Lower Tertiary Marine Microfossils from the Qiong Dong Nan Basin, South China Sea

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ABSTRACT

Microfossil age control developed for the Qiong Dong Nan Basin in the South China Sea has improved stratigraphic correlations by providing bracketing ages for subsurface formations and for distinct regional hiatuses. Dating the formations and unconformities shows a clear relationship of local transgressions and regressions to published global coastal onlap curves. Exploration wells in the basins penetrate a thick Upper Tertiary clastic sedimentary interval to test shallow marine clastic sediments surrounding the Upper Oligocene Lingshui III Formation gas sand.

Biostratigraphic ages for Lower Tertiary hydrocarbon exploration units were determined from intermittent occurrences of calcareous nannofossils and smaller benthonic foraminifera, very rare planktonic foraminifera, and the restricted occurrences of two distinctive shallow marine arenaceous foraminifera. The Lower Miocene Lingshui I Formation is characterised by the arenaceous foraminifer *Gaudryina pseudohayasakai* Chang (1960) whereas the Upper Oligocene Lingshui II and III Formations are characterised by *Gaudryina hayasakai* Chang (1954a). The Lingshui III and Yacheng Formations underlying the reservoir target have rare occurrences of Lower Oligocene to Upper Eocene nannofossils and marginal marine foraminifera.

INTRODUCTION

High-resolution biostratigraphy is a key technology by which seismic and sequence stratigraphers control and check their interpretations. The Haq *et al.* (1987, 1988) global coastal onlap curve shows 42 potential sequence boundaries during the Cenozoic. Due to low shelfal relief of many Late Tertiary offshore Southeast Asian basins, the Exxon "slug" model of sequence stratigraphy (Vail *et al.*, 1977) is difficult to apply to available geophysical datasets. Numerous discoveries of gas in Lower Tertiary marine sediments in the Southeast Asian region have prompted a reliance on biostratigraphy for age control, correlations across structures, and palaeo-environmental interpretation. We find that nannofossils yield the most reliable ages for marine sediments, whereas foraminifera provide the best evidence for depositional environments. Paly-nology is considered to have the most potential for non-marine units, but its development and application lag behind that of the marine fossil groups. The greatest difficulty in employing any of the microfossil groups in the South China Sea exploration area is that dating is complicated by severe down-hole contamination ("caving") in inadequately cased holes and the frequent use of a locally derived lignite drilling mud additive that is rich in Late Miocene palynomorphs.

Chronostratigraphy in the South China Sea shelf areas discussed here (Figure 1) is based on seismic and well studies in the Ying Ge Hai (YGN) and Qiong Dong Nan (QDN) Basins (Thompson & Abbott, 1995; Cucci *et al.*, 1997a, b). Micropalaeontologic studies undertaken for many years in Taiwan (see Huang, 1970) form an important body of work directly applicable to the area because of its close proximity. The first robust stratigraphy for the QDN area appears in the Chinese operational handbook "Tertiary Paleontology of North Continental Shelf of South China Sea" of which the foraminifera chapter is by Wang *et al.* (1981). An English version of the marine micropalaeontology of several Chinese basins was published by Wang (1985, 1990). More recently, Chen *et al.* (1993) published a seismic sequence stratigraphy for the QDN and Pearl River Basins which tied the sequences to the global coastal onlap curves of Haq *et al.* (1987). In this report, we use Berggren *et al.* (1996) time scale for correlation of time stratigraphic units.

Using biostratigraphic control, we have dated a long term period of subsidence during the development of the QDN Basin. The oldest sediments recovered in the uppermost Eocene to Lower Oligocene are dominantly nonmarine, with very shallow marine flooding events. Continued marine transgression in the Early and Middle Miocene gradually covered

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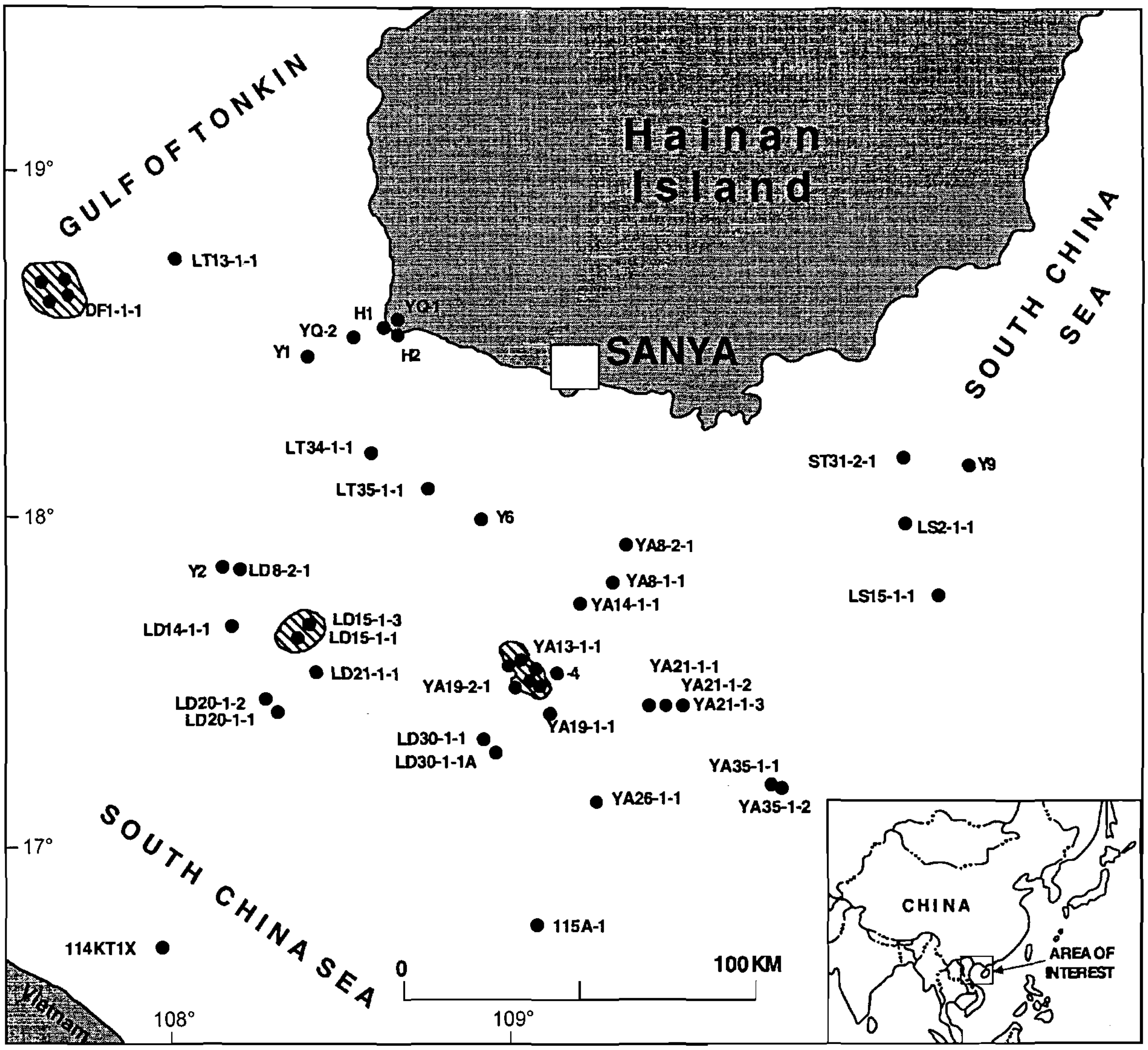

