

Organic Geochemistry of Sediments in the Southwestern Coastal Plain, Taiwan

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ABSTRACT

Core samples collected from three research wells in the southwestern coastal plain, Taiwan, were analyzed for the total organic carbon content and biomarkers including n-alkanes, triterpanes, and steranes. The results reveal that the sediments are generally lean in organic matter and contain biomarkers derived from the sediments in the early mature stage. These organic characteristics imply that allochthonous reworked organic matter from the ancient sediments in the catchment area is the major organic matter in the southwestern coastal plain as a result of the high sedimentation rate, considerable surface runoff and poor fresh organic matter preservation. The biomarker parameters in the coastal plain show an unusual reverse maturation trend with depth, reflecting that the formations of less maturity level were eroded and re-deposited prior to the more mature formations buried deeper in the catchment area. As indicated by the biomarkers present in the coastal plain, the eroded formations in the catchment area were deposited in a shallow marine environment with a significant organic input of terrestrial higher plants and have been buried to reach the early mature stage.

Key words: organic geochemistry, biomarker, coastal plain, depositional environment

INTRODUCTION

The southwestern coastal plain of Taiwan is a typical lagoonal coastal plain with an altitude less than 50 meters and covered by alluvial deposits derived from eastern foothills area through fluvial transportation. Regional geological studies reveal that the sedimentation rate since the

Pliocene is very high in this area. Three all-coring research wells, i.e. Sanliaowan (SLW), Tzaikang (TK) and Yichu (YC) well, were drilled in the coastal plain and were preliminarily studied for the depositional environment determination (Sung *et al.*, 1996). Oung *et al.* (1997) reported the n-alkane distribution and its geological significance in the Tzaikang core samples.

Organic geochemistry has expanded greatly in recent years. Biological markers (biomarkers), with their chemical structures unambiguously linked to the biological precursors, are studied and widely applied in organic geochemistry. Typical applications of the biomarker study include the characterization of source organic matter and depositional environment, and the assessment of maturity level and biodegradation extent. Further, the biomarker distributions in geological samples may also be used as a molecular 'fingerprint' for the purpose of correlation (Mackenzie, 1984; Philp, 1985).

In this study organic geochemical analyses including total organic carbon (TOC) and biomarker measurements were carried out on core samples recovered from SLW, TZ and YC wells to examine the characteristics of the organic matter and their geological significance in the southwestern coastal plain.

SAMPLES AND EXPERIMENTAL METHODS

Samples

Figure 1 shows the map of the southwestern coastal plain and the location of three wells analyzed in this study. The lithology columns of these wells are shown in Figure 2. Alluvial deposits of clay, silt, and fine-grained sand cover extensively the coastal plain. The exposed formations in the upstream area of the rivers in this plain are of Plio-Pleistocene in age. Sediments washed into the plain are mainly fine-grained clastics, making the alluvium mainly of clay and silt. Foraminifer and mollusk fossils have been found in many intervals of these wells and were used to reveal the depositional environments (Sung *et al.*, 1996). Age determinations based on ^{14}C measurement have been carried out and shown in Figure 2. Figure 3 shows the burial history diagrams of the wells studied. As shown in these diagrams, the sedimentation rate calculated for the last 10,000 years in this area is very high.

Experimental methods

Selected core samples were collected and transported to the laboratory immediately after recovery and stored in a freezer prior to the analyses. Organic geochemical analyses including the total organic carbon content and biomarker determination were carried out by using a TOC analyzer and gas chromatography-mass spectrometry (GC-MS), respectively. Experimental procedures are described in Oung *et al.* (1997) in detail.

RESULTS AND DISCUSSION

Total organic carbon content

Figure 4 shows TOC distribution of the wells studied. It reveals that the sediments in the coastal plain are generally lean in organic matter, with the exception of several samples containing visible carbonaceous matter and showing TOC values higher than 1%. The mean TOC content in the Sanliaowan well is 0.39%; Tzaikang well, 0.26%; and Yichu well, 0.32%.

