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Subsidence nature of a strike-slip related basin: an example learned from the Sarawak Basin

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Abstract: The subsidence nature of a strike-slip related basin is the least understood as compared to the rift basin and the basin formed by the lithospheric flexure which is also known as a foreland basin. In brief, the rift basin of McKenzie model has a subsidence profile which is characterised by fast initial subsidence and followed by a slower thermal subsidence. In contrast, the foreland basin is characterised by a slower initial subsidence and followed by rapid subsidence to the end of basin formation.

The subsidence profile of Sarawak Basin was selected for this discussion as the seismic interpretations concluded that the basin was formed by strike-slip tectonism, contradicting to a foreland basin in terms of its tectonic origin; i.e. it was created by lithospheric flexure by the subduction of South China Sea oceanic crust beneath the NW Sarawak continental crust.

The study has been conducted using commercial software, Basin Modelling System Version 4 by Platte River Associates. The result of the study shows that the burial history curves for the wells representative of the Sarawak Basin show many of the profiles with early rapid subsidence followed by a later phase where basement subsidence is slower, indicative of rifted style of tectonic origin. These are followed either by a series of later compressional basin inversion or continued with thermal subsidence similar to a rift basin profile.

The evaluation of stretching factors and heat-flow shows a direct relationship through out the basin which are consistent with the origin of a basin dominated by strike-slip tectonics. The finding of this study helps in understanding the nature of subsidence in the strike-slip related basin which concurrently challenges earlier models for a subduction-related origin for the Sarawak Basin.

INTRODUCTION

The current interpretation of the tectonic setting of the Sarawak Basin is that the basin was developed as a result of subduction of South China Sea oceanic crust beneath the NW Sarawak continental crust (James, 1984). If that interpretation is correct, the Sarawak Basin therefore would conform most closely to a foreland basin in terms of its tectonic origin (Allen and Allen, 1990); i.e. it was created by lithospheric flexure.

The most recent regional seismic studies on the Sarawak Basin (Ismail, 1996), instead, interpreted the basin was formed related to the strike-slip movement along five major lineaments. If this interpretation is correct, instead of foreland basin or trench- associated basin (Kingston *et al.*, 1983), the Sarawak Basin can be classified as a strike-slip related basin.

Besides the information from seismic, the basin subsidence modelling is among the other alternative independent techniques to determine the nature and origin of a sedimentary basin. For this reason, the subsidence history of nine wells from the Sarawak Basin has been used to investigate the tectonic origin of the basin using commercial software, Basin Modelling System Version 4 by Platte River Associates, with the aim to verify the interpretations derived from the seismic studies.

BACKGROUND

Theoretically, the subsidence history experienced by a basin formed by lithospheric stretching or extensional basin and a basin formed by flexure are distinguishable. The subsidence history for basins due to flexure (foreland basin) is normally characterised by increasing subsidence rate with time (Fig. 1). Extensional basins can be generally divided into two types. Those which conform to McKenzie's (1978) model and those which do not. A basin generated within strike-slip zones may be expected to show rapid but short-lived subsidence, alternating with compression and uplift (Kneller, 1991).

McKenzie (1978) proposed a two-phase model for development and evolution of a rift-type sedimentary basin.

The first phase consists of rapid stretching of continental lithosphere, which thins the lithosphere allowing passive upwelling of hot asthenosphere.

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This stage is associated with block faulting and subsidence.

The second phase is characterised by thermally controlled subsidence due to lithospheric cooling and contraction, as the asthenosphere or lithosphere boundary returns to its original position. The amount of stretching (ß) can be estimated from changes in the thickness of continental crust, by analysis of extension of pre-rift markers, by analysis of fault heave and by examination and interpretation of the subsidence history (burial history curves).

OBJECTIVES

The objectives of the study are:

1. To determine the tectonic subsidence history of the Sarawak Basin using the well data and to compare the profiles with those for classical foreland and rift basins.
2. To determine whether the McKenzie rift basin model can be used as a model for the rifting and subsidence history of the Sarawak Basin.
3. To compare the geothermic data, including geothermal gradients and present day heat flow estimated from the bore holes by the other workers, with values from modelling estimates.
4. To use the basin subsidence study as independent techniques for basin classification.

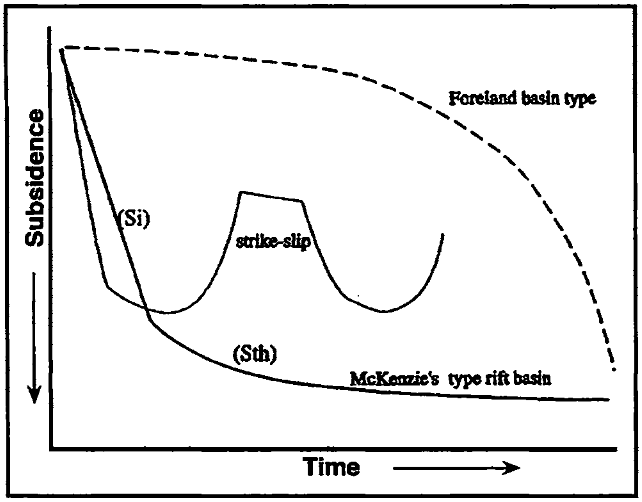

Figure 1. Different types of subsidence between foreland, rifts basin and McKenzie's type of rift basin, modified after Kneller, 1991.

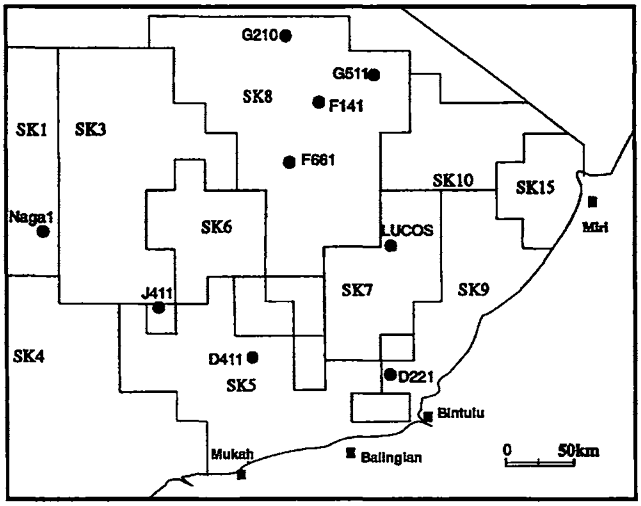

Figure 2. Map showing the location of the wells used for BasinMod studies.

DATA

In order to compute the basement subsidence from the well data it is necessary to have the data on the stratigraphy and sedimentary thickness, water depth during deposition, sea-level and lithology.

Nine wells from the Sarawak Basin were selected for the purpose of basin modelling studies. The locations of the wells are shown in Figure 2. The available well data are in the form of composite well logs plus original copies of several electric logs. All the well composite logs are furnished with gamma ray, resistivity and sonic curves in addition to the interpretation of the depositional environments, biostratigraphic data, dip meter and cycle boundaries. The geographic coordinates, spud date, water depth and drill floor elevation could also be obtained from the composite well logs.

The coded names of the selected wells are; **D411, J411, NAGA1, D221, LUCOS, F661, F141, G511, G210.**

Data on the lithological percentage, water depth and the depositional environments were obtained from well logs. In the well data input for BasinMod (Table 1), the total depths (TD) of the well were also incorporated, which indicate that all the data below the well TD was not obtained from the well but from the seismic or based on the information from nearby wells. Detailed on the techniques used in obtaining the stratigraphic boundaries, lithological assemblages, paleo-water depth and sea level are described below.

Stratigraphic scheme and datum

The stratigraphic scheme used here follows the stratigraphic scheme for the Sarawak Basin (Mat-Zin and Tucker, 1997). Once the sequence boundaries were fixed, the age of each sequence was determined using the stratigraphic chart. Mean sea level was used as the datum for depth measurement for all the wells, which means all the depth values for top of each formation from the composite well logs has been converted from measured to sub-sea depth.

Table 1a. Input for BasinMod 1-D modelling: Sarawak Basin wells.

Well: D411 Water depth: 101 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep.Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	101	1.5	99	10ss/20slt/70sh	HIN/120	-164
T6S	200	3	101	10ss/20slt/70sh	HIN/120	-164
T5S	301	5.2	400	10ss/20slt/70sh	HIN/120	196
T4S	701	11.5	600	20sst/25slt/45sh	HIN/120	-164
T3S	1,301	16	400	20sst/25slt/45sh	HIN/120	396
Erosion		17	-600			
Haitus T2		18				
Missing T2S		22	600	35ss/20slt/45sh	LCP/0	295
T1S	1,701	37	6,560	35ss/20slt/35sh	LCP/0	164
Basement	8,079					
Well TD	8,261					

Well: J411 Water depth: 173 ft.

Sequence	Formation Top (ft.BSL)	Beginnin g Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	173	1.5	777	10ss/35slt/55sh	HIN/120	-164
T6S	950	3	773	10ss/35slt/55sh	HIN/120	-164
T5S	1,723	5.2	583	10ss/20slt/70sh	HMN/300	196
T4S	2,306	11.5	1,342	30ss/30slt/40sh	HMN/300	-164
T3S	3,648	17	821	65lst/15slt/15sh	HIN/120	396
T2S	4,469	22	1,340	40ss/20slt/40sh	LCP/0	295
T1S	5,809	32	7,314	45ss/20slt/35sh	LCP/0	164
Well TD	7,459					
Basement	13,123					

Table 1b. Input for BasinMod 1-D modelling: Sarawak Basin wells.