Figure 1. Location map of wells in the Ying Ge Hai Basin (southwest of Hainan Island) and Qiong Dong Nan Basin (south and southeast of Hainan Island). Inset map show the study area relative to the South China Sea region.

the nonmarine and shallow marine units with increasingly deeper marine units.

Stratigraphic Sequences

Although some Tertiary rocks outcrop on Hainan Island, most formations defined for the QDN and YGH Basins are limited to the subsurface. Subsurface formations have been described by Wang *et al.* (1985a), Wang (1990), and Chen *et al.* (1993). These are shown on Figure 2 with generalised lithologies. We use these formation names cautiously because the lithology varies considerably across the region. The origin of this lithological variability is a response to the long-term rifting of the South China Sea enhanced by the gradual marine flooding and the vast non-marine sediment contributions of numerous large rivers.

Study of seismic profiles and wireline logs had led to a correlation scheme known as T-horizons (see Chen *et al.*, 1993; Cucci *et al.*, 1997a, b). The variable lithologies present in the YGH and QDN Basins produce good seismic reflection profiles. Some of the reflector horizons are distinctive and persist throughout the area. Early ties of these key seismic horizons to well logs and biostratigraphy indicated that basic correlations were possible. Seismic stratigraphers working in the region have long employed a system of Tx nomenclature for the horizons, where 'x' is a number that increases downsection. For example, the seafloor horizon is T0 and pre-Tertiary igneous/metamorphic basement is T10; subdivision within major packages has the form Tx-x (e.g., T6-2) or less commonly T6.2. The key horizons are based on seismic reflection character that is then tied to the well logs. The most widely recognised horizon is T4 (top of Middle Miocene). Production in the Yacheng Field is from the Yacheng 13-1 Sand (Lingshui III Formation) below Late Oligocene Horizon T6-2 (Figure 2).

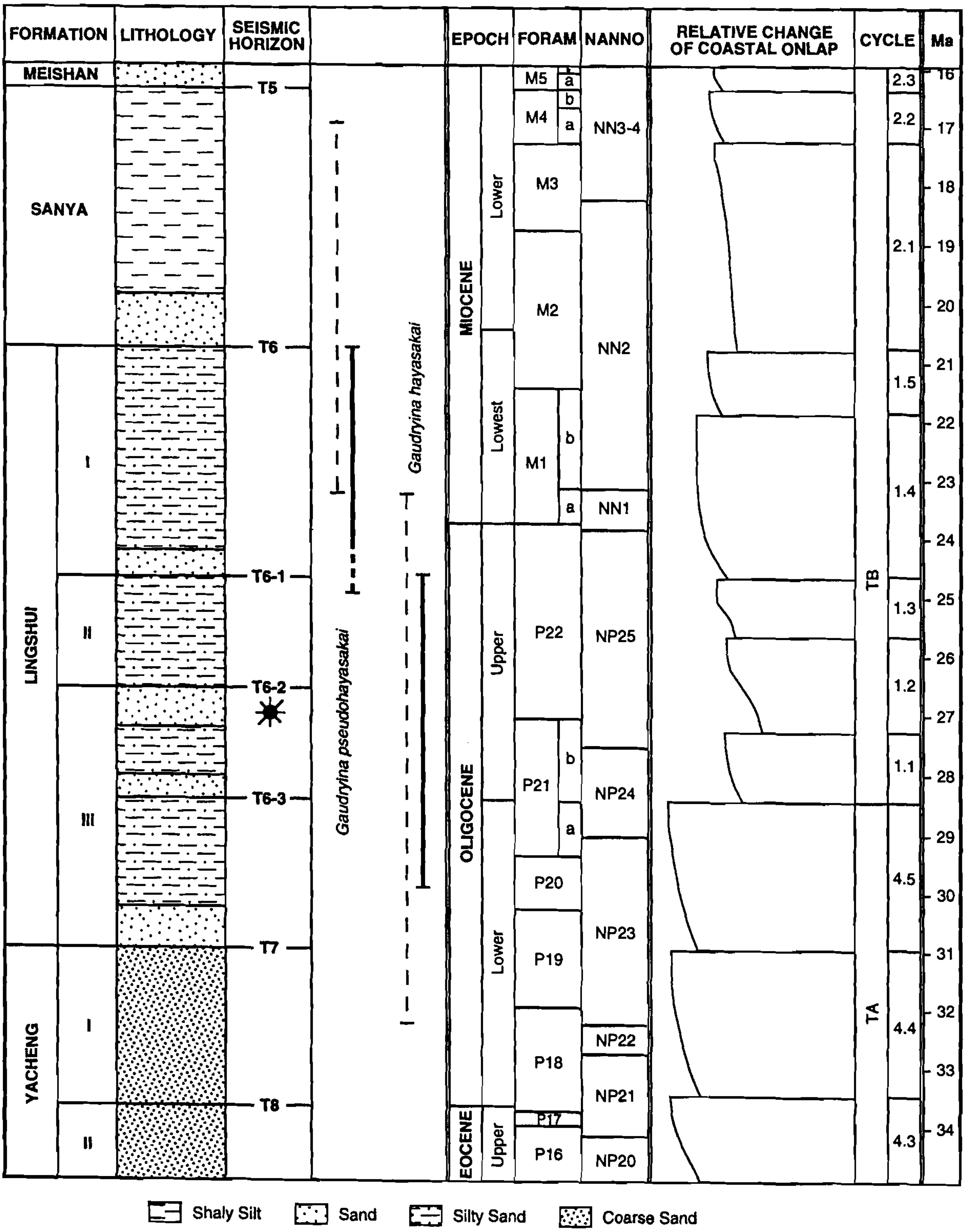

Figure 2. General stratigraphic section for the Lower Miocene to Upper Eocene of the Qiong Dong Nan Basin. Arrows mark the position of microfossil datums and their numerical ages in Ma. Chronostratigraphy is from Berggren *et al.* (1995) and the coastal onlap curve is from Haq *et al.* (1987, 1988) rescaled to the Berggren *et al.* (1995) chronostratigraphy. Dashed lines indicate ranges on Taiwan.