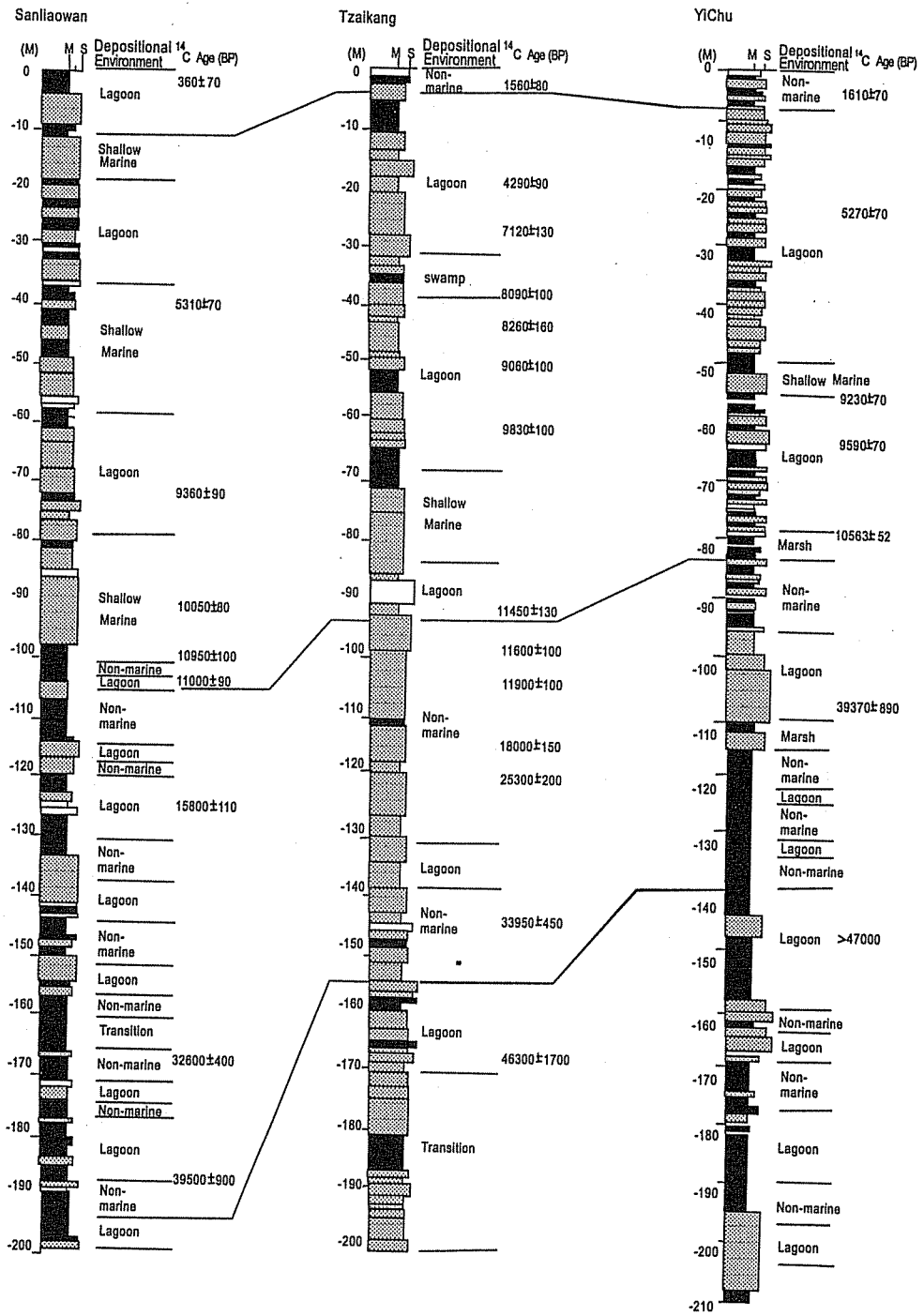


Figure 1. Map of the southwestern coastal plain showing the location of three wells studied.

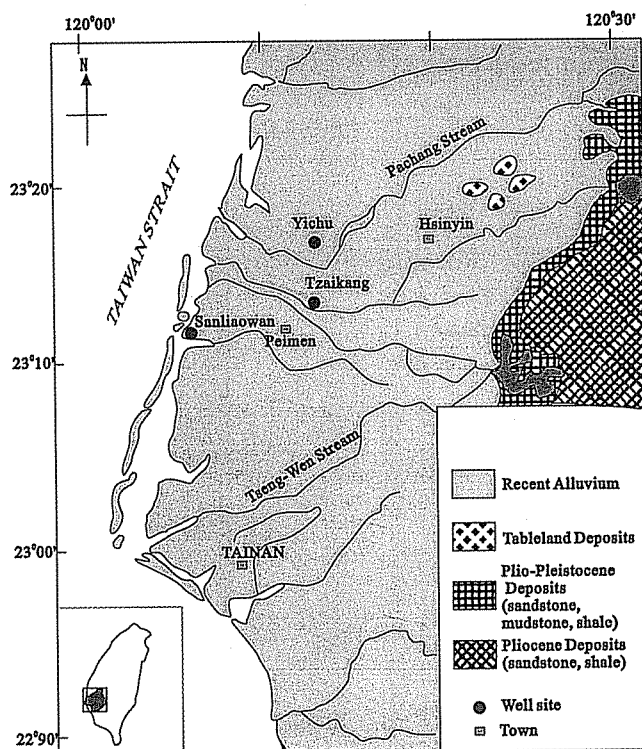


Figure 2. Lithology columns of the wells studied, age determinations based on ^{14}C dating are also shown.

The organic content of Recent sediments can be attributed to three factors: the primary biological productivity, preservation rate of organic matter and rate of organic deposition versus mineral deposition (Tissot and Welte, 1984). The reasons for such low organic matter contents in the coastal plain are probably the dilution effect caused by the high sedimentation rate and the poor preservation of the fresh organic matter. In the high-energy parts of coastal areas, where primary productivity is adequate but where strong currents and the high oxygen content of the waters intensifies, both biological and chemical degradation of the organic matter is considerable. The organic matter in the coastal plain is therefore very lean and believed to be mainly reworked organic matter derived from the original sediments in the foothills area.

Figure 5 shows the relationship between TOC value and grain size of the sediments in the Tzai kang well. The organic carbon content increases with a decrease in sediment grain size. Clays and silts with a median diameter of less than $50\mu\text{m}$ have a TOC content higher than 0.2%. Fine-grained sands with grain size higher than $50\mu\text{m}$ usually have TOC content less than 0.2%, indicating that organic matter content generally increases from the high-energy to low-energy sediments (sands to muds).

Biomarker distribution

n-Alkane

M/z 99 fragmentogram in Figure 6 shows a typical n-alkane distribution of the sediments in the coastal plain. The n-alkanes with carbon numbers ranging from 15 through 35 are the dominant hydrocarbons in the sediments. In most samples, the n-alkanes are superimposed on

a distinct unresolved complex mixture (UCM) of branched and cyclic hydrocarbons in the range between $n\text{-C}_{16}$ and $n\text{-C}_{27}$. The UCM is believed to be the products of secondary processes, e.g., weathering, water washing and biodegradation occurred during the erosion, transportation and re-sedimentation, on the hydrocarbons originally present in the reworked sediments.

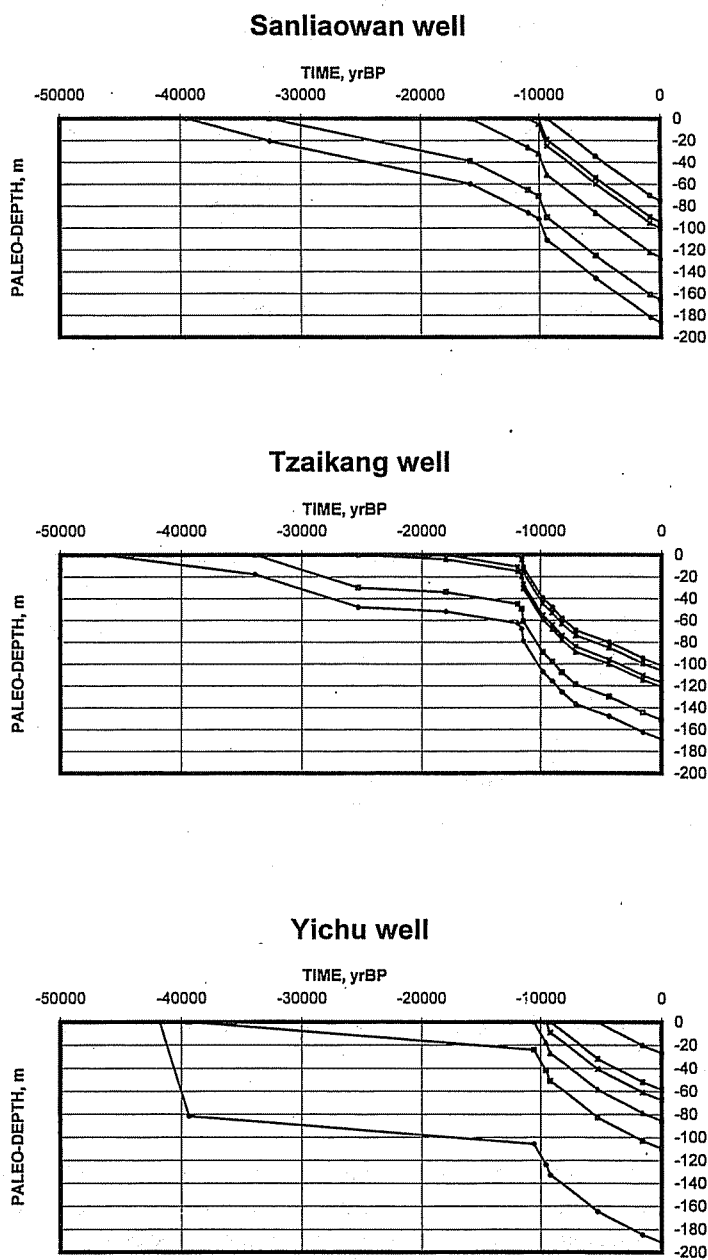


Figure 3. Burial history diagrams of the wells studied.