Well: Naga1 Water depth: 308 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./ water depth (ft)	Eustatic sea-level (ft)
T7S	308	1.5	692	10ss/90sh	HMN/300	-164
T6S	1,000	3	1,691	20ss/23slt/57s	HMN/300	-164
T5S	2,691	5.2	2,347	5ss/10slt/85sh	HON/600	196
T4S	5,038	11.5	17,271	23ss/57slt/20s	HIN/120	-164
Well TD	7,183					
T3S	22,309	17	3,937	30ss/35slt/35s	HIN/120	396
Basement	26,246					

Well: D221 Water depth: 120 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./water depth (ft)	Eustatic sea-level (ft)
T7S	210	1.5	340	20sst/25slt/55sh	HIN/120	-164
T6S	550	3	358	40sst/20slt/ 40sh	COL/60	-164
T5S	908	5.2	539	40sst/20slt/ 40sh	COL/60	196
Erosion		6	-2,500			
Haitus		8				
Missing T4S		10	2,500	20sst/25slt/55sh	HIN/120	-164
T4S	1,447	11.5	1			-164
Erosion		12	-3,000			
Haitus		13				
Missing T3S		15	3,000	40sst/20slt/ 40sh	COL/60	396
T3S	1,448	17	578	40sst/20slt/ 40sh	COL/60	396
T2S	2,026	22	5,708	30sst/25slt/45sh	LCP/0	295
T1S	7,734	37	8,670	35sst/20slt/45sh	LCP/0	164
Well TD	8,582					
Basement	16,404					

Table 1c. Input for BasinMod 1-D modelling: Sarawak Basin wells.

Well: LUCOS Water depth: 214 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./water depth(ft)	Eustatic sea-level (ft)
T7S	214	1.5	336	15ss/15slt/70sh	HIN/120	-164
T6S	550	3	385	15ss/15slt/70sh	HIN/120	-164
T5S	935	5.2	1,695	30sst/20slt/50sh	HIN/120	196
T4S	2,630	11.5	6,195	55sst/20slt/25sh	COF/60	-164
T3S	8,825	17	1,905	40lst/20slt/40sh	HIN/120	396
T2S	10,730	22	7,314	20sst/25slt/55sh	HIN/120	295
Well TD	10,890					
T1S	18,044	37	14,764	40sst/20slt/40sh	COL/60	164
Basement	32,808					

Well: F661 Water depth: 277 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./water depth(ft)	Eustatic sea-level (ft)
T7S	277	1.5	429	15ss/15slt/70sh	HIN/120	-164
T6S	706	3	940	15ss/15slt/70sh	HIN/120	-164
T5S	1,646	5.2	2,404	10slt/90sh	HMN/300	196
T4S	4,050	11.5	2,817	100 lst	HIN/120	-164
T3S	6,867	17	1,371	60lst/10slt/30sh	HIN/120	396
T2S	8,238	22	11,446	20sst/25slt/55s	HIN/120	295
Well TD	10,919					
T1S	19,684	37	16,403	20sst/25slt/55s	HIN/120	164
Basement	36,088					

Table 1d. Input for BasinMod 1-D modelling: Sarawak Basin wells.

Well: F141 Water depth: 347 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./water depth(ft)	Eustatic sea-level (ft)
T7S	347	1.5	1,164	5ss/25slt/70sh	HIN/120	-164
T6S	1,511	3	988	5ss/25slt/70sh	HIN/120	-164
T5S	2,499	5.2	1,767	10 slt/90sh	HMN/300	196
T4S	4,266	11.5	3,937	100 lst	HIN/120	-164
Well TD	4,804					
T3S	8,203	17	8,201	35 lst/10ss/ 10slt/45sh	HIN/120	396
T2S	16,404	22	9,842	10ss/20slt/70sh	HMN/300	295
T1S	26,246	37	16,404	20sst/25slt/55sh	HIN/120	164
Basement	42650 ft					

Well: G511 Water depth: 369 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./water depth(ft)	Eustatic
T7S	369	1.5	1,416	5ss/25slt/70sh	HON/600	-164
T6S	1,785	3	8,057	5ss/25slt/70sh	HON/600	-164
Well TD	3,940					
T5S	9,842	5.2	4,921	35lst/25slt/40sh	HON/600	196
Erosion		7	-3,000			
Haitus		10				
MissingT4S		12.5	3,000			-164
T3S	14,763	17	3,281	5ss/25slt/70sh	HON/600	396
T2S	19,784	22	4,921	5ss/25slt/70sh	HON/600	295
T1S	26,246	37	19,685	10ss/20slt/70sh	HMN/300	164
Basement	41010 ft					

Table 1e. Input for BasinMod 1-D modelling: Sarawak Basin wells.

Well: G210 Water depth: 468 ft.

Sequence	Formation Top (ft.BSL)	Beginning Age (Ma)	Thickness (ft)	Lithology percentage	Dep. Env./water depth(ft)	Eustatic sea-level (ft)
T7S	468	1.5	1,360	5ss/25slt/70sh	HON/600	-164
T6S	1,828	3	2,053	5ss/25slt/70sh	HON/600	-164
T5S	3,881	5.2	2,237	100 lst	HON/600	196
T4S	6,118	11.5	930	5ss/25slt/70sh	HON/600	-164
T3S	7,043	17	9,956	20sst/25slt/55sh	HIN/120	396
T2S	7,994	22	2,239	10ss/20slt/70sh	HMN/300	295
T1S	10,233	37	3,500	20sst/25slt/55sh	HIN/120	164
Well TD	10,921					
Basement	13,265 ft					

Lithological percentage

The actual percentage of each lithology was calculated from the original wireline logs. For wells without the original wireline logs, an estimation was made using composite logs. For some of the wells in which the stratigraphic penetration was not deep enough to reach the basement, the lithological percentage beneath the maximum depth reached was estimated based on the depositional environments of the sequences present above basement, using the depositional environment maps for each of the sequence (Ismail, 1996a).

Water depth and sea level

The water depth during deposition was estimated, based on the palaeo-depositional environments of each sequence. The data on the palaeo-depositional environment interpretations are mainly based on the occurrence of benthonic foraminifera, obtained from the composite well logs. The relationship between water depth and depositional environment for the Sarawak Basin was established by Ho (1978). More often than not, the depositional environment for a sequence changed from shallower environment to deeper environment or vice versa. In this study, the maximum water depth is taken as the depositional depth of the particular sequence.

The changes in sea-level through time was determined using the third order eustatic sea-level curve of Haq *et al.* (1987). The average between the maximum and minimum sea level in the sequence interval was taken as the sea level value for the sequence.

TECHNIQUES TO GENERATE SUBSIDENCE CURVES

The methods used in analysing the well data are described in this section BasinMod 1-D for Windows Basin Modelling System Version 4 by Platte River Associates, hereafter referred to as BasinMod, was used to generate the subsidence curves for the nine wells from Sarawak Basin. The input data were obtained from either well logs or the seismic lines. In addition, BasinMod has its own default values for some parameters; for example thermal conductivity, compaction curves and poroperm.

Once both the input and default values were keyed into the programme, BasinMod is able to generate several options of display including *Burial History,* either with or without compaction correction, *Geohistory,* with or without ocean display, and *Tectonic Subsidence* curves which facilitates the analysis of subsidence history of the basin in the vicinity of the selected wells. For this study, only the total and tectonic subsidence for all the nine wells are displayed.

Before discussing the subsidence history of the basin, it is appropriate to outline the process involved in generating the subsidence curves and to provide a brief description of both the default and the input data required by BasinMod.

Default data

The rock data not required as a direct input into BasinMod include porosity and permeability values. BasinMod can supply default values using several calculation options offered by the programme, since BasinMod contains a lithology library. The library starts out with a default set of eight pure lithologies along with their rock property values which BasinMod requires for its calculations. The rock properties include initial porosity, compaction algorithms, density, grain size, conductivity and heat capacity. In practice, the formations to be modelled are often a mixture of these pure lithologies. The user can utilise the *Lithology Mixed* option for the default values. When the lithology of a formation cannot be effectively described in terms of a mixture of pure lithologies, BasinMod also allows definition of lithologies in terms of mineral composition.

a) Porosity

BasinMod calculates effective porosity by using the following equation:

$$\phi_* = \phi - 3.1 \times 10^{-10}\ So$$

Where; ϕ_* = Effective porosity
ϕ = Porosity (initial) from BasinMod lithology library
So = Specific surface area of rock, i.e., the surface area to volume ratio using the surface area of a sphere and the volume of a cube. Grain size is equal the diameter of the sphere and the side of the cube.

b) Permeability

Fluid flow (single phase) through porous media is modelled using Darcy's Law for the flow of water through sands. Later experiments using various fluids and porous materials showed that viscosity and density of the fluid plus size of grains all effect the flow. The equation (form the BasinMod software manual) has evolved to:

$$V = -\frac{k\rho g}{\mu} \times \frac{dh}{dl}$$

Where; V = Specific discharge
g = Gravitational acceleration
k = Permeability
μ = Viscosity
ρ = Density
dh/dl = Hydraulic gradient

BasinMod offers several methods for estimating permeability values including the Kozeny-Carman, Power Function and user-specified Porosity-Permeability relationships. The Kozeny-Carman method of calculation was used for all the wells, as measured porosity-permeability data for the nine wells are not available.

Input data required by the BasinMod

The data needed as input to BasinMod for creating tectonic subsidence curves are as follows:

a) *Stratigraphy* includes Formation Name, Beginning Age, Well Top, Thickness, Hiatus and Missing Section, and Lithological Composition.
b) *Present Day Information* includes the present day water depth.
c) *Time Values* are the paleo-water depth and eustatic sea-level through time.