Syn-Rift Sediments

It is postulated that rifting commenced in the Eocene. As noted by Chen *et al.* (1993), the nature of the oldest pre-rift units is conjectural because a complete stratigraphic section for the syn-rift sediments has not been drilled. Localised depressions controlled by graben formation captured lacustrine sediments and alluvium. Exploration drilling has penetrated only the youngest portion of the continental lithofacies. Short lived marine transgressions introduced nearshore marine sediments to some areas. It is likely that the YGN Basin, located on the downthrown side of the No. 1 Fault, was flooded earlier than the QDN Basin. The marine incursion began in the Early Oligocene, but it did not reach wells in the Central Platform and locations near Hainan Island until the Early Miocene.

Post-Rift Sediments

Thermal subsidence replaced rifting during the Early Oligocene (Chen *et al.*, 1993). Evidence of this subsidence is the gradual changes in lithology, log character, and microfossil palaeobathymetry in the wells penetrating units of this age. From the Lower Oligocene upwards, there is a long term flooding of the area. The flooding is gradual until the Middle Miocene when the basin deepens more rapidly due to a change in regional tectonics. The basins reached maximum palaeobathymetry near the Miocene/Pliocene boundary. Massive progradation of clastics is characteristic of the Pliocene-Recent interval.

Chronostratigraphy

During the exploration program of the YGN and QDN Basins, we have examined over 2,600 foraminiferal samples and 4,600 nannofossil samples from 27 rotary wells (Figure 1). Biostratigraphic age of well samples is recognised through the succession of key microfossil tops (LADs) shown in Figure 2. Figures 3-5 show nannofossil and foraminifera distributions in three representative wells. The numerical ages in the literature are based on a direct calibration of the microfossil's ranges to palaeomagnetic chrono-stratigraphy in deep ocean cores and Deep Sea Drilling Project/Ocean Drilling Program boreholes. Application of these open ocean ages to occurrences in industry wells, however, has two major drawbacks. First, the clastic sediments are poorly lithified so that caved uphole material contaminates downhole cuttings samples. This caved material distorts the true ranges of the fossils, particularly at the base of their stratigraphic distribution. To minimise the uphole interference, we mainly use the first downhole occurrence of a fossil for biostratigraphy; bottom ranges (FADs) cannot normally be trusted. It is useful to know the depth of well casing points because these levels represent a minimum depth of uphole contamination.

Second, the relatively nearshore locations of our drilling sites means that low salinity coastal waters probably influenced the presence or absence of many species. We commonly find that our highest abundance of fossils coincide with the marine shales, suggesting marine transgressions. Low abundance or barren samples coincide with sand-rich lithologies, suggesting regressions. When we record the stratigraphic tops of fossil ranges, these often occur just prior to a regression. On these evidences, we are able to evaluate whether the fossil top has the same chrono-stratigraphic age as that published for the open ocean extinction for the taxon. We do find a remarkable coincidence of datable marine flooding events and undatable regressions with those depicted on global coastal onlap curves. It is useful to employ the onlap stratigraphy as a supplement to our local bio-stratigraphic succession.

Microfossil studies reported here are limited to foraminifera and calcareous nannofossils. We have compared the results carefully for all wells and find that the nannofossils correlate more often than do the foraminifera. This appears to be the result of the nearshore palaeoecology during the middle Tertiary which excluded key planktonic foraminiferal taxa or severely shortened their ranges. Although benthonic foraminifera flourished in these environments, they have limited chronostratigraphic value. Thus, we have found it useful to follow the lead of the Taiwanese micropalaeontologists who first define relative stratigraphic units on the basic of benthonic foraminifera, and then slowly revised the ranges using planktonic foraminifera (e.g., Huang & Cheng, 1983) and calcareous nannofossils (e.g., Huang, 1976, 1977, 1978, 1979) (see Figure 6).

Early Miocene

Three potential sequence boundaries (TB2.2, 2.3, 2.4) of Haq *et al.* (1987, 1988) exist near the Early Miocene-Middle Miocene boundary. Although detailed global biostratigraphic zonations can be applied to wells of the region, we are commonly unable to distinguish which of these sequence boundaries is present at the top of the Lower Miocene Sanya Formation (horizon T5). Biostratigraphic dating indicates that it is probably the base of the TB 2.3 cycle (16.4 Ma). The nannofossils *Cyclicargolithus floridanus* (LAD=16.2 Ma), *Helicosphaera ampliaperta* (LAD=16.2 Ma), and *Sphenolithus belemnos* (LAD=17.4 Ma) are reliable markers for the upper part of the Lower Miocene. Rare specimens of the planktonic foraminifera *Praeorbulina circularis* (LAD=15.0 Ma), *P. glomerosa* (LAD=15.2 Ma), *Globigerinatella insueta* (LAD=15.0 Ma), and *Catapsydrax dissimilis* (LAD=17.3 Ma) have been observed in wells where the Lower Miocene is present. In other wells, a much younger section disconformably overlies older units.

The top of the Lingshui I Formation (horizon T6) is delineated by the Lower Miocene TB 2.1 sequence boundary (20.8 Ma) with the nannofossils *Triquetrorhabdulus carinatus* (LAD=19.8 Ma), *S. dissimilis* (LAD=21.5 Ma), *Sphenolithus conicus* (LAD=22.9 Ma) and *Discoaster druggi* (FAD= 23.2 Ma). The distinctive agglutinated benthonic foraminifer *Gaudryina pseudohayasakai* occurs only in the uppermost part of the Lingshui I Formation.