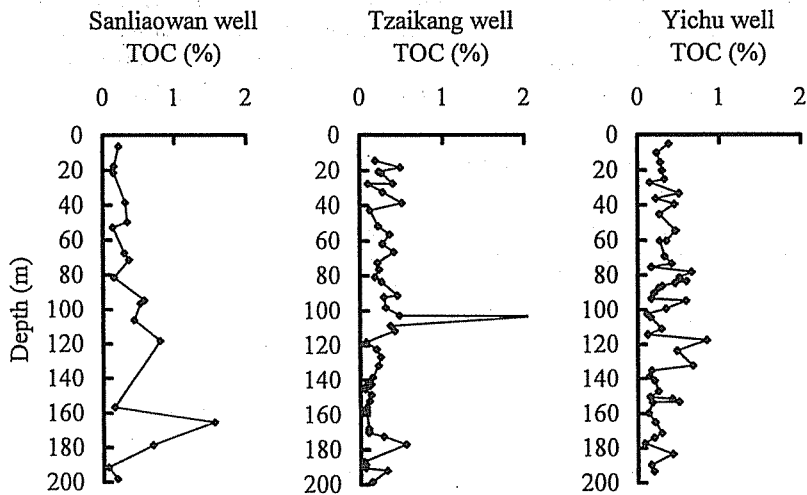


Figure 4. TOC content of the wells studied.

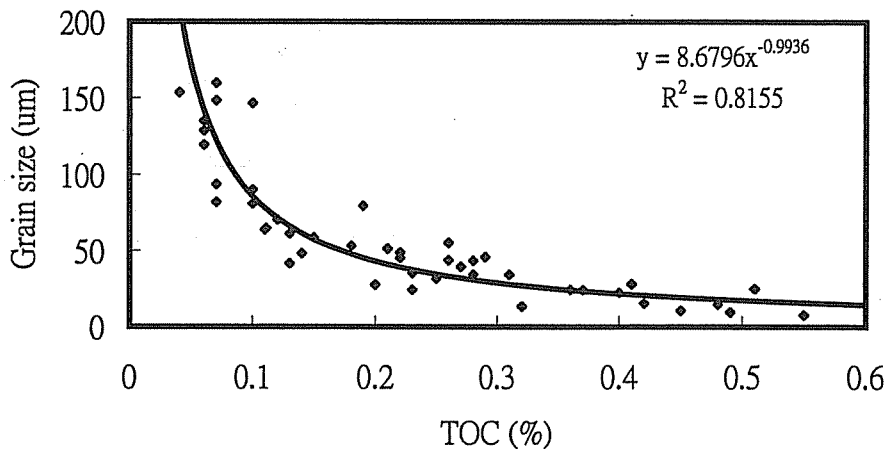


Figure 5. Cross plot diagram of TOC content versus sediment grain size of the core samples from Tzaikang well.

As shown in Figure 6, three n-alkane series, i.e., n-C₁₄~n-C₂₀, n-C₂₀~n-C₂₆, and n-C₂₅~n-C₃₅ are present in the sediments. The n-alkane distributions have been used to indicate the organic sources, depositional environments and secondary processes for the Tzaikang well (Oung *et al.*, 1997). Generally speaking, the n-C₁₄~n-C₂₀ alkane series is related to the mature hydrocarbons or an organic source of microorganisms and/or algae. The n-C₂₀~n-C₂₆ alkane

series, with a maximum at $n\text{-C}_{22}\sim n\text{-C}_{23}$ and without an odd-to-even predominance is ubiquitous in most samples in the southwestern coastal plain. It is believed that this series is indicative of mature hydrocarbons originally occurred in the reworked sediments. The $n\text{-C}_{25}\sim n\text{-C}_{35}$ alkane series with a predominance of odd-numbered carbon indicates a source of terrigenous higher plants. Relative abundance of these three n -alkane series in the wells studied is shown in Figure 7. Samples from various wells and depths show distinct variation in the n -alkane distribution. This variation reflects mainly the effects of secondary processes and only partially the depositional environments.

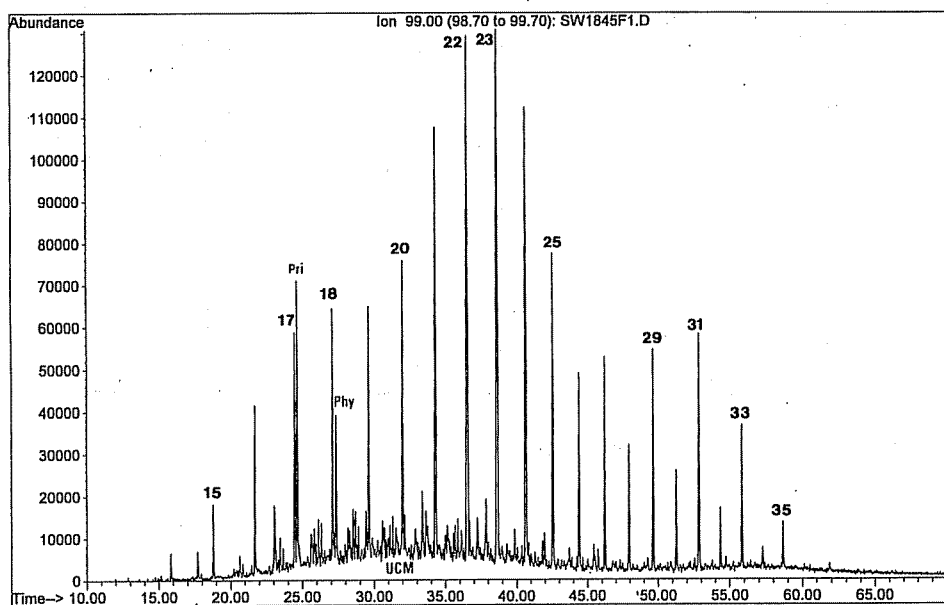


Figure 6. M/z 99 fragmentogram showing the typical n -alkane distribution of the sediments in the southwestern coastal plain. Carbon numbers of n -alkanes are indicated, pri: pristane, phy: phytane.