Correction for compaction (decompaction)

To calculate the thickness of a sediment layer at any time in the past, it is necessary to move the upper layer upwards along the appropriate porosity-depth curve: this is equivalent to sequentially removing overlying sediment layers and allowing the layer of interest to decompact. In doing so, we keep mass constant and consider the changes in volume and therefore thicknesses (Allen and Allen, 1990).

The curve corrected for compaction (decompacted) is always deeper than the uncompacted curve in the burial history plot. However, the beginning and end points of both curves are the same so the greatest variances will occur toward the middle of the burial history curves. The basic assumption of mechanical compaction is that the thicknesses of sediments and rocks are reduced by a predictable amount related to porosity reduction, varying according to lithology and depth of burial.

BasinMod offers four methods of correction for compaction including algoriths developed by Sclater and Christie, Falvey and Middleton, Baldwin and Butler and porosity table with coupled fluid flow compaction. For this study, the Sclater and Christie method was used because the modelled wells are dominated by siliciclastics, similar to the rocks for the North Sea which constitute the data for Sclater and Christie (1980). The porosity based on Sclater and Christie is:

$$P = P_0\ \mathrm{Exp}^{(-kz)}$$

Where: P_0 = Initial Porosity
k = Compaction factor to adjust for varying compressibility of different lithologies
z = Depth

Total subsidence and tectonic subsidence

The total subsidence in a basin is a combination of basement (tectonic) subsidence and subsidence due to sediment loading. The process used to determine the amount of load-induced subsidence is isostatic backstripping. This method removes sediment layers, correcting for decompaction, fluctuation of sea level and sea-depth, and, assuming airy isostacy, adjusts for isostatic rebound. The equation used by BasinMod to calculate the effect of load-induced subsidence:

$$Y = S\left(\frac{\rho m-\rho s}{\rho m-\rho w}\right) - \Delta SL\left(\frac{\rho w}{\rho m-\rho w}\right) - (Wd - \Delta SL)$$

Where: Y = depth of basement corrected for sediment load
S = total thickness of sediment column corrected for compaction
ρm = average mantle density
ρs = average sediment density
ρw = average water density
ΔSL = change in elevation of mean sea level
Wd = paleo sea depth

Once we know the load-induced component of total subsidence, we also know the amount of tectonic subsidence. The results of this computation are displayed on a backstripped subsidence curve (Graph/Burial history/Subsidence).

In summary, the **Total Subsidence** of a basin is derived by the cumulative factors as listed below:

1. Sediment loading (from stratigraphic data)
2. Change in water depth (from palaeo-environment maps)
3. Change in eustatic sea-level (from Haq *et al.*, 1987)
4. Tectonic (basement) subsidence (from burial history curves of BasinMod).

METHOD TO ANALYSE SUBSIDENCE CURVES

The computer-generated results were analysed primarily according to descriptions by Allen and Allen (1990), by firstly assuming that the basin has experienced a subsidence history consistent with McKenzie's (1978) model. The results of McKenzie (1978) quantitative model of stretching can be summarised as follows:

1. The total subsidence in an extensional basin is made of two components; an initial fault controlled subsidence (Si) which is dependent on the initial thickness of the crust and the amount of stretching (ß); and a subsequent thermal subsidence (Sth) caused by relaxation of lithospheric isotherms to their pre-stretching position, and which is dependent on the amount of stretching (ß) alone.
2. Whereas the fault-controlled subsidence is modelled as instantaneous, the rate of thermal subsidence decreases exponentially with time. This is the result of decrease in heat with time. The heat flow reaches its original value after about 50 Ma for a lithosphere of 'standard' thickness, so at this point after the cessation of rifting, the dependency of the heat flow on b is insignificant.

Initial subsidence

According to the McKenzie (1978) model, at time = 0 a unit length of continental lithosphere is suddenly extended to length ß, causing upwelling of hot lithosphere. The resultant thermal perturbation gradually decays, producing subsidence. The simplest model ignores the radioactivity of continental rocks and assumes that the temperature at a depth corresponding to the initial thickness of the lithosphere is fixed. Subsidence of the lithosphere is isostatically compensated both before and after extension. In brief, the model assumes:

1. Instantaneous stretching
2. No volcanism
3. Vertical heat conduction
4. Uniform extension
5. Thermal equilibration
6. Isostatic equilibrium.

The Initial Subsidence (Si) is given by:

$$Si = \frac{a\left(1-\frac{1}{\beta}\right)\left[\frac{tc}{a}(\rho m-\rho s)\left(1-\frac{\alpha Tl\rho c}{2a}\right)-\frac{\alpha\rho m Tl}{2}\right]}{\rho m(1-\alpha Tl)-\rho s}$$

.... Equation (1)

Where:

Thickness of unextended lithosphere (a) = 125 km
Thickness of unextended crust (tc) = 35 km
Density of crust at 0°C (ρc) = 2.8 g cm^{-3}
Density of mantle at 0°C (ρm) = 3.33 g cm^{-3}
Density of basin infill (water) (ρs) = 1.03 g cm^{-3}
Coefficient of thermal expansion (α) = 3.28×10^{-5} °C
Temperature at base of lithosphere (Tl) = 1,333°C

The values of the parameters above are taken from McKenzie (1978). The unextended crustal thickness is estimated for the Sarawak Basin based on the average crustal thickness in Asia, for Tarim Basin and Korea (Holmes, 1965 in Allen and Allen, 1990). A similar crustal thickness was used for the Gulf of Thailand by Helingger *et al.* (1984). The initial subsidence (Si) has an exponential relationship with b and is less significant when β is more than 3, as shown in Figure 3 and the table below:

β	1.00	1.50	2.00	3.00	4.00	5.00	6.00	7.00
Si (km)	0.00	1.50	2.30	2.90	3.40	3.60	3.70	3.80

Thermal Subsidence

The thermal subsidence (*Sth*) can be predicted from the extension factor (β), where:

$$Sth = \frac{4a\rho m\alpha Tl}{\pi^2(\rho m-\rho s)}\left[\frac{\beta}{\pi}Sin\frac{\pi}{\beta}\right]\left(1-e^{\frac{-t}{\tau}}\right)$$

.... Equation (2)

Lithospheric thermal time constant (τ) = 62.8 Ma

By using the same parameters for the Initial Subsidence to equation (2) with β as variable, the relationship between b and thermal subsidence (*Sth*) can be understood as shown in Figure 4. In the same way as for the initial subsidence, the thermal subsidence (*Sth*) is less significant when b is greater than 3 (Fig. 4).

Total Subsidence (*St*)

The total subsidence (St) at time 't' after extension, based on Chadwick (1986), can be expressed by:

$$(St) = (Si) + (Sth)$$

.... Equation (3)

Solution of Equation (1) and (2), using the parameters in Equation 1, allows the subsidence history of a sediment-starved basin (filled only with sea water), formed by varying amounts of lithospheric extension, to be computed (Fig. 5).

INTERPRETATION OF RESULTS

The subsidence pattern of the Sarawak Basin, and estimates of the stretching factors involved in the formation of the basin, are described in this section. Discussion on the validity of the selected model using guidelines and comparison between the model estimates and the geothermal estimations based on the well information from the basin (Wan Yussof, 1990), are also made.

For each well, two curves are displayed on the *geohistory* diagram, namely the Tectonic Subsidence Curve and Total Subsidence Curve (Figs. 6 to 10). Tectonic Subsidence Curve is derived after the removal of subsidence due to sediment load, correction for variations in water depth (palaeobathymetry) and eustatic sea-level fluctuation, and after the correction for compaction were made to the present day stratigraphic thickness.

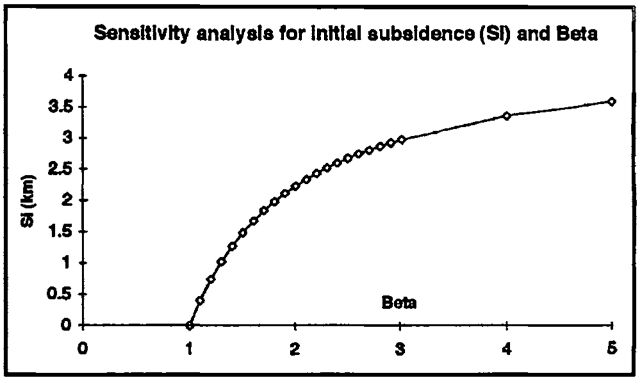

Figure 3. Sensitivity curve for initial subsidence (Si) with no sediment loading assumed, and stretching factor (β).

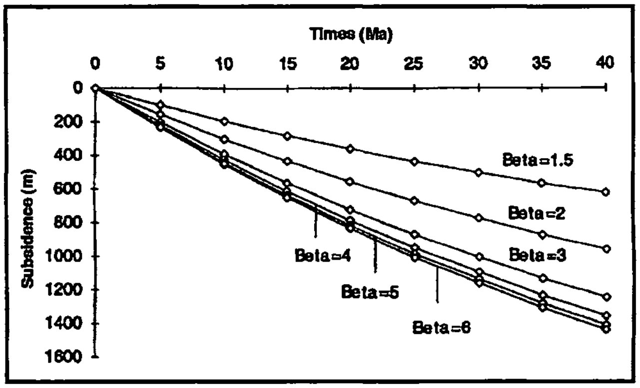

Figure 4. Sensitivity curves for thermal subsidence (Sth) with no sediment loading assumed, and stretching factor (β).