Late Oligocene

Although the Oligocene/Miocene boundary is clearly defined elsewhere on the globe, it is a

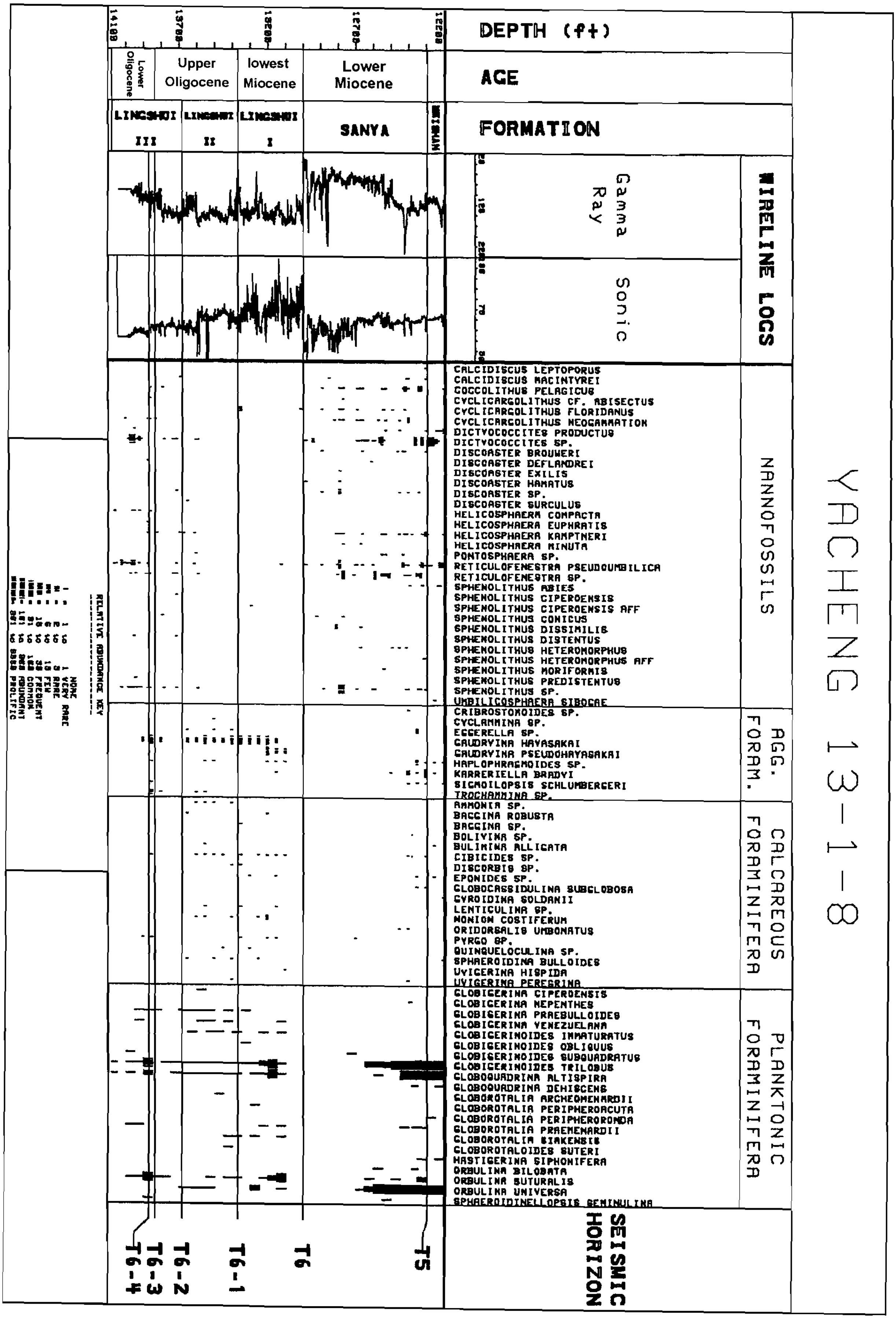

Figure 3. Microfossil distribution in Yacheng 13-1-8 well between 12,200′ – 14,100′ (TD) relative to wireline logs, and interpreted seismic horizons, formations, and ages.

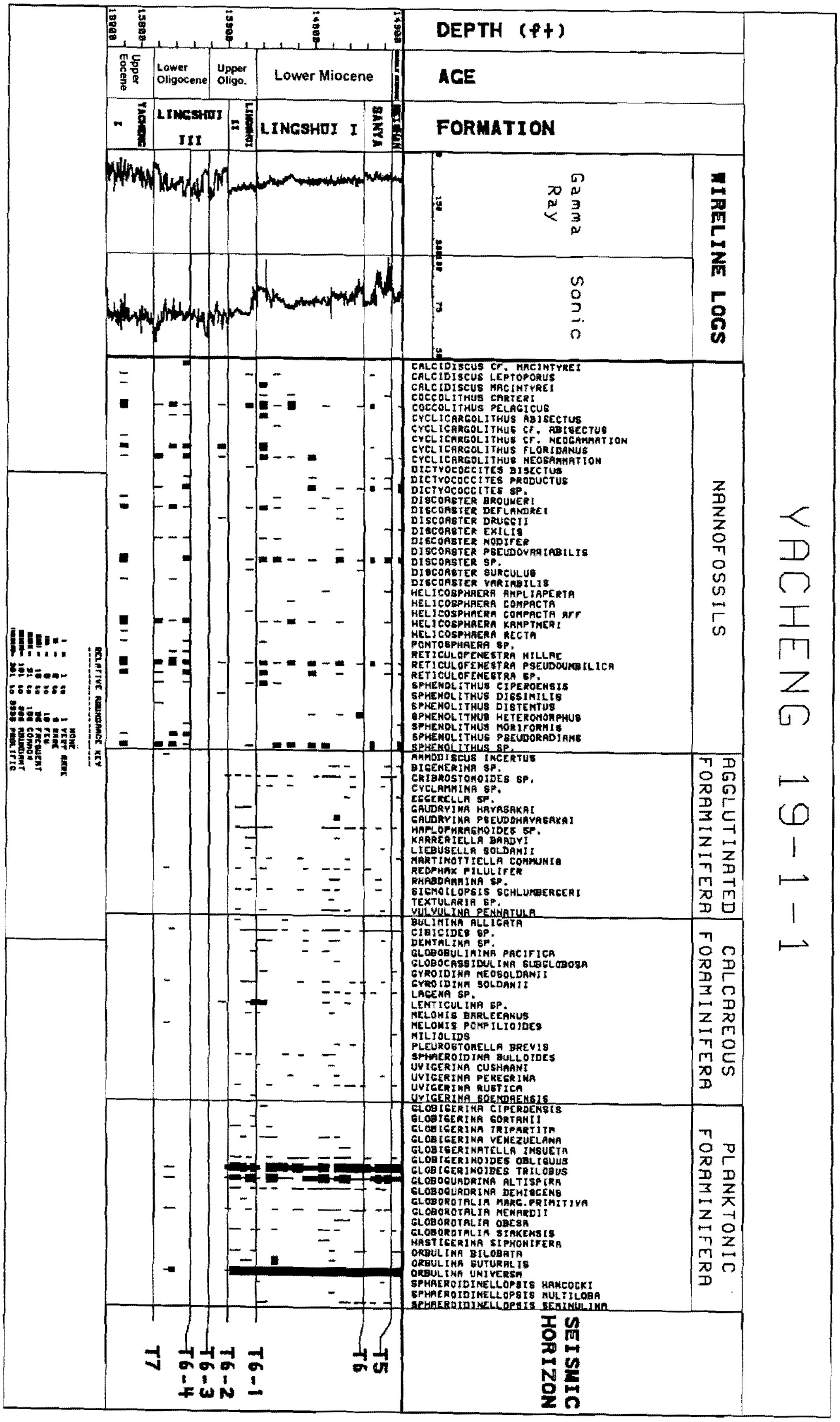

Figure 4. Microfossil distribution in Yacheng 19-1-1 well between 14,300' – 16,000' relative to wireline logs, and interpreted seismic horizons, formations, and ages.

