899	42.0
	5650	1722	16.0
	5700	1737	15.5
	5750	1752	14.0
	5800	1768	18.0
	5850	1783	16.0
	5900	1798	16.5
	5950	1814	16.0
	6050	1844	18.0
	6150	1874	21.5
	6200	1890	19.0
	6250	1905	11.5
	6300	1920	11.0
	6350	1935	16.5
TT-2	1050	320	49.0
	1250	381	53.0
	1300	396	55.0
	1350	411	45.0
	1400	427	51.0
	1450	442	39.0
	1500	457	50.0
	1550	472	41.0
	1600	488	39.0
	1650	503	46.0
	1700	518	44.0

Well	depth		Porosity
	ft	m	(%)
TT-2 (cont.)	1750	533	36.0
	1850	564	31.0
	1900	579	33.0
	1950	594	36.0
	2000	610	36.0
	2150	655	30.0
	2200	671	37.0
	2250	686	48.0
	3000	917	17.0
	3050	930	31.0
	3100	945	22.0
	3150	960	19.0
	3200	975	21.0
	3300	1006	26.0
	3350	1021	29.0

The porosity-depth curve obtained for limestone is presented in Fig. 4, with equation :

$$\phi = 59\, e^{-0.00073z} \qquad (6)$$

Following Sclater and Christie (1980), decompaction of each lithologic unit can then be accomplished using the appropriate porosity-depth curve as can be seen in Figs.5 and 6, except for basal sands. As already mentioned, there are no reliable log data which can be used to produce porosity-depth curves for sand/sandstone. Although the Eocene sand column in both wells is not decompacted, it will not alter the subsidence history significantly as it is only a part of the initial fault-controlled subsidence. The thermal subsidence calculation is carried out from the Lower Miocene carbonates as presented by Situmorang (1982).

Variation in basement subsidence and sediment thickness through time in TT-1 and TT-2 is presented in Figs. 7 and 8, before and after being corrected for the effect of compaction. There are other necessary corrections that need to be applied to the subsidence values in Figs. 7 (b) and 8 (b) i.e. sediment loading, paleo-water depth and the sea level changes. However, it will not be discussed here as it is beyond the scope of this paper.