Subsidence patterns

The tectonic subsidence curves give an immediate visual impression of the basement subsidence history, indicative of the nature of the driving force responsible for basin formation and development (Allen and Allen, 1990). This seems to be true when we are able to classify and group the type of subsidence patterns seen in the Sarawak Basin, which in turn may be used to determined the possible driving forces and the type of the basin for the each sub-area. By looking at Figures 6 to 10, three primary conclusions about the tectonic subsidence patterns of the area are found:

1. No single well has a subsidence pattern characteristic of a foreland basin (compare with Fig. 1).
2. Visually several wells have a profile which matches a typical McKenzie rift basin, including wells J411 (Fig. 6), Lucos and F661 (Fig. 8) and F141 (Fig. 9).

3. Other wells, namely D411 (Fig 6), D221 (Fig 7), G511 (Fig 9) and G210 (Fig. 10), are characterised by subsidence patterns which conform to neither a foreland basin nor a McKenzie rift basin. Comparison of Figure 1 and the above mentioned figures illustrates a strong *prima facie* argument for these wells to have been drilled into a strike-slip related type of basin. Specifically the repetition of uplift and subsidence is not a characteristic of a McKenzie-type rift basin.

In the Eastern Sub-Basin (the area to the east of the West Balingian Basin; Fig. 11), all the wells seem to experience an initial subsidence episode for the first few million years of the basin history, which suggest the whole area has undergone extensional tectonics during the initial formation of the basin. If this area has experienced lithospheric extension, the fault controlled subsidence (*Si*) and the post-tectonic thermally controlled subsidence (*Sth*), should yield the same values of β.

Beta (β1) values from Initial Subsidence.

The initial subsidence for each of the wells was taken from the first subsidence episode of the tectonic subsidence curve, marked by the dotted lines on Figures 6 to 10. The calculation of stretching factor (β1) from the initial subsidence was then made using Equation (1). Other parameters are assumed to be similar to the Central Graben, North Sea (McKenzie, 1978) and Wessex Basin (Chadwick, 1986). The beta values for the wells in the study area are shown below, plus timing of stretching.

WELL	Initial Subsidence (km)	(β1)	Duration (Ma)
J411	1.45	1.49	15.00
D411	1.15	1.36	15.00
Nagal	1.12	1.34	6.00
D221	2.15	1.96	17.50
Lucos	2.35	2.15	15.00
F661	3.00	3.16	15.00
F141	3.00	3.16	15.00
G511	2.90	2.95	15.00
G210	1.10	1.33	15.00

Beta (β2) values from Thermal Subsidence

The calculation of stretching factor (β2) from the thermal subsidence was made based on the amount of subsidence after the initial subsidence. The estimation of the amount of subsidence is very complicated as curves are not smooth. However, the data for the calculation was taken from the best fit lines shown as dotted lines on Figures 6 to 10. The estimated stretching factors (β2) from thermal and (β1) from initial subsidence for the nine wells are as below, plus duration of subsidence.

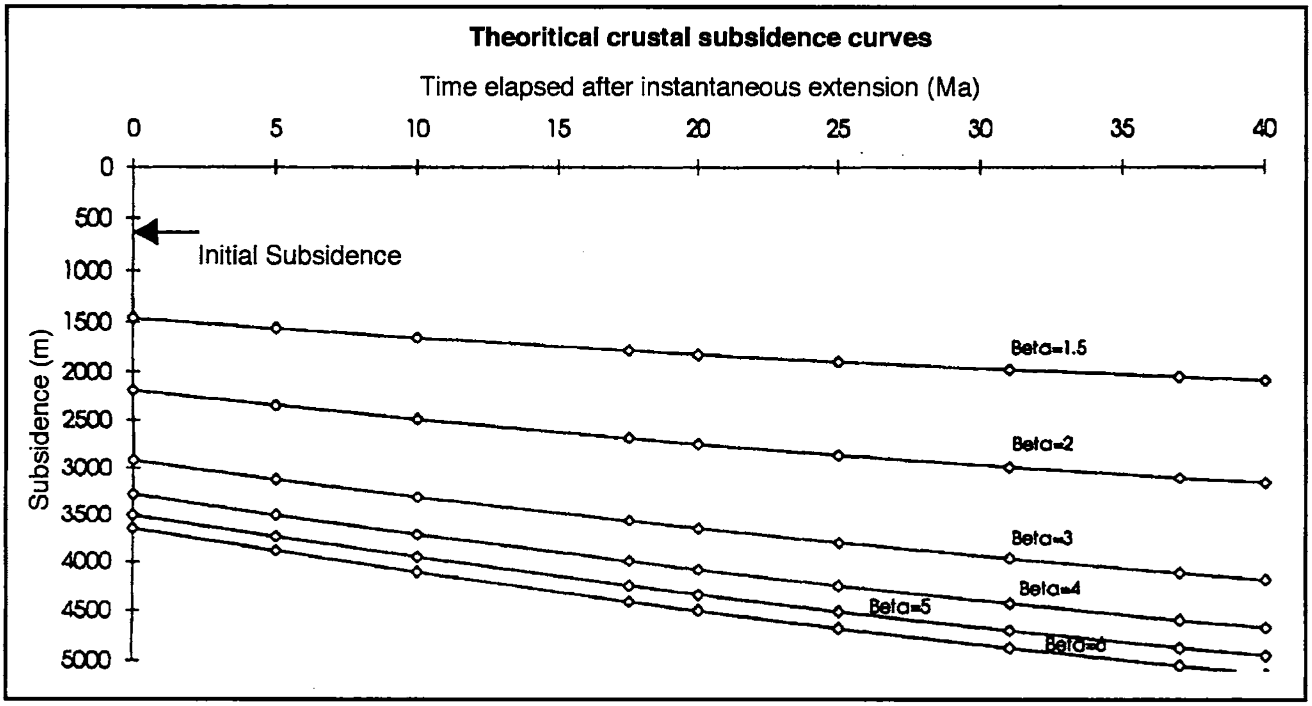

Figure 5. Sensitivity curves for total crustal subsidence (St) in sediments-starved basin by various amount of lithospheric stretching factor (β).

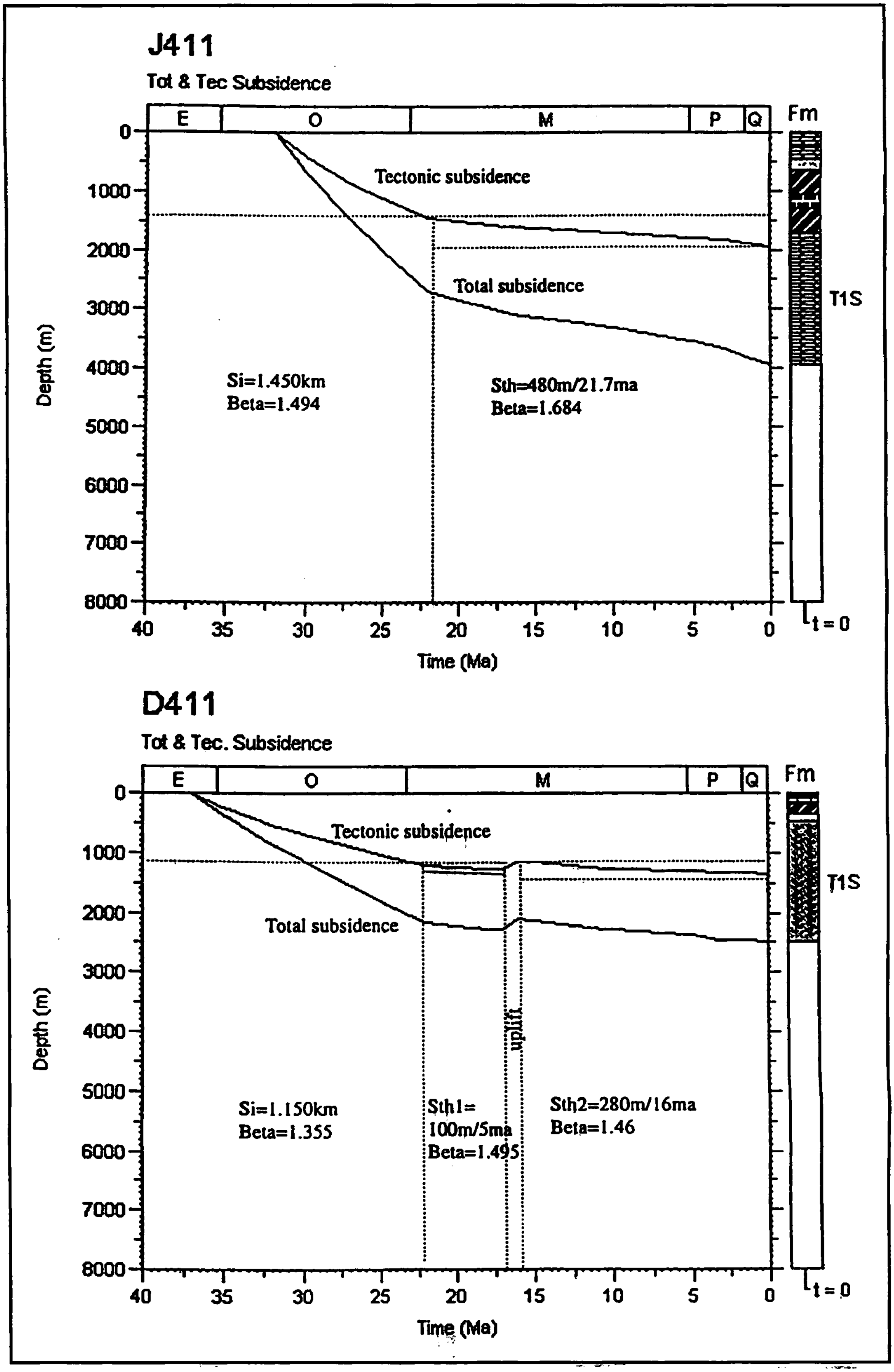

Figure 6. Total and tectonic subsidence curves for the J411 and D411 wells.