The predominance of n -alkanes with odd carbon numbers can be measured by the "carbon preference index, CPI", i.e., the ratio, by weight, of odd to even molecules. Bray and Evans (1961) originally proposed CPI to evaluate the maturity level of sediments. The Recent sediments containing terrestrial higher plant organic matter always show a strong predominance of odd carbon atoms and a high CPI value in the long-chain n -alkane range ($\text{C}_{25}\sim\text{C}_{33}$). The odd predominance of n -alkanes disappears with the maturity increasing and CPI value is getting close to 1. Figure 8 shows CPI values of wells in the southwestern coastal plain. The CPI values show variations downcore and are generally less than 4, much smaller than what is expected for the Recent sediments. It is believed that these n -alkanes are mainly derived from reworked rocks which is in the early mature stage.

The n -alkane distributions indicate that hydrocarbons present in the sediments in the southwestern coastal plain are mainly derived from reworked rocks containing terrestrial organic matters and in the early mature stage.

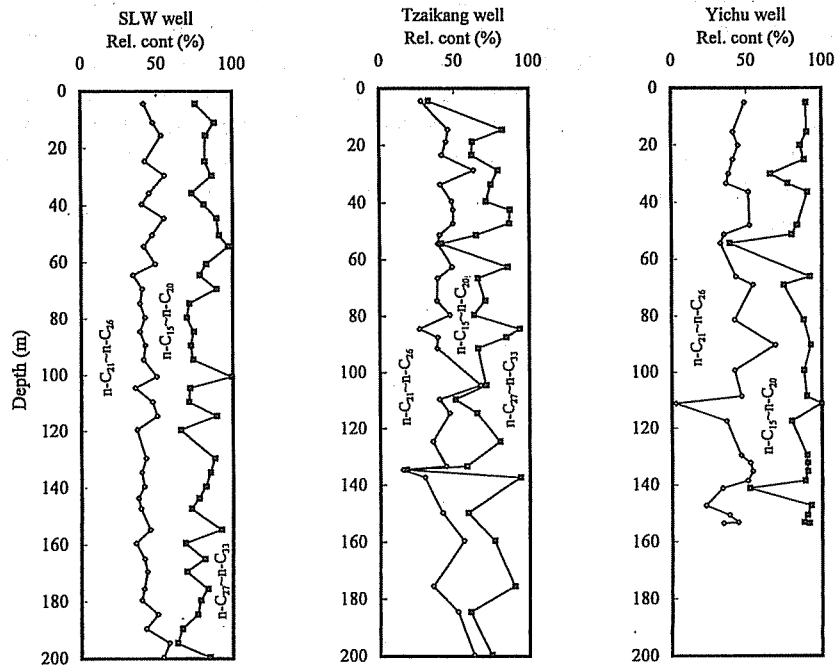


Figure 7. n-Alkane composition in the wells studied.

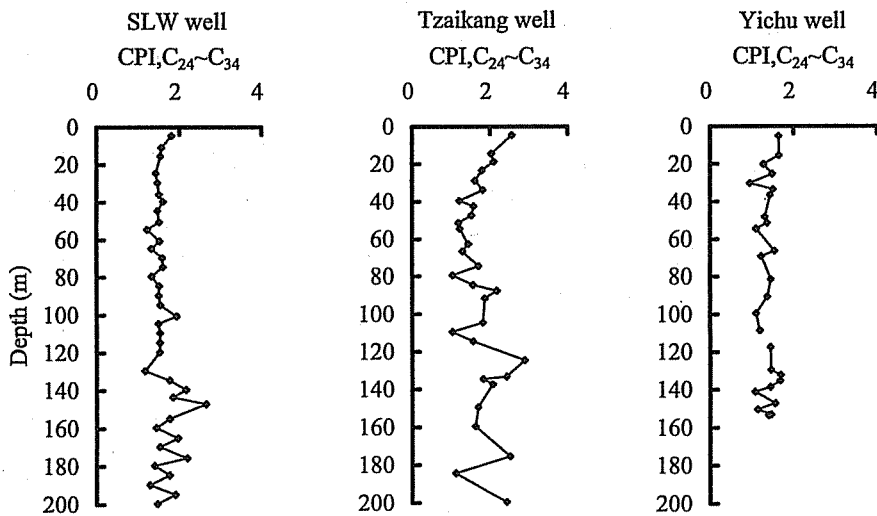


Figure 8. CPI versus depth for wells studied.

Figure 8.

Terpenoids and steranes

Terpenoids and steranes are two important classes of biomarker in organic geochemistry. In this study, pentacyclic triterpenoids and steranes are surveyed. Compared to the n-alkane distribution, which shows significant variations, both triterpenoid and sterane distributions of various samples in the southwestern coastal plain are more consistent, indicating that these compounds are more resistant to the secondary processes, e.g., weathering, water washing and biodegradation occurred during the sediment transportation and re-deposition.

Terpenoids

M/z 191 fragmentogram in Figure 9 shows the typical triterpenoid distribution of the sediments in the southwestern coastal plain. The triterpenoids include saturated hopanes and non-hopanes, and unsaturated triterpenes. Peak identifications are listed in Table 1. The hopane series with carbon numbers ranging from 27 to 32 is the most dominant triterpenoids.

Hopane-type triterpanes are ubiquitous pentacyclic triterpanes in ancient sediments. Their precursors, diploptene and C₃₅ tetrahydroxylhopane, are widely distributed among bacteria and cyanobacteria (blue-green algae), tropical trees, some grasses, lichens and several ferns (Ourisson *et al.*, 1979). The naturally occurring precursor compounds have specific biological stereochemical characteristics and configurations. With the maturation increases, isomerization of the precursor occurs. The extent of nuclear and side-chain isomerization at various chiral centers within the molecule therefore has been widely used to assess organic maturity level of the sediments (Seifert and Moldowan, 1978; Mackenzie *et al.*, 1980).