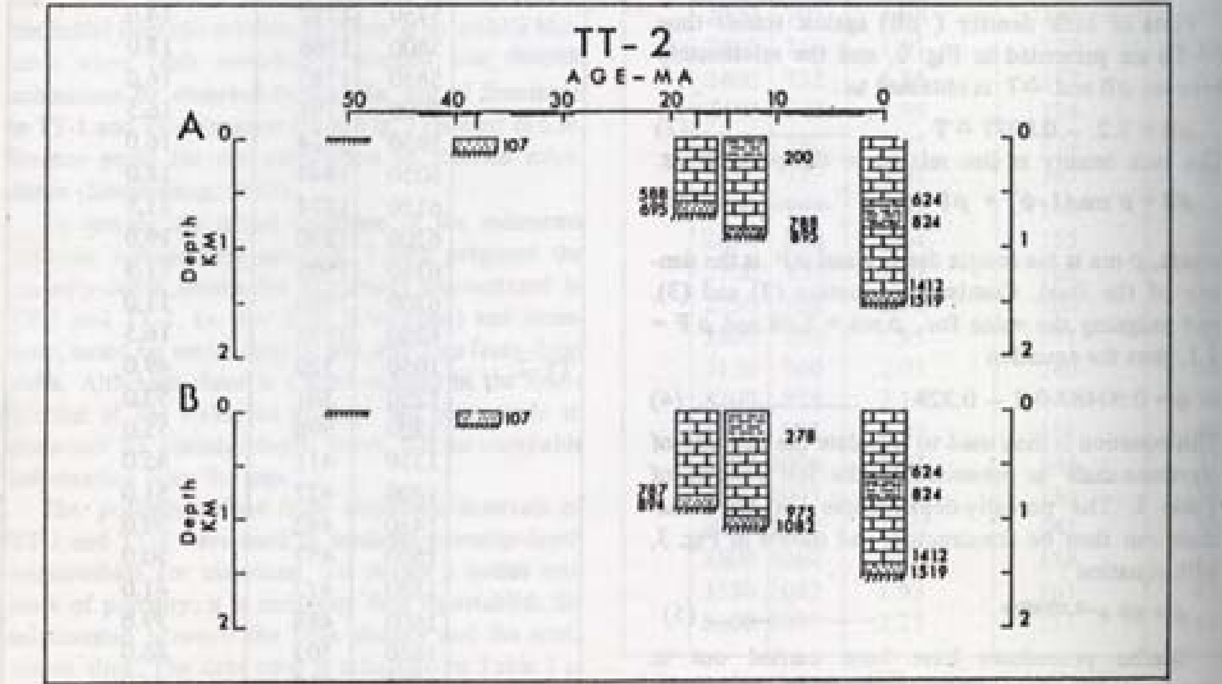

Figure 8 Variation of basement subsidence at TT.2 : (A) Uncorrected, (B) Corrected for compaction. The stratigraphic section has been simplified.

IV. CONCLUSIONS

From the foregoing discussions it can be concluded that compaction is undoubtedly an important parameter in basin evaluation as it is closely related with porosity decrease of the sediment. This relationship enable us for instance, to estimate the maximum burial depth of stratigraphic units, to calculate the eroded thickness of stratigraphic sections, and to estimate the basement subsidence. The latter which is the subject of this paper is shown for well TT-1 and TT-2 in the South Makassar Basin.

It appears that in well TT-1 compaction alone can reduce the thickness of the sediments as much as up to 100 m in the Upper Miocene and 398 m in the Lower Miocene (Fig. 7). Observation in well TT-2 shows that decrease in sediment thickness due to compaction is 187 m in the Middle Miocene and 199 m in the Lower Miocene (Fig. 8).

This evaluation has been carried out without decompaction of basal sands in both well. In terms of stretching mechanism it will not change basement subsidence-hence subsidence history-significantly as it is part of the initial fault-controlled subsidence.

It is suggested that in order to have a better understanding on the effect of compaction in basement subsidence, similar study as presented in this paper should be performed for each type of lithologies in each Indonesian Tertiary sedimentary basin.

REFERENCES

Athy, L.F., 1930. Density, porosity and compaction of sedimentary rocks, *Amer. Assoc. Petrol. Geol. Bull*, 14, 1 – 24.

Hardenbol, J., Vail, P.R. and Ferrer, J., 1981. Interpreting paleoenvironments, subsidence history and sea level changes of passive margins from seismic and biostratigraphy, *Oceanologica Acta, Supplement on Vol.* 4, 33–44.

Hedberg, H.D., 1936. Gravitational compaction of clays and shales, *Amer. J. Sci.*, 31, 241–287.

Magara, K., 1968. Compaction and migration of fluids in Miocene mudstone, Nagaoka plain, Japan, *Amer. Assoc. Petrol. Geol. Bull.*, 52 (12), 2466–2501.

Magara, K., 1976 a. Thickness of removed sedimentary rocks, paleopore pressure, and paleotempe rature, southwestern part of Western Canada basin, *Amer. Assoc. Petrol. Geol. Bull.*, 60 (4) 554–565.

Magara, K., 1976 b. Water expulsion from clastic sediments during compaction-directions and volumes, *Amer. Assoc. Petrol. Geol. Bull.*, 60 (4), 543–553.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, 40, 25–32.

Perrier, R. and Quiblier, J., 1974. Thickness changes in sedimentary layers during compaction history; methods for quantitative evaluation, *Amer. Assoc. Petrol. Geol. Bull.*, 58 (3), 507–520.

Schmoker, J.W. and Halley, R.B., 1982. Carbonate porosity versus depth : A predictable relation for South Florida, *Amer. Assoc. Petrol. Geol. Bull.*, 66 (12), 2561–2570.

Sclater, J.G. and Christie, P.A.F., 1980. Continental stretching -an explanation of the post-early Cretaceous subsidence of the Central Graben of the North Sea, *J. Geophys. Res.*, 85, 3711–3739.

Situmorang, B., 1982. The formation of the Makassar basin as determined from subsidence curves, *Proc. Indones. Petrol. Assoc., 11th Ann. Conv.*, 1, 83–107.

Van Hinte, J.E., 1978. Geohistory analysis – Application of micropaleontology in exploration geology, *Amer. Assoc. Petrol. Geol. Bull.*, 62 (2), 201–222.

Widiastuti, R., Baharuddin and Situmorang, B., 1985. Analisis geohistori beberapa sumur eksplorasi di cekungan Sumatera Utara : Suatu nota pendahuluan, *Lembaran Publikasi Lemigas*, 2, 19–31.