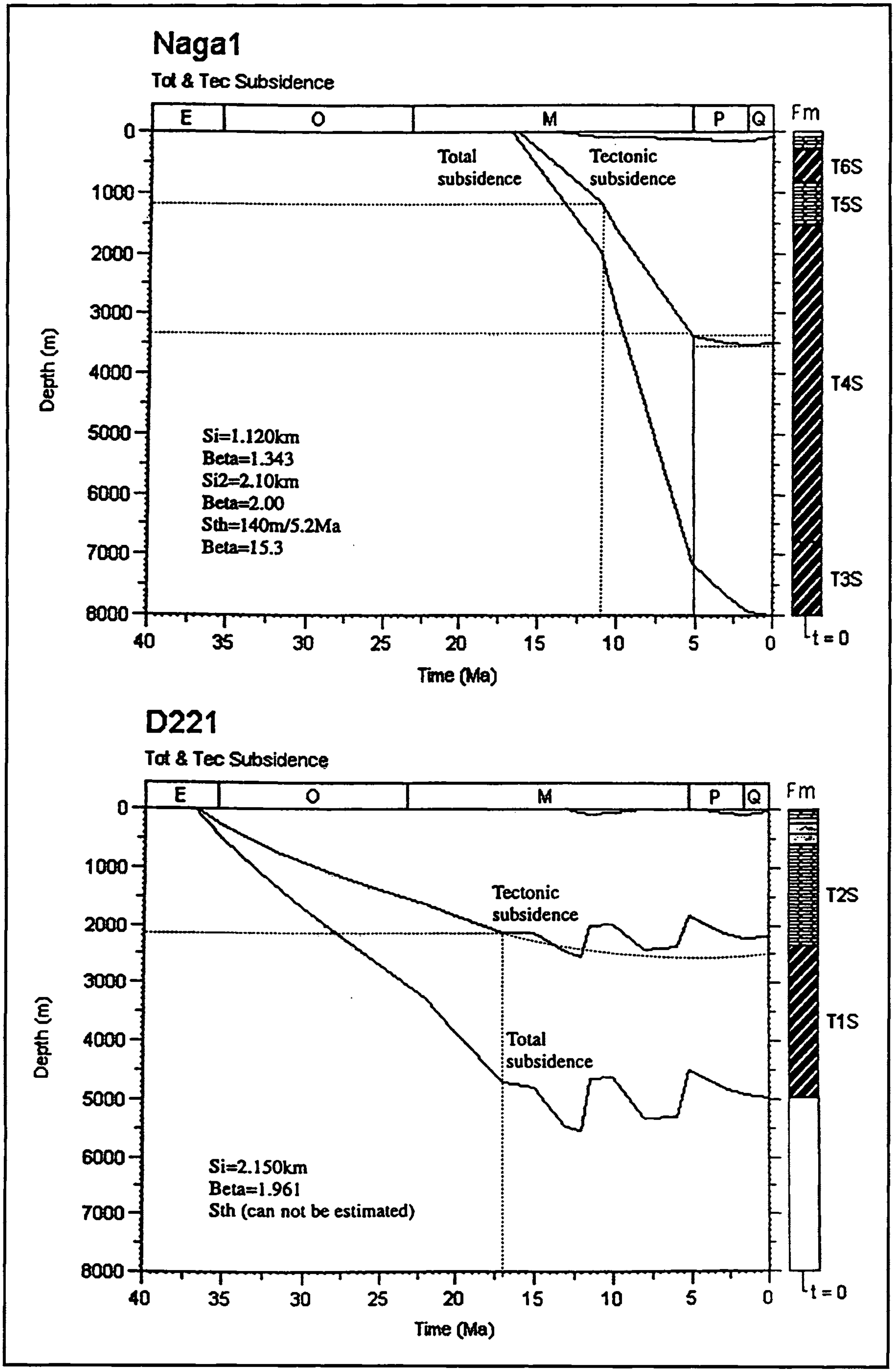

Figure 7. Total and tectonic subsidence curves for the Naga1 and D221 wells.

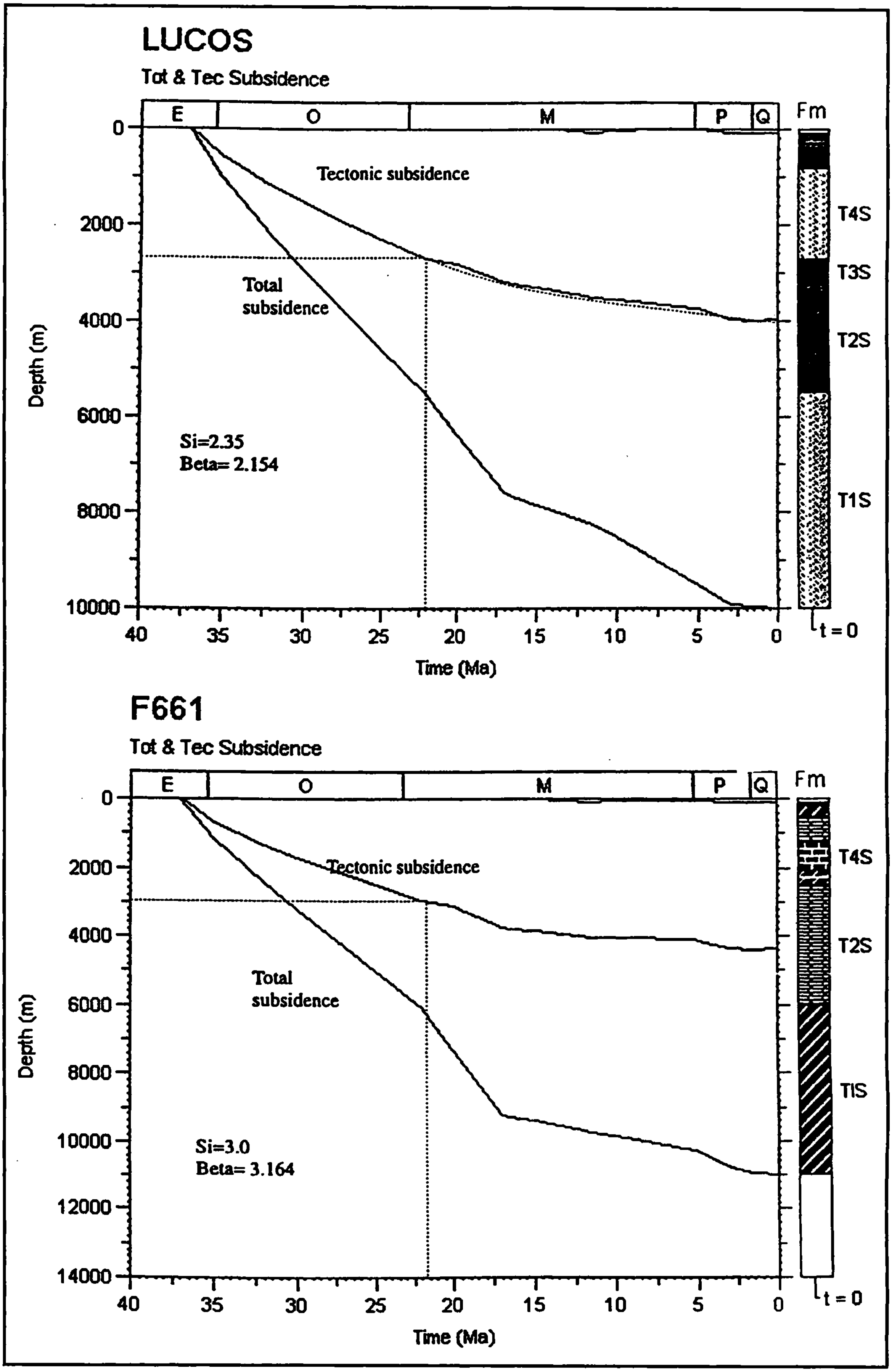

Figure 8. Total and tectonic subsidence curves for the Lucos and F661 wells.