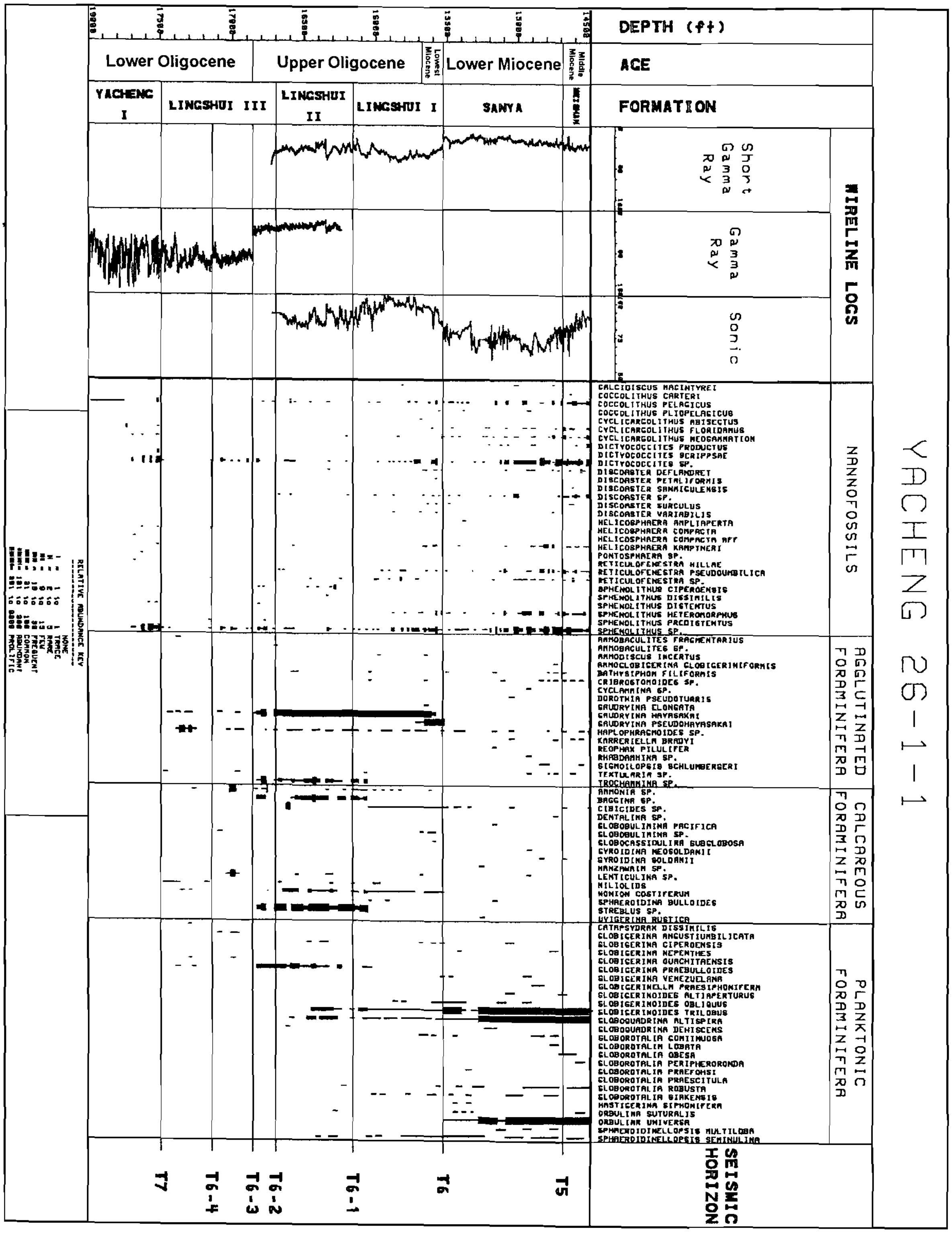

Figure 5. Microfossil distribution in Yacheng 26-1-1 well between 14,500′ – 18,000′ relative to wireline logs, and interpreted seismic horizons, formations, and ages.

difficult boundary to locate in many Southeast Asia wells and sections because the standard defining/bracketing microfossils are usually absent and several depositional sequence boundaries commonly merge on the structural highs commonly chosen for drilling. We recognise the Oligo/Miocene (23.8 Ma) and the TB1.4 (horizon T6-1) sequence boundary (24.6 Ma) with the nannofossils *Helicosphaera recta* (LAD=23.5 Ma), *Cyclicargolithus abisectus* (LAD=23.7 Ma), *Sphenolithus delphix* (LAD=23.8 Ma), *Zygrhabdolithus bijugatus* (LAD=24.5 Ma), and *Sphenolithus ciperoensis* (LAD=25.2 Ma). Foraminiferal events associated with the base of the Miocene include the initial appearances of the major genera *Globigerinoides*, *Globoquadrina*, and *Sphaeroidinellopsis*. In downdip wells, we find the tops of *Globigerina ouachitaensis* and *G. ciperoensis* (LAD=25.2 Ma). The distinctive agglutinated benthonic foraminifer *Gaudryina hayasakai* appears to be characteristic of the Upper Oligocene in the QDN Basin, and ranges nearly as high as *S. dissimilis*.

In the Yacheng Field of the QDN Basin, the Yacheng 13-1 Sand of the Lingshui III Formation is a major gas exploration target. Core and cuttings indicate that this reservoir sand interval is a coastal lithofacies association and may be comprised of two sand-rich units of which the upper has greater porosity. Although easily recognisable by an abundance of coarse sand and lignite, the Yacheng 13-1 Sand is barren of fossils. From our biostratigraphic bracketing, we feel that the top of the unit represents the transgression (horizon T6-2 at about 26.6 Ma) over lowstands of TB1.2 sequence boundary (27.3 Ma). In some downdip wells, a weakly fossiliferous section is present between the sands. The lower contact of the Yacheng 13-1 Sand interval is a change from fossil-barren sand above to fossiliferous silt below. We suggest that the base represents the TB 1.1 sequence boundary (28. 5 Ma).