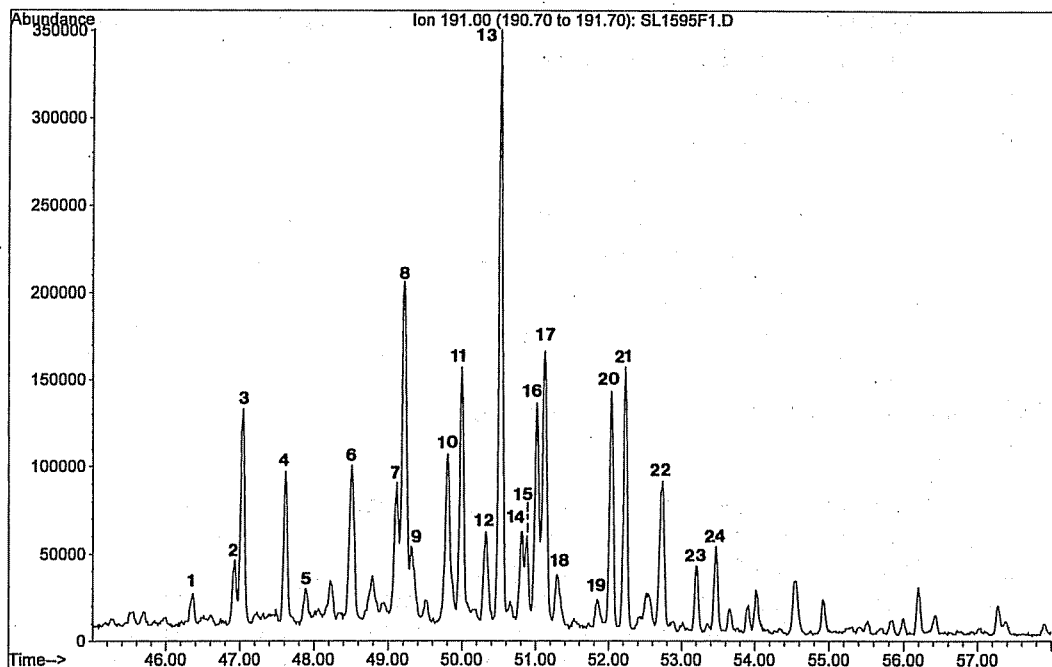


Figure 9. M/z 191 fragmentogram showing the typical triterpenoid distribution of the sediments in the southwestern coastal plain. Peak identifications are listed in Table 1.

Table 1. Assignments of the triterpenoids in the m/z 191 fragmentogram.

Peak No.*	Compound	Formula	Molecular weight
1	18 α (H)-22,29,30-Trisnorneohopane (Ts)	C ₂₇ H ₄₆	370
2	22,29,30-Trisnorhop-17(21)-ene	C ₂₇ H ₄₄	368
3	17 α (H)-22,29,30-Trisnorhopane (Tm)	C ₂₇ H ₄₆	370
4	17 β (H)-22,29,30-Trisnorhopane	C ₂₇ H ₄₆	370
5	Unknown pentacyclic triterpene	C ₃₀ H ₅₀	410
6	17 α (H),18 α (H),21 β (H)-28,30-Bisnorhopane	C ₂₈ H ₄₈	384
7	Unknown pentacyclic triterpene	C ₃₀ H ₅₀	410
8	17 α (H),21 β (H)-30-Norhopane	C ₂₉ H ₅₀	398
9	18 α (H)-30-Norneohopane (C ₂₉ Ts)	C ₂₉ H ₅₀	398
10	Hop-17(21)-ene	C ₃₀ H ₅₀	410
11	17 β (H),21 α (H)-30-Norhopane (Normoretane)	C ₂₉ H ₅₀	398
12	18 α (H)-Oleanane	C ₃₀ H ₅₂	412
13	17 α (H),21 β (H)-Hopane	C ₃₀ H ₅₂	412
14	Hop-13(18)-ene	C ₃₀ H ₅₀	410
15	Unknown C ₂₉ pentacyclic triterpene	C ₂₉ H ₅₀	398
16	Hop-22(29)-ene	C ₃₀ H ₅₀	410
17	17 β (H),21 α (H)-Hopane (Moretane)	C ₃₀ H ₅₂	412
18	Unknown pentacyclic triterpene	C ₃₀ H ₅₀	410
19	Unknown C ₃₀ pentacyclic triterpene	C ₃₀ H ₅₂	412
20	17 α (H),21 β (H)-Homohopane (22S)	C ₃₁ H ₅₄	426
21	17 α (H),21 β (H)-Homohopane (22R)	C ₃₁ H ₅₄	426
22	17 β (H),21 α (H)-Homohopane (Homomoretane)	C ₃₁ H ₅₄	426
23	17 α (H),21 β (H)-Bishomohopane (22S)	C ₃₂ H ₅₆	440
24	17 α (H),21 β (H)-Bishomohopane (22R)	C ₃₂ H ₅₆	440

* Peak No. refers to m/z 191 fragmentogram in Figure 9.

Several maturity parameters based on the hopanoid isomerization extent are investigated for the sediments in the southwestern coastal plain.

1. Ratio of 22S/(22S+22R) for the C₃₁ homohopanes

The biologically produced precursors for hopanes have the R configuration at the C-22 position (called 22R). The 22R compounds are gradually converted to a mixture of 22R and 22S diastereomers. Usually C₃₁- or C₃₂-homohopanes are used for calculations of the 22S/(22S+22R) ratio. The 22S/(22S+22R) ratio rises from 0 to about 0.6 (0.57 to 0.62 = equilibrium) during maturation. Sediments with the maturity level equivalent to Ro=0.6% show 22S/(22S+22R) ratios in the range 0.5 to 0.54 (Peters and Moldowan, 1993).

The ratios of 22S/(22S+22R) measured for C₃₁ 17 α (H),21 β (H)-homohopanes of the samples in the southwestern coastal plain are plotted in Figure 10. Most samples show this ratio in the range of 0.4~0.5, indicating that these hydrocarbons are derived from sediments in the early mature stage.

2. Ratio of $\beta\alpha$ -moretane/ $\alpha\beta$ -hopane

The naturally occurring precursors for the hopanoids have the 17 β (H),21 β (H) stereochemistry. This biological 17 β (H),21 β (H)-configuration (called $\beta\beta$) of hopanoids is very unstable and only present in the Recent sediments or very immature sediments. The $\beta\beta$ -hopanoids readily convert to $\beta\alpha$ -moretanes and $\alpha\beta$ -hopanes with the latter thermodynamically more stable than the former. The ratio of 17 β (H),21 α (H)-moretanes to their corresponding 17 α (H),21 β (H)-hopanes ($\beta\alpha$ -moretane/ $\alpha\beta$ -hopane) decreases with increasing thermal maturity. Usually this ratio decreases from about 0.8 in immature stage to values of less than 0.15 in mature stage and a minimum of 0.05 (Mackenzie *et al.*, 1980; Seifert and Moldowan, 1980).

The ratios of $\beta\alpha$ -moretane/ $\alpha\beta$ -hopane of the sediments in the coastal plain are plotted in Figure 10. Most samples show this ratio in the range of 0.2~0.6, indicating the early mature stage (equivalent to Ro=0.5%) for these biomarkers.