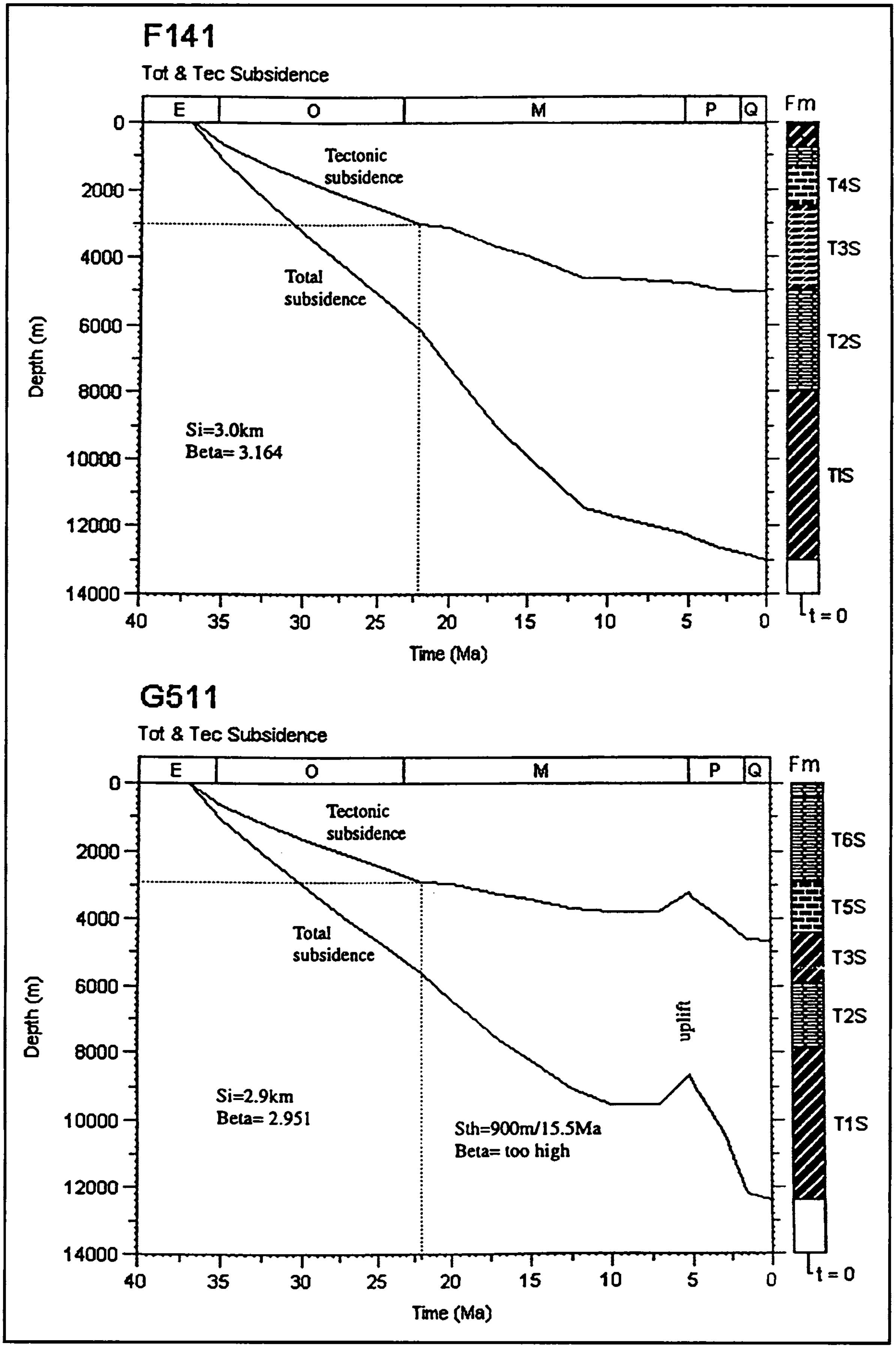

Figure 9. Total and tectonic subsidence curves for the F141 and G511 wells.

WELL	Subsidence (m)	Duration (Ma)	β2
J411	480.00	21.70	1.68
D411	100.00	5.00	1.50
Nagal	110.00	5.20	1.54
D221			
Lucos	1,200.00	22.00	> 10
F661	1,500.00	22.00	> 10
F141	2,000.00	22.00	> 10
G511	900.00	15.50	> 10
G210	520.00	12.25	4.90

Relationship between Subsidence Patterns and Tectonic History

Prior to discussing the relationship between the subsidence pattern and the tectonic history of the basin, it is appropriate to discuss the criteria for a McKenzie rift basin. It is then possible, using the subsidence pattern in each of the nine wells to determine whether or not they are of McKenzie-type. The criteria for a McKenzie-type rift basin can be summarised as:

1. Fault-controlled initial subsidence or uplift is followed by thermally-controlled regional sag.
2. The stretching factor from the initial subsidence (β1) should be similar to the stretching factor from the thermal subsidence (β2).
3. No major uplift during thermally controlled subsidence.
4. Evidence of volcanism when β is higher than 4.0.

By referring to Figure 11, it can be seen that the nine wells selected for the BasinMod studies are representative for several different tectonic regions of the Sarawak Basin. The wells and the tectonic areas in which they are, are as below:

J411 — SW Luconia Sub-Basin (SWLB) within the basement high area, formed as a releasing overstep basin.

D411 — Basement high area, close to the West Balingian Line, interpreted as strike-slip faults.

D221 — Southern part of Eastern Sub-Basin in the compressional area with faulted-fold structures.

Nagal — Southern part of NW Sub-Basin, formed as a releasing overstep basin.

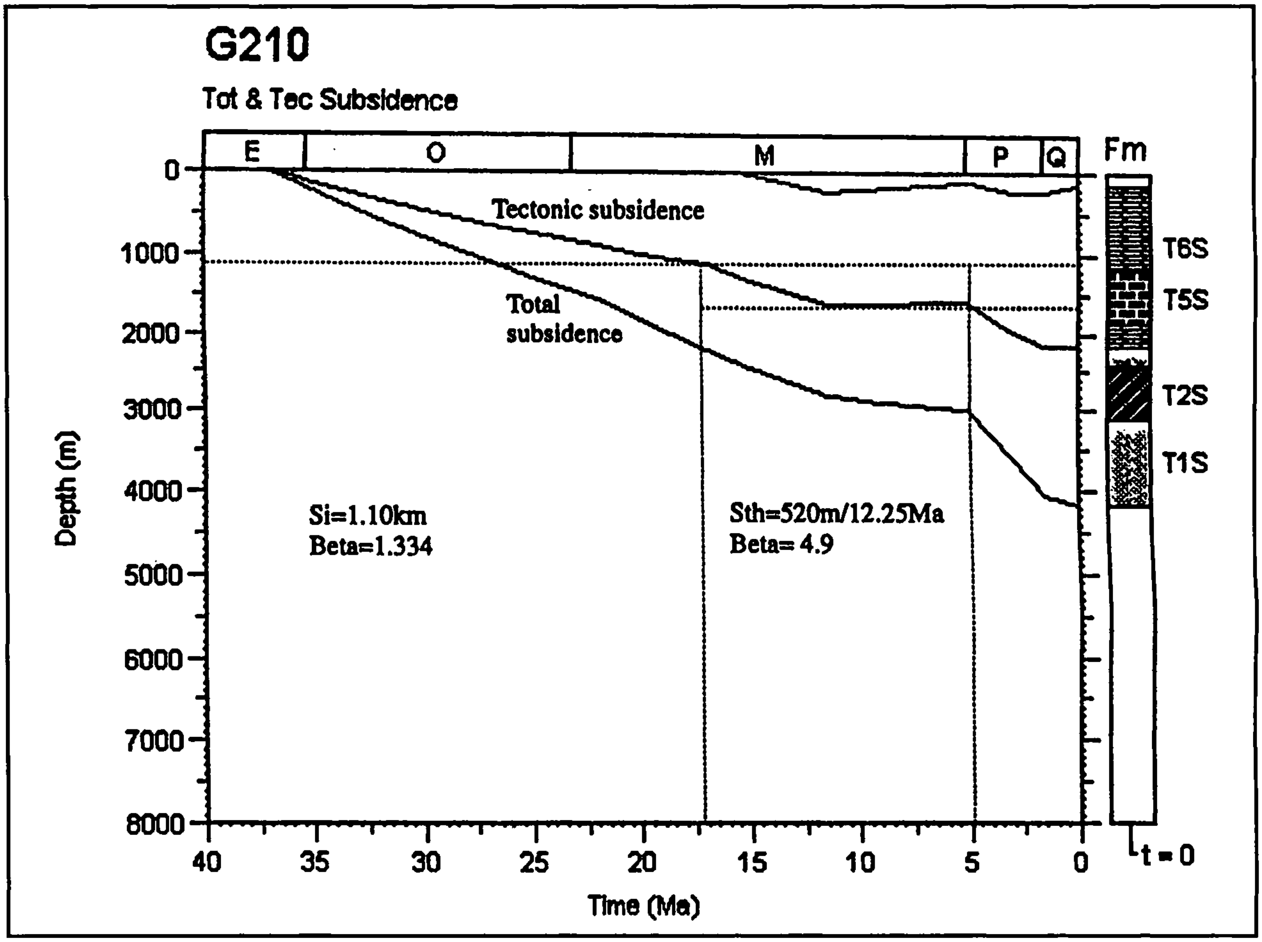

Figure 10. Total and tectonic subsidence curves for the G210 well.

G210 and G511 — In the deep-water area, within the Eastern Sub-Basin.

F141, F661 and Lucos — Middle part of Eastern Sub-Basin, interpreted to be formed as a strike-slip related basin.

In summary, from the subsidence profiles of the nine wells from the Sarawak Basin, it can be shown that:

a) The subsidence profile of one well (J411) matches a McKenzie-type stretching model, but the tectonic setting shows that the area formed in a releasing overstep (pull-apart) within a strike-slip setting, rather than a true rift basin.
b) Other wells in the basin have very different values of β1 and β2, which suggest they were not formed in a McKenzie-type basin, in particular they yield very high values of β2.
c) There is also evidence in several wells for local intermittent episodes of compression and subsidence.

Relationship between stretching factors and geothermal gradient

The geothermal gradient of the Sarawak Basin was obtained from PETRONAS's in-house geothermal gradient map compiled and produced by Wan Yussof (1986), and redrawn in Figure 13. Based Wan Yussof (1990), the geothermal gradient at each well was determined from the borehole formation temperature determined during logging, the known depth of measurement and the average temperature of the surface where drilling begins. Linear regression analysis was applied to the parameters to obtain the geothermal gradient, with corrections for time since circulation of the mud, etc. A large dataset of thermal conductivity measurement of core samples was available.