Early Oligocene

The TB 1.1 global sequence boundary (locally, horizon T6-3) at about 28.5 Ma is prominent in marine basins around the world. Because of the perceived shift in coastal onlap, Vail *et al.* (1977, p. 89) used this point ("30 Ma") as their lowest position of sea level drop. The calcareous nannofossils *Sphenolithus distentus* (LAD=28.2 Ma), *S. predistentus* (LAD= 28.4 Ma), *Zygrhabdolithus bijuga*tus (LAD= 29.7 Ma), and *Helicosphaera compacta* (LAD=30.2 Ma) occur occasionally in the Lingshui III Formation. We find a thin shaley unit in the Lingshui III interval below the Yacheng 13-1 Sand. The calcareous nannofossil *H. compacta* appears to be a reliable top providing age control but is generally stunted or close to half its normal size. It is often associated with very small *Sphenolithus* spp. Benthonic foraminifera recovered include rare small *Ammonia*, *Florilus*, *Trochammina*, and, in basinward wells, *G. hayasakai*. These floral and faunal assemblages represent very shallow marine, estuarine, or brackish environments, and perhaps low salinity conditions. The break is below, but close in time to, the TB1.1 sequence boundary (28.4 Ma) and we are using it to delineate the 30.1 Ma flooding event in the area.

Eocene and older

Eocene or older units are rarely reached by drilling in southeast Asian basins. That period is best represented in the non-marine section of the Bohai Basin and strata uplifted in continental blocks, such as the Chilteh section in western Java and the fluvial-deltaic redbeds in southwest Sulawesi. Lithologies range from igneous and metamorphic rocks to volcanics to non-marine, lacustrine, and marginally marine rocks, to fully deep marine clastics. In the Bohai Basin, Sulawesi, and other basins, this interval is considered the time of initiation of source rock deposition within the lacustrine settings. Where drilled in the Qiong Dong Nan Basin, basement is granitic with an overlying interval of weathered granite.

Regional extension in the region was responsible for the formation of many of the non-marine basins and operated during the Early Tertiary following a major Late Cretaceous collision event, the collision of the Indian craton and other microcontinental blocks with Eurasia. Nearly all basins exhibit intensely deformed Mesozoic or older strata overlain by Eocene or Oligocene strata, often with angular truncation, indicating a substantial period of deformation and exhumation associated with this collision.

We observe a pronounced marine transgression of the shallow marine Lingshui III Formation over the non-marine Yacheng Formation of the Yacheng Field at horizon T7. Most samples from the QDN Basin have only poorly dated palynomorphs from the Yacheng Formations below the Lingshui II Formation. We observe a distinctive change in the character of the gamma and sonic logs to a distinctly 'ratty' pattern quite different from that above. In several wells, we found isolated occurrences of the Upper Eocene to Lowest Oligocene nannofossils *Reticulofenestra davisi*, *R. scissura* (LAD=31.0), *R. hillae* (LAD=34.5 Ma), *R. umbilica* (LAD=32.3 Ma), *Ericsonia formosa* (LAD=32.8 Ma), *E. subdisticha*, *Helicosphaera wilcoxonii*, and *Markalius inversa* (LAD=32.0). Although these fossils could be reworked from still older units, they may also represent evidence of marine incursions of this age. With this limited control, we have equated the top of the Yacheng I Formation (horizon T7) with the TA 4.5 sequence boundary (31.0 Ma). Extremely rare and deformed individuals referred to *Haplophragmoides* sp. were seen in one well, suggesting a marginal marine depositional setting. We have arbitrarily assigned the base of this interval (top of Yacheng II Formation, horizon T8) to the TA 4.4 sequence boundary (33.4 Ma) or where it unconformably overlies basement.

SYSTEMATIC TAXONOMY

Gaudryina collinsi elongata Chang, 1962a
Plate 2, Fig. 5

Gaudryina collinsi Cushman, - Chang, 1954, p. 106, pl. 1, figs 6a-b, 7a-b, 8a-b.
Gaudryina (Gaudryina) collinsi Cushman subsp. *elongata* Chang, 1962a, p. 60, pl. 1, fig. 17

Remarks. Chang (1954a) first reported this species from the Taitozoan Formation of Taiwan, dated at the time as Lower Oligocene. In the formal description, Chang (1962a, p. 106) gave the type level as