3. Ratio of Ts/(Ts+Tm)

The 17 α (H)-22,29,30-trisnorhopane (called Tm) and 18 α (H)-22,29,30-trisnorhopane (called Ts), two C₂₇ pentacyclic triterpanes, are often applied to assess the maturity level of sediments (Peters and Moldowan, 1993). The 17 α (H)-trisnorhopane (Tm) shows lower relative stability than 18 α (H)-trisnorhopane (Ts) during maturation (Seifert and Moldowan, 1978). Therefore, the ratio of Ts over Tm (Ts/Tm) or Ts/(Ts+Tm) is used as a maturity parameter. The larger the value of Ts/Tm or Ts/(Ts+Tm), the higher mature the sediments are in relation to other samples of a similar organic source.

The Ts/(Ts+Tm) ratios of the samples in the southwestern coastal plain are shown in Figure 10. Most samples show this ratio in the range of 0.1~0.4.

All these maturity parameters indicate that these hydrocarbons are derived from sediments in the early mature stage. As shown in Figure 10, the maturity level indicated by the maturity parameters decreases with increasing depth. This unusual reverse maturity trend will be discussed in the later section.

Among the hopanoid compounds, the presence of the C₂₈ bisnorhopane in the southwestern coastal plain is of interest. Bisnorhopane is a desmethylhopane which occurs as 17 α (H),18 α (H),21 β (H)-, 17 β (H),18 α (H),21 α (H)-, and 17 β (H),18 α (H),21 β (H)-epimers. High concentration of bisnorhopane has been used as an indication of an anoxic depositional environment (Mello *et al.*, 1990) or organic matter derived from bacterial mats (Williams, 1984). The bisnorhopane is also used as a specific compound for correlation. In the southwestern coastal plain sediments, only the thermal stable 17 α (H),18 α (H),21 β (H)-28,30-bisnorhopane is detected. It is therefore believed that the bisnorhopane is derived from the reworked sediments transported from the upstern catchment area. Figure 11 shows the relative concentration of bisnorhopane, measured as bisnorhopane/hopane ratio, of the samples in the southwestern coastal plain. Most samples show this ratio in a narrow range around 0.2, indicating that the sediments in the southwestern coastal plain are all sourced from formations with a similar organic matter source and depositional environment.

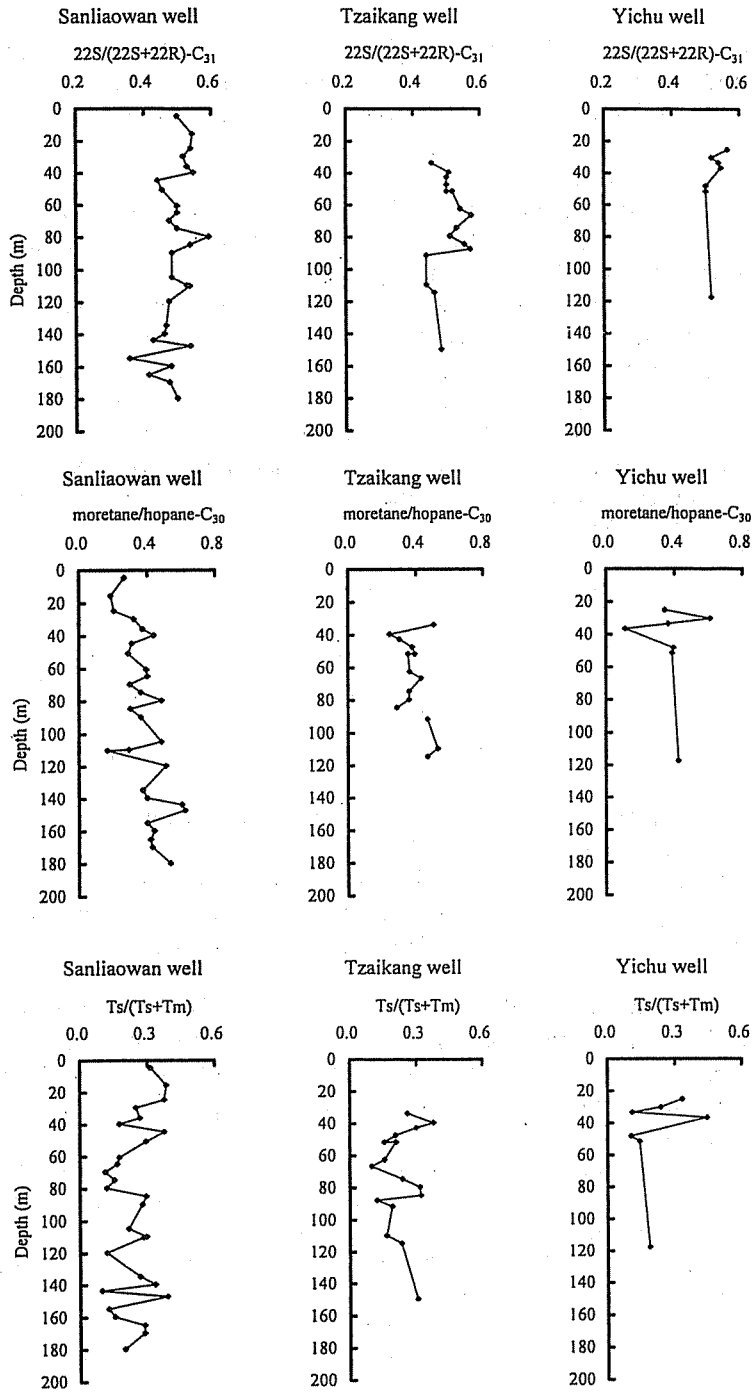


Figure 10. Hopanoids maturity parameters versus depth for wells studied.