According to Wan Yussof (1990), the heat flow value was determined at well locations assuming only vertical conduction of heat. In the well, the heat flow is considered constant, with the

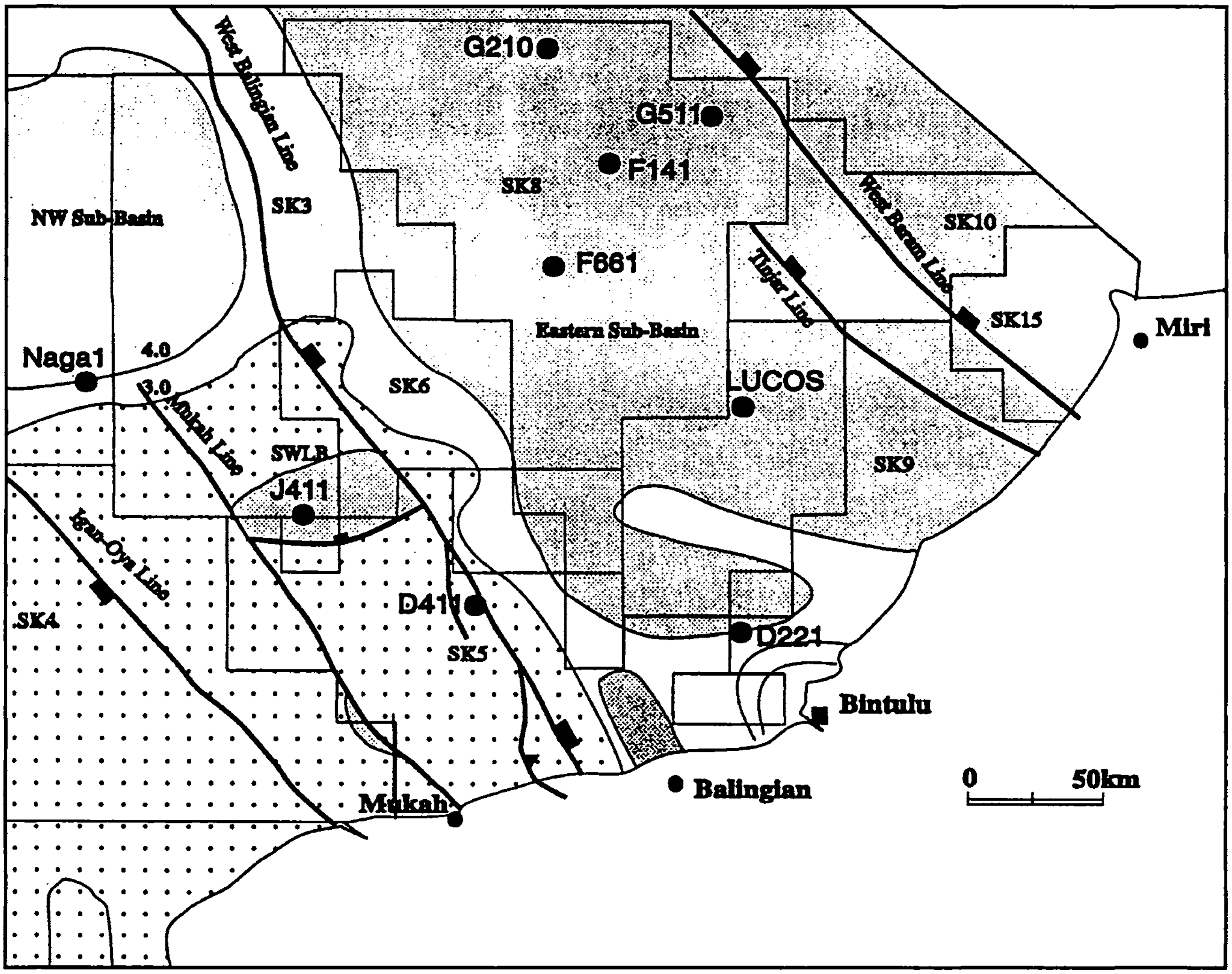

Figure 11. Map showing the location of the nine wells used for BasinMod analyses, in respect to the tectonic regions of the Sarawak Basin. SWLB = SW Luconia Sub-Basin.

geothermal gradients and the thermal conductivity varying. It is assumed here that the same techniques were used to generate the 1986 geothermal gradient map for the Sarawak Basin, which has been used.

The amount of well data available varies across the Sarawak Basin, leading to variability in the accuracy of the map (Fig. 13). The geothermal gradient for the area to the west of the West Balingian Line is least well constrained. This is because the number of the wells drilled in the area is small, as compared to the number of the wells in the area to the east. For example, to date, only five wells have been drilled in the NW Sub-Basin. Out of that number, two of the wells, including Nagal, were drilled in the years after 1986, after the map was generated. The other three wells were drilled in the early 1970's. Further, the wells were only drilled in the basement high area, in the area in the vicinity of J411 and D411. No well was drilled on the basement high area to the west of D411 in block SK5.

In the Eastern Sub-Basin, the beta values and the geothermal gradients show a relationship between the areas with high stretching factor (Fig. 12) and with high geothermal gradient (Fig. 13). Specifically, the data suggest that the areas with a high geothermal gradient (> 5°C/100 m) coincide with the areas which have experienced high stretching factor (> 2.5) i.e. high rate of subsidence and high rate of sedimentation (Figs. 8 and 9).

DISCUSSIONS

The subsidence curves for the nine wells from Sarawak Basin (Figs. 6 to 10), are characterised by rapid rate of subsidence which is exceeding 10 km in 37 Ma for the area in the Eastern Sub-Basin, as compared to the North Sea Graben which is mainly less than 4 km in 100 Ma. Consequently, the stretching factor (β) calculated for the Sarawak Basin is high, reaching the value of 3.16, when compared to the North Sea Graben which is in the range of 1.5 to 2.0 (Sclater and Christie, 1980 ; Wood, 1981). The β values are similarly very high when compared to the Wessex Basin, Southern England, which are about 1.147 (Chadwick, 1986). The two basins mentioned above are classified as rift basins, although the Wessex Basin has some influence of strike-slip (Chadwick, 1986). The stretching factor for the Sarawak Basin is almost the same as the Pattani Trough (Gulf of Thailand, Hellinger *et al.*, 1984) which is in the range of 1.21 to 3.23.

For the normal crustal thickness (30–40 km) and geothermal gradient (2.5–3.0 °C/km), a β value of approximately 4.0 can be used as a basis for determining whether volcanism is likely or not. Where the geothermal gradient is higher, a lower β value should lead to volcanism. In the case of the Sarawak Basin, where the geothermal gradient is close to 5.0°C/km as an average (Fig. 13), the β value of > 3.0 might be expected to lead to volcanism when the McKenzie-type lithosphere extension by pure shear occurs. The absence of volcanism is indicative of non-pure shear stretching for the Sarawak Basin, possibly because, as argued above, the basin has a major strike-slip component.

Little is known about the stretching factor (β) for true strike-slip basins. Most data come from strike-slip related basins in California. However, it is known that strike-slip basins are characterised by extremely rapid rates of subsidence, even more rapid than many grabens and foreland basins. This is generally matched by an abundant sediment supply, leading to very thick stratigraphic sections, in comparison with the lateral basin dimension. For example,

a) About 13 km of sediment accumulated in the Ridge Basin, California, in only 7 Ma,
b) About 5 km of sediments were deposited in the Vellecito-Fish Creek Basin in about 4 Ma and,
c) The Ventura Basin, California, subsided nearly 4 km in the past 1 Ma.

Another potentially important mechanism for basin subsidence along strike-slip faults, in addition to crustal extension, is loading due to local convergence of crustal blocks.

Strictly for the purpose of comparison between the Sarawak Basin and known strike-slip basins, the tectonic subsidence has been assumed to be about 50% of the total subsidence (as could be seen in all cases in Sarawak Basin) and the basins are assumed to be in the fault-related stage of subsidence. The estimated stretching factor, $\beta 1$, of these basins (by using Equation 1 and other parameters similar to the Sarawak Basin), are as below:

BASIN	$\beta 1$
Ridge Basin	> 10
Vellecito-Fish Creek Basin	2.32
Ventura Basin	1.83

Pitman and Andrews (1985) found that strike-slip basins are characterised by very rapid subsidence and sediment accumulation in small "pull-apart" basins, and can be modelled using a McKenzie-type model. This study arrives at a similar conclusion for the J411 where the subsidence profile of the well fits to the McKenzie-type of rift basin. However, it is not applicable for other areas of the Sarawak Basin where many of the subsidence profiles are characterised by episodic uplift and subsidence taking place in different places and times around the Sarawak Basin as might be expected in areas close to strike-slip lineaments which variably experience extension and compression.

The rapid initial subsidence of small strike-slip basins is caused by crustal thinning combined with lateral heat lost to the basin wall, and the initial width has a major influence on the subsidence history, the narrowest basins loose heat most rapidly to the sides and therefore subside at a greater rate and with a greater magnitude than wider basin (Pitman and Andrews, 1985). This fits the data for the J411 well where the $\beta2$ value is slightly higher than $\beta1$. However for other wells elsewhere in the Sarawak Basin which have experienced episodic tectonic movements, this observation is obscured.