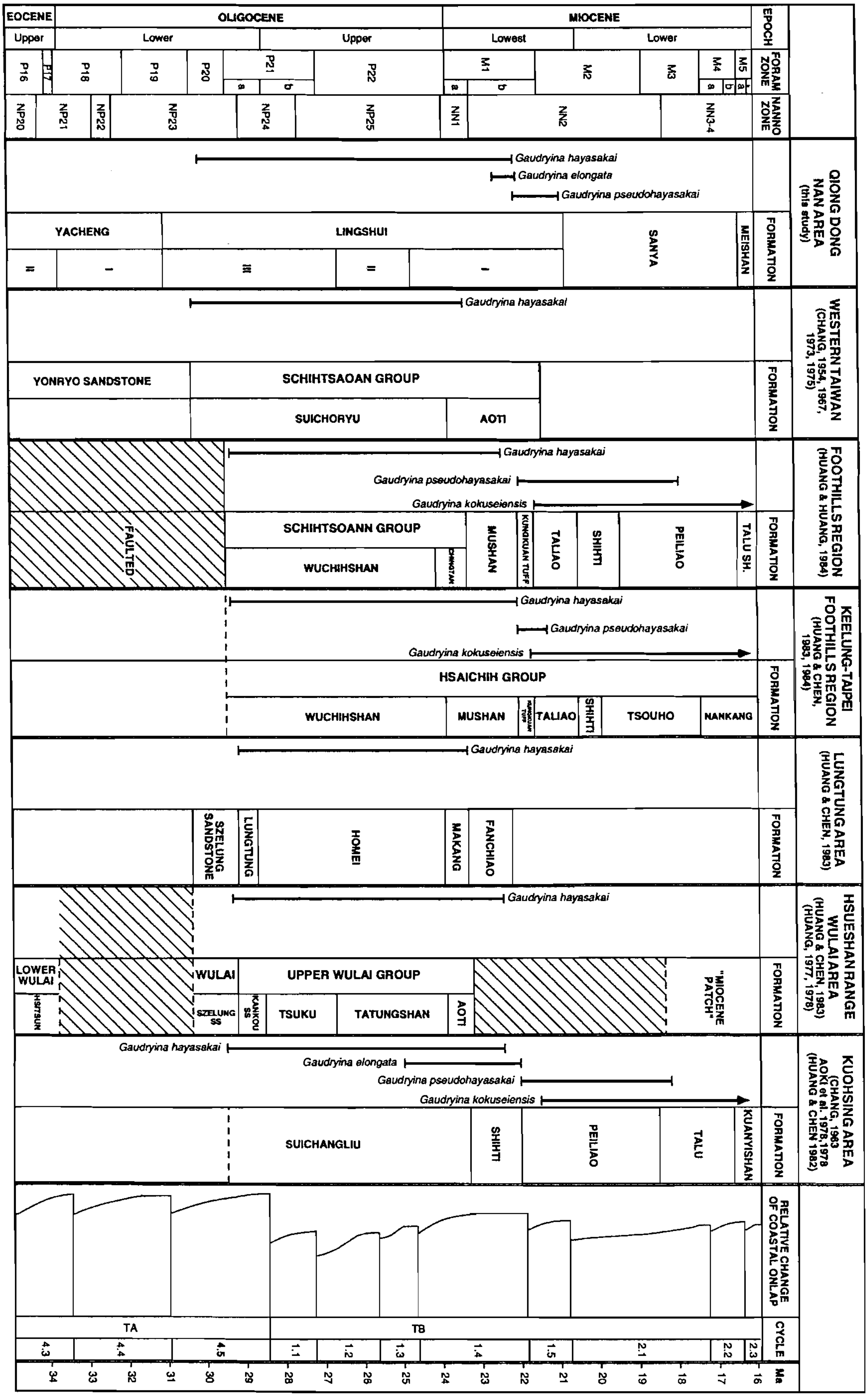

Figure 6. Correlation of the Qiong Dong Nan Basin subsurface stratigraphy to published outcropping units on Taiwan. Diagonal ruling indicates reported hiatus. Note the diachronous ranges of *Gaudryina* species.

the Oligocene Kanko Formation. Later, he (Chang, 1975, p. 342) listed it a component of the *Gaudryina hayasakai* Zone fauna (N1-N4). Y. Chang (1963, table 2), however, recorded it from the stratigraphically younger *Gaudryina pseudohayasakai* – *Gaudryina kokusiensis* Zonule (Lower Miocene). Huang & Cheng (1982), using biometrics, restricted the range of *G. elongata* to the upper part of the Suichangliu and Shihti Formations (uppermost Oligocene) of Taiwan.

There is considerable variability in the morphology as displayed in published illustrations of this species by Chang (1954, pl. 1, figs 6-8), Chang (1962a, p. 1, fig. 17), and Huang & Cheng (1982, pl. 1, figs 1-3). The illustrations of *G. elongata* by Huang & Cheng are particularly difficult to distinguish from *G. hayasakai* in the same publication. Without comparative material, we have been cautious in using the species in our study.

Stratigraphic Distribution. This species is rare and found in the late portion of the stratigraphic range of *G. hayasakai*.

Gaudryina hayasakai Chang, 1954
Plate 1, Figs 1-11

Gaudryina hayasakai Chang, 1954a, pp. 106-107, pl. 1, figs 9-15.

Diagnosis. Test relatively small in size, compressed, generally twice as long as wide. Early portion triserial with angular chamber edges, later biserial portion quadrate with rounded chamber edges. Chambers distinct, triserial chambers small and not inflated whereas biserial chambers, particularly the last two chambers, are well inflated and often make up two-thirds to three-quarters of the length. Sutures depressed and faintly curved. Wall finely arenaceous. Aperture is a slit in a re-entrant at the base of the last chamber

Remarks. The test is sometimes small but can be readily identified in the samples. In most individuals studied, the biserial stage is reduced and the chambers do not enlarge much over the length. In their biometric study, Huang & Cheng (1984) observed that *G. hayaskai* has less than 4 chamber pairs in the triserial portion and 3 or 4 in the biserial part [in contrast to *G. pseudohayasakai* which has more than 4 chamber pairs in the triserial part and 3 or 4 pairs in the biserial part]. Individuals recovered from the base of it range in the upper part of the Lingshui III Formation are quite small and have a relatively large biserial portion relative to the triserial portion (Plate 1, figure 5). Because most individuals were recovered from great burial depths, the shell colour has been altered to a dark brown -black.

A number of *Gaudryina* species have been described superficially resembling *G. hayasakai* because of the relatively reduced biserial stage. Theses include *G. carinata* Franke [Cretaceous], *G. convexa* var. *sandiegensis* Cushman & Hanna [Eocene], *G. inflata* Israelsky [Upper Palaeocene or Lower Eocene], *G. karihaensis* Asano {Pliocene], *G. laevigata* Franke [Upper Cretaceous], *G. matulaensis* Ansary and Tewfik [Turonian], *G. praepyramidata* Hercogová [Cenomanian], and *G. rugosa* Karrer (not d'Orbigny) [Cretaceous].

Stratigraphic Distribution. Chang (1954a) first reported that *G. hayasakai* occurred in abundance from his Yuhang locality in the Suichoryu Formation [Taiwan], thought to be lowest or Lower Oligocene. He subsequently (Chang, 1960a) proposed use of the species for the *Gaudryina hayasakai* Zone for the Suichoryu Formation, noting (Chang, 1962b) the occurrence of *Globigerina ampliapertura* in the basal part of the zone in central Taiwan. Chang (1963), studying the Wu-Chi Section of Taiwan, located the *G. hayasakai* Zonule between the underlying Poor Zone (possibly Eocene based on correlation to sections with larger foraminifera) and a faulted contact with the overlying *Gaudryina pseudohayaskai-G. kokusiensis* Zonule. Later Chang (1967, p. 59) recorded *G. hayasakai* in association with the planktonic foraminifera *Globoquadrina* cf. *venezuelana* and *Globorotaloides suteri* and the mollusc *Amussipecten yabei*, suggesting that the *Gaudryina hayasakai* Zone ranged into the Aquitanian. Huang & Cheng (1982, fig. 4) used biometric studies of *Gaudryina* to define the range of *G. hayaskai* from within the *G. ampliapertura* Zone to the upper-middle part of the *Globigerinoides primordius* Zone. Huang & Huang (1984, p. 213-215, figs 4 [Datum B1]) showed that *G. hayasakai* ranged from the Early Oligocene foraminiferal P19/P20 zone high into the Early Miocene N4 [M1b] and noted that the extinction of *G. hayasakai* and the first appearance of *G. pseudohayasakai* are in the same horizon in the Lower Miocene Kungkhan Tuff. In the QDN area, *G. hayasakai* occurs rarely in the upper part of the Lingshui III Formation (Lower Oligocene) and ranges throughout the Lingshui II Formation (Upper Oligocene) and occurs in abundance in the Lingshui I formation (Upper Oligocene to Lowest Miocene).