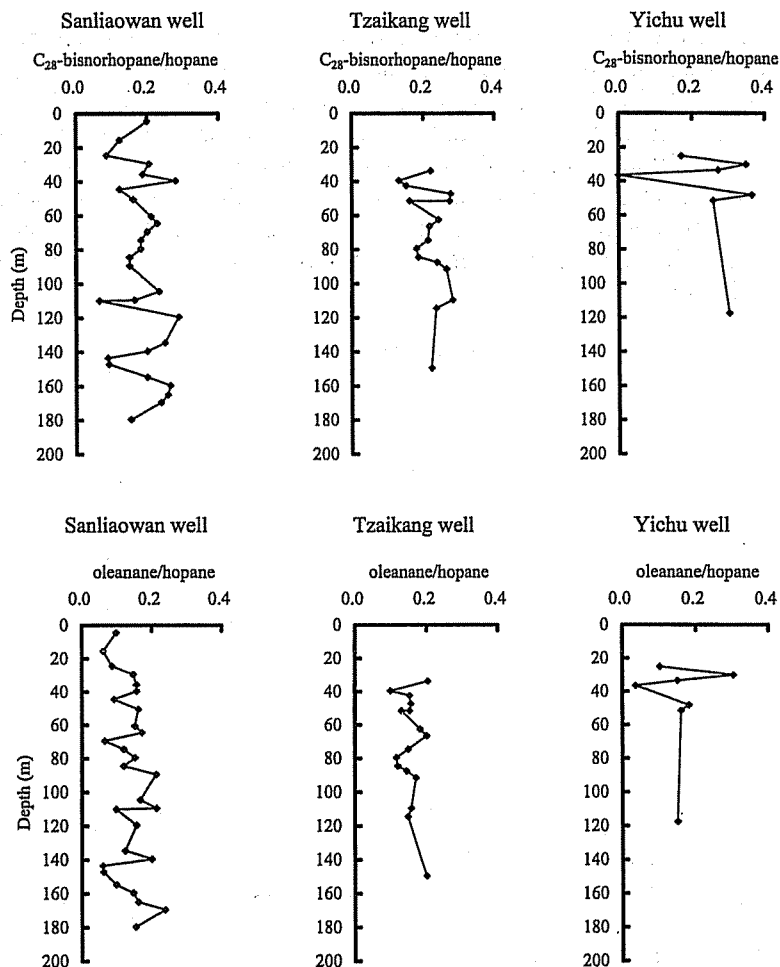


Figure 11. Ratios of C₂₈ bisnorhopane/hopane and oleanane/hopane versus depth for wells studied.

Oleanane, a non-hopane pentacyclic triterpane is present in sediments in the southwestern coastal plain. The oleanane is thought to be a Cretaceous or younger higher plant marker. Oleananes are probably derived from betulins (Grantham *et al.*, 1983) and other pentacyclic triterpenes in angiosperms (ten Haven and Rullkotter, 1988) and therefore the presence of oleanane suggests that the organic source is related to terrestrial higher plants of angiosperms (Philp and Gilbert, 1986). Two isomers, i.e., 18 α (H)- and 18 β (H)-oleanane are reported in the geological samples. The 18 β (H)-configuration is thermally less stable than the 18 α (H)-isomer. In the southwestern coastal plain, only the thermal stable 18 α (H)-oleanane is detected. This indicates that the oleanane is reworked. As shown in Figure 11, the oleanane index (measured as oleanane/hopane) of the sediments in the southwestern coastal plain is mainly in the range of 0.1~0.2, indicating that the organic inputs of the original sediments contain the terrestrial higher plants of angiosperms.

Steranes

Steranes are derived from sterols which are widely dispersed in plants and microorganisms, with the C_{27} and C_{28} sterols most abundant in marine organisms and C_{29} sterols in higher plants (Huang and Meinschein, 1979). Therefore high concentration of C_{29} steranes (24-ethylcholestanes) compared to the C_{27} - and C_{28} -steranes may indicate a land-plant source (e. g., Czochanska *et al.*, 1988). M/z 217 fragmentogram showing the typical sterane distribution of the sediments in the southwestern coastal plain is given in Figure 12. Peak identifications are listed in Table 2. The sterane distribution shows the presence of C_{27} - C_{29} steranes with the predominance of the C_{29} steranes, indicating terrigenous organic matter being the main organic source of the sediments.

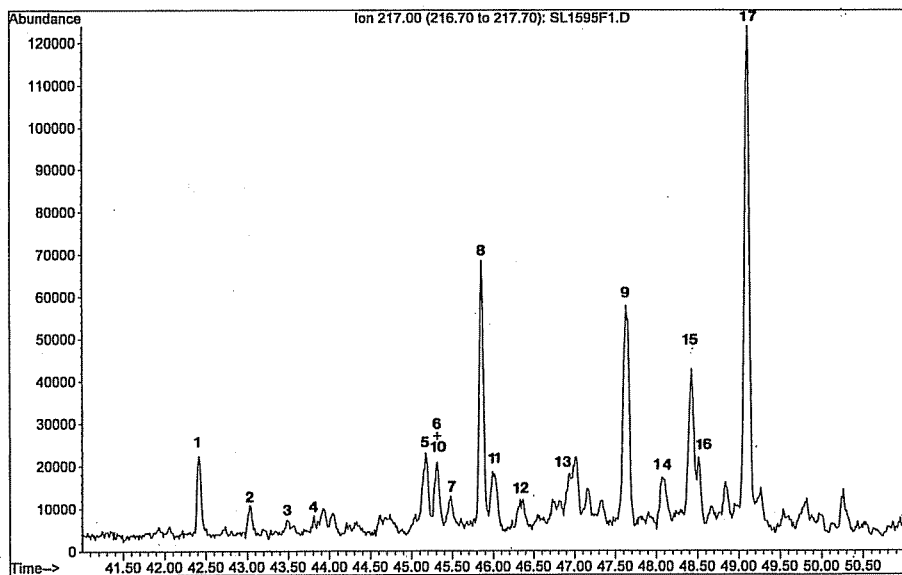


Figure 12. M/z 217 fragmentogram showing the typical sterane distribution of the sediments in the southwestern coastal plain. Peak identifications are listed in Table 2.

One major application of steranes in organic geochemistry is the maturity determination based on the thermal effects on the stereochemical complexity of their basic skeletons (Seifert and Moldowan, 1978 and 1981). Only the R configuration at C-20 (called 20R) is found in steroid precursors in living organisms, and it gradually converts during burial maturation to a mixture of the R and S sterane configurations. The extent of side-chain epimerization at C-20 ($20R=20R+20S$), measured as $20S/(20S+20R)$ for the $5\alpha(H),14\alpha(H),17\alpha(H)$ C_{29} -steranes, rises from 0 to about 0.5 (0.52 to 0.55=equilibrium, equivalent to $Ro=0.8\%$) with increasing maturity (Peters and Moldowan, 1993).

The ratios of $20S/(20S+20R)$ for the $5\alpha(H),14\alpha(H),17\alpha(H)$ C_{29} -steranes of the samples in the southwestern coastal plain are plotted in Figure 13. This ratio is in the range of 0.1~0.3 (around 0.2), indicating that the steranes are derived from sediments in the early mature stage equivalent to $Ro=0.5\%$.

Table 2. Assignments of the steranes in the m/z 217 fragmentogram.