Judging from the stretching factors, the rate of subsidence, the polycyclic episodes of deposition and uplift, the overall subsidence profile for the Sarawak Basin, is consistent with other known strike-slip basins elsewhere. This observation agrees with other evidences i.e. the basin is characterised by distinct shifts in the depositional setting with different source of provenance and migration of depocenter, the occurrence of several smaller sub-basins and the occurrence of strike-slip bounding faults. Therefore the subsidence data support the model for the Sarawak Basin as a strike-slip related basin as opposed to rift or foreland basin. The finding is extremely consistent with the interpretation based primarily on seismic data.

CONCLUSIONS

1) In the strike-slip related Sarawak Basin, most of subsidence profile shows early rapid

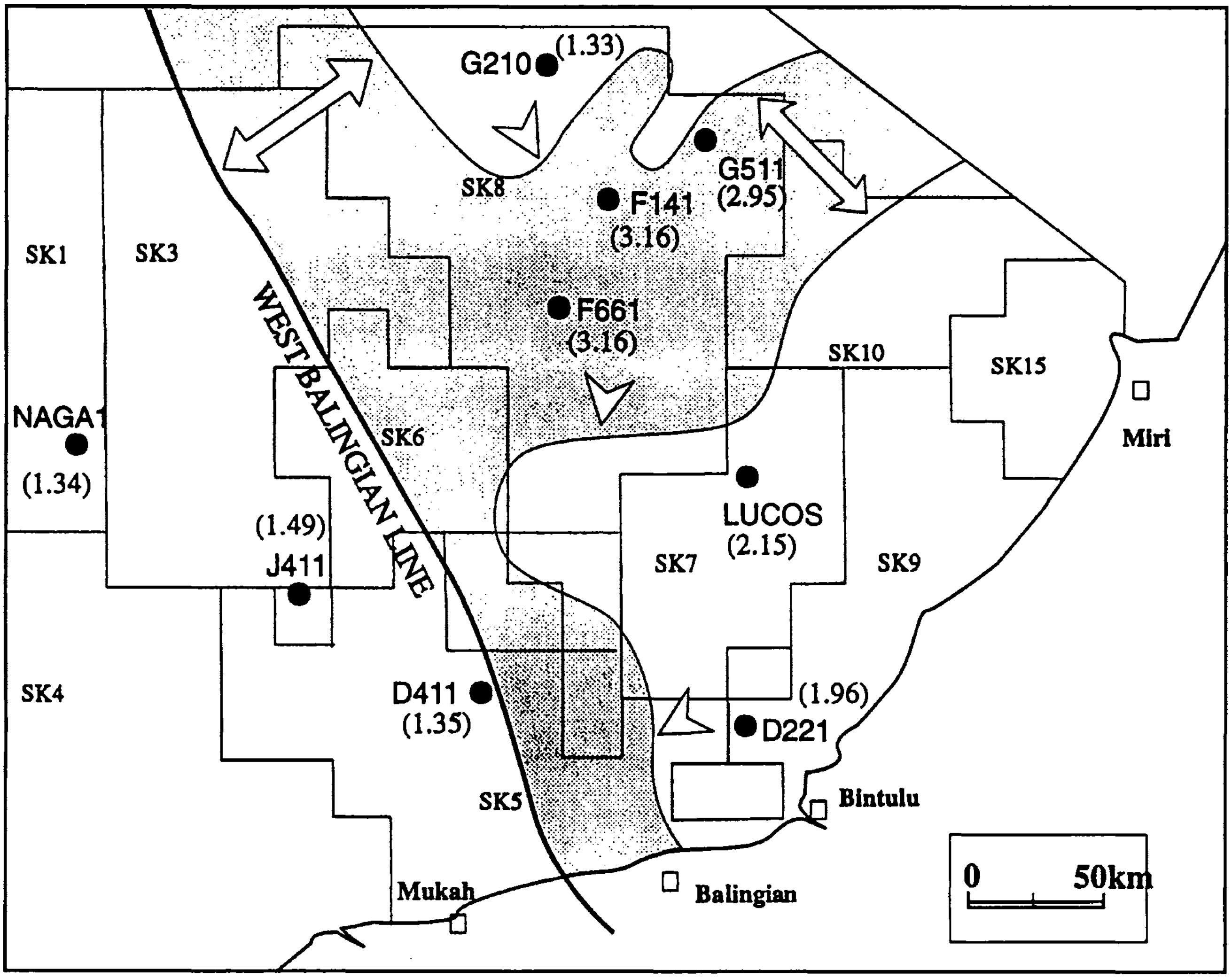

Figure 12. Map showing the shaded area as the area with high beta values (> 2.5) which is coincident with the high geothermal gradient area. The beta values are shown in brackets. Double headed arrows show the directions of extension and arrow heads indicate the directions of compression seen on seismic.

subsidence followed by a later phase of local episodes of compression interspersed with extension. These phenomena resemble the subsidence nature of both rifted and strike-slip tectonic origin. None of the burial history curves show the basin was not formed as a typical foreland basin. This conclusion challenges earlier models for a subduction-related origin for the basin.

2) In most areas of the Sarawak Basin, the subsidence pattern is characterised by a high rate of subsidence, high β values plus local episodes of compression interspersed with extension. However, in some areas such as J411 and D411, the subsidence patterns agree with McKenzie's rift model.
3) The geothermal gradient of the Eastern Sub-Basin shows a linear relationship with the value of the stretching factor. The central part of the basin which was subjected to a higher stretching factor is characterised by a higher geothermal gradient than the area at the fringe of the basin in the north and south. However, the same relationship does not hold for the shallow basement area to the west. The relationship cannot be established for western part of the basin possibly because the geothermal gradient data from the area is limited.
4) The evaluation of stretching factors and heat-flow for the Sarawak Basin are consistent with the origin of a basin dominated by strike-slip tectonics.

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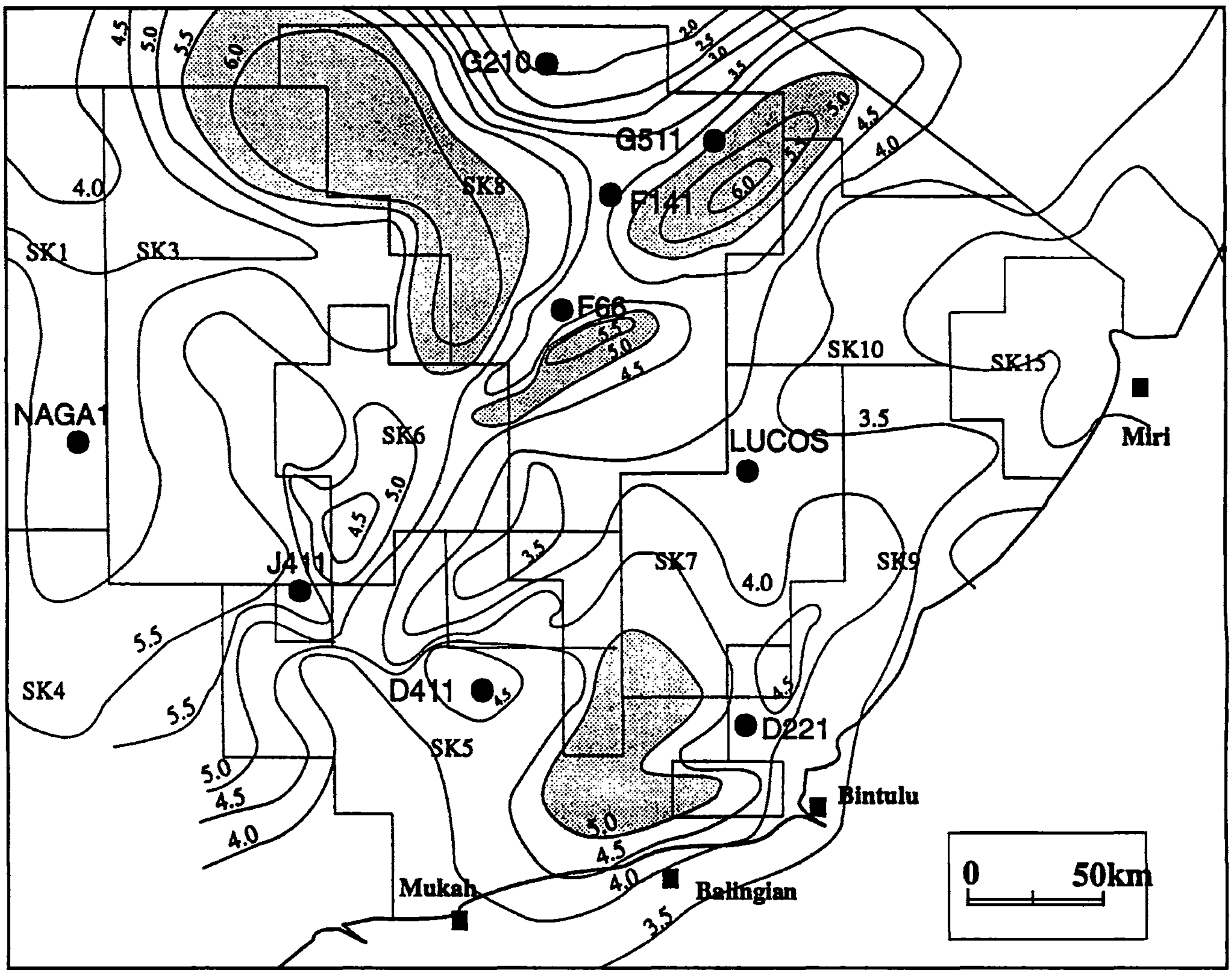

Figure 13. Geothermal gradient map of Sarawak Basin (after Wan Yussof, 1986) with contour interval of 0.50°C/100 m and the location of the wells used for BasinMod studies.

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