Peak No.*	Compound	Formula	Molecular weight
1	13 β (H), 17 α (H)-diacholestane (20S)	C ₂₇ H ₄₈	372
2	13 β (H), 17 α (H)-diacholestane (20R)	C ₂₇ H ₄₈	372
3	13 α (H), 17 β (H)-diacholestane (20S)	C ₂₇ H ₄₈	372
4	13 α (H), 17 β (H)-diacholestane (20R)	C ₂₇ H ₄₈	372
5	14 α (H), 17 α (H)-cholestane (20S)	C ₂₇ H ₄₈	372
6	14 β (H), 17 β (H)-cholestane (20R)	C ₂₇ H ₄₈	372
7	14 β (H), 17 β (H)-cholestane (20S)	C ₂₇ H ₄₈	372
8	14 α (H), 17 α (H)-cholestane (20R)	C ₂₇ H ₄₈	372
9	24-methyl-14 α (H),17 α (H)-cholestane (20R)	C ₂₈ H ₅₀	386
10	24-ethyl-13 β (H),17 α (H)-diacholestane (20S)	C ₂₉ H ₅₂	400
11	24-ethyl-13 β (H),17 α (H)-diacholestane (20R)	C ₂₉ H ₅₂	400
12	24-ethyl-13 α (H),17 β (H)-diacholestane (20S)	C ₂₉ H ₅₂	400
13	24-ethyl-13 α (H),17 β (H)-diacholestane (20R)	C ₂₉ H ₅₂	400
14	24-ethyl-14 α (H),17 α (H)-cholestane (20S)	C ₂₉ H ₅₂	400
15	24-ethyl-14 β (H),17 β (H)-cholestane (20R)	C ₂₉ H ₅₂	400
16	24-ethyl-14 β (H),17 β (H)-cholestane (20S)	C ₂₉ H ₅₂	400
17	24-ethyl-14 α (H),17 α (H)-cholestane (20R)	C ₂₉ H ₅₂	400

* Peak No. refers to m/z 217 fragmentogram in Figure 12.

Geological significance of organic matter

The abundance and characteristics of organic matter in sediments are related to the depositional environment. The southwestern coastal plain is formed under deposition in the environment of marginal marine. The organic matter present in these sediments may be autochthonous to the environment where it is deposited, i.e., it originated in the water column above or within the sediment in which it is buried, or it may be allochthonous, i.e., foreign to its environment of deposition. Allochthonous material may include terrigenous organic matter, e. g., higher plant debris, and the reworked organic matter eroded from the ancient sediments and transported by rivers to the site of deposition (Gadel and Ragot, 1974). Due to the high sedimentation rate, considerable surface runoff and poor fresh organic matter preservation, reworked organic matter is often the main source of organic material in the southwestern coastal plain. The organic carbon content of the sediments is therefore very lean.

The biomarkers, including n-alkanes, pentacyclic terpenoids and steroids in the samples also show mature characteristics, indicating the presence of hydrocarbons derived from mature sedimentary rocks. The ancient sedimentary rocks in the upstream area, which were in the early mature stage and have been generating hydrocarbons, were eroded and transported by rivers and eventually re-deposited in the coastal plain. Correlations of triterpane and sterane

distributions between the samples in the coastal plain and the outcrops in the catchment area confirm their relationships. In the catchment area, the formations of less maturity level were eroded and re-deposited in the coastal plain prior to the more mature formations buried deeper. The biomarker parameters in the coastal plain therefore show an unusual reverse maturation trend with depth.

Geological and geochemical processes, e.g., water washing and biodegradation occurred during the transportation and re-deposition of the sediments, did alter the n-alkane distributions but not the pentacyclic terpenoid and steroid distributions in the reworked sediments. Therefore the terpenoid and steroid distributions can be used to reveal the organic source, depositional environments, and the maturity level of the eroded sediments in the catchment area. As indicated by these biomarker distributions, the eroded formations in the catchment area were deposited in a shallow marine environment with a significant organic input of terrestrial higher plants and have been buried to reach the early mature stage.

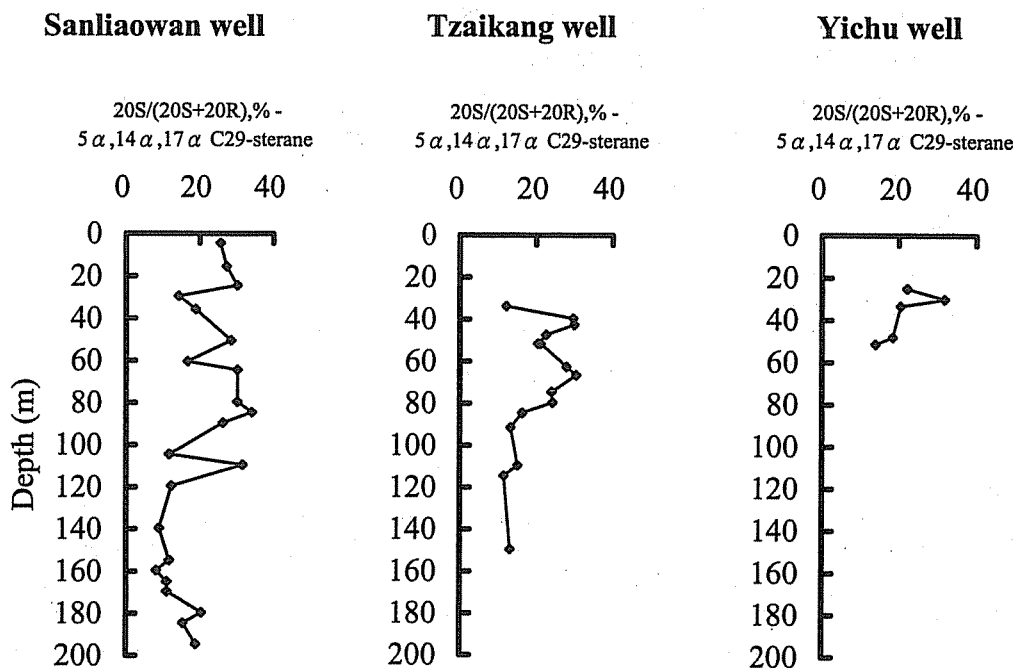


Figure 13. Ratios of C₂₉-sterane 20S/(20S+20R) versus depth for wells studied.

CONCLUSIONS

The sediments in the southwestern coastal plain are generally lean in organic matter and contain biomarkers derived from the sediments in the early mature stage. These characteristics imply that allochthonous reworked organic matter from the ancient sediments in the catchment area is the major organic matter in the coastal plain as a result of the high sedimentation rate, considerable surface runoff and poor fresh organic matter preservation.

The biomarker parameters in the coastal plain show an unusual reverse maturation trend with depth, reflecting that the formations of less maturity level were eroded and re-deposited prior to the more mature formations buried deeper in the catchment area.

As indicated by the biomarkers present in the southwestern coastal plain, the eroded formations in the catchment area were deposited in a shallow marine environment with a significant organic input of terrestrial higher plants and have been buried to reach the early mature stage.

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