Palaeoecology. The species *Gaudryina hayasakai* dominates Upper Oligocene foraminiferal assemblages from QDN, often numbering many tens of specimens per sample. It is accompanied by very low numbers of *Haplophragmoides, Trochammina, Streblus, Florilus, Lenticulina.* Fine-grained sand and minor pyrite and very rare glauconite characterise the mineral portions of washed samples. We evaluate the association as very shallow marine and probably close to delta front. The time equivalent units in Taiwan have a much deeper palaeobathymetry (outer neritic to bathyal) judging from the long and diverse taxa lists in L-S. Chang (1954, 1975a) and Y. Chang (1963).

Gaudryina kokusiensis Chang, 1954

Gaudryina (Pseudogaudryina) kokusiensis Chang, 1954b, p. 59, pl. 1, figs 1-6.

Remarks. This species has not been identified in the QDN wells studied, but will be discussed here because it is used a zonal marker in Taiwan. From the type illustrations, several seemingly distinct forms have been combined.
Stratigraphic Distribution. Chang (1954b) reported the species as abundant and occurring in the Lower to Middle Miocene Nanko Sandstone, Sogo Formation, Shangtao Shale, and Daroku Shale. Chang (1960a) utilised the range of this taxon to define two Miocene zones: the *Gaudryina pseudohayasakai-G. kokusiensis* Zone [defined by the overlap of the two species] and the *Gaudryina kokusiensis* Zone [defined by that portion of the species range stratigraphically above *G. pseudohayasakai*]. The two species occur together in the Kokan Tuff, a unit correlated to the lower part of the *Globigerinoides bisphericus* Zone [M4-M5]. The top of the species range (Chang, 1975a) is at the first occurrence of *Orbulina suturalis* [M6]. Huang & Cheng (1982, fig. 4) used biometric studies of *Gaudryina* to define the base of the range of *G. kokusiensis* in the uppermost part of the *Globigerinoides primordius* Zone [M1a].

Gaudryina pseudohayasakai Chang, 1960
Plate 2, Figs 1-4, 6-11

Gaudryina (Gaudryina) pseudohayasakai Chang, 1960, p. 82, pl. 6, figs 1-3.

Diagnosis. Test elongate, about three times as long as wide. Early portion triserial and triangular, with sharp edges, forming about one-half of the test length, later biserial portion quadrate with rounded chamber edges. Chambers distinct, triserial chambers distinct but small and not inflated, biserial chambers inflated and gradually increasing in size as added. Sutures depressed, curved, and more distinct later. Wall finely arenaceous. Aperture is a slit in a re-entrant at the base of the final chamber.
Remarks. The species differs from *G. hayasakai* in its overall larger test size due to the long triserial portion, and a pronounced twisted nature (about one-eighth turn over the length) of the test. In their biometric study, Huang & Cheng (1984) observed that *G. pseudohayasakai* has more than 4 chamber pairs in the triserial part and 3 or 4 pairs in the biserial part [in contrast to *G. hayaskai* which has less than 4 chamber pairs in the triserial portion and 3 or 4 in the biserial part].

Due to the long triserial stage and overall large test size, a few species resemble *G. pseudohayasakai*. These include *G. africana* LeRoy [Lower Eocene or Palaeocene], *G. (Pseudogaudryina) atlantica* var. *pacifica* Cushman & McCulloch [Recent], and *G. oinomikadoi* Huang [Pleistocene]. As with *G. hayasakai*, the colour of many individuals is dark brown due to great depths of burial.
Stratigraphic Distribution. In western Taiwan, Chang (1960b, p. 82) first reported the species from the upper part of the Wuchihshan and Seitan Formations ("rather rarely"), the Kohan Tuff (holotype), to the lower and middle Taiyro Formation ("considerably high frequencies"). He used the short range of the species to define two Lower Miocene subdivisions (Chang, 1960a): the *Gaudryina pseudohayaskai* Zonule corresponding to the upper half of the Wuchihshan Formation, and the *G. hayaskai-G. kokusiensis* Zonule comprising the Kokan Tuff and Tairyo Formation exclusive of its upper part. Chang (1963) determined that the top of the *G. pseudohayasakai/G. kokuseiensis* Zone was stratigraphically higher in the Sogo Formation in northern Taiwan, equivalent to the *Globorotalia fohsi barisanensis* Zone [M6]. Chang (1967, table 1) reported that the top of the *Gaudryina pseudohayaskai /G. kokuseiensis* Zone correlated with the *Globigerinatella insueta/ Globigerinoides bisphericus* Zone [M4b]. He also found it rarely in the upper part of the Wuchihshan and Seitan Formations, correlated to the *Globigerinatella insueta/ Globigerinoides trilobus* Zone [M4a]. Huang & Cheng (1982, fig. 4) used biometric studies of *Gaudryina* to define the appearance of *G. pseudohayaskai* in the upper part of the *Globigerinoides primordius* Zone [M1a] and concluded (Huang & Cheng, 1983, 1984) that the *Gaudryina* specimens in the Wuchihshan and Mushan Formations were *G. hayasakai* rather than *G. pseudohayasakai*. Huang & Huang (1984, fig. 4 [Datum B1]) show this form ranging in the Early Miocene foraminiferal zones N4 to N6. In the QDN area, *G. pseudohayasakai* occurs only in the uppermost Lingshui I Formation (Lower Miocene); its highest stratigraphic occurrence is truncated by a major stratigraphic regression.
Palaeoecology. *Gaudryina pseudohayasakai* dominates foraminiferal assemblages, often numbering ten of more specimens per sample. It is accompanied by very low numbers of ostracods, *Haplophragmoides*, *Trochammina*, *Textularia*, *Cibicides*, *Florilus*, *Baggina*, *Ammonia*, and irregular occurrences of *Globigerinoides trilobus* which may be caved. Fine-grained sand and pyrite, and rarely glauconite, constitute the minerals in washed samples. We evaluate this association as open but shallow marine and close to delta front.

CONCLUSION

Using calcareous nannofossil and planktonic foraminiferal control, we have dated the long term subsidence during the development of the Qiong Dong Nan Basin. Biostratigraphic dates occur in marine floodings which alternate with undatable clastic regressions. These regressions correlate with global sealevel curves and indicate a strong eustatic control on marine sedimentation. Two agglutinated benthonic foraminifera, *Gaudryina pseudohayasakai* (Lower Miocene) and *G. hayasakai* (Upper Oligocene), provide two datums for exploration drilling that consistently occur near and above the Lower Oligocene Lingshui III reservoir unit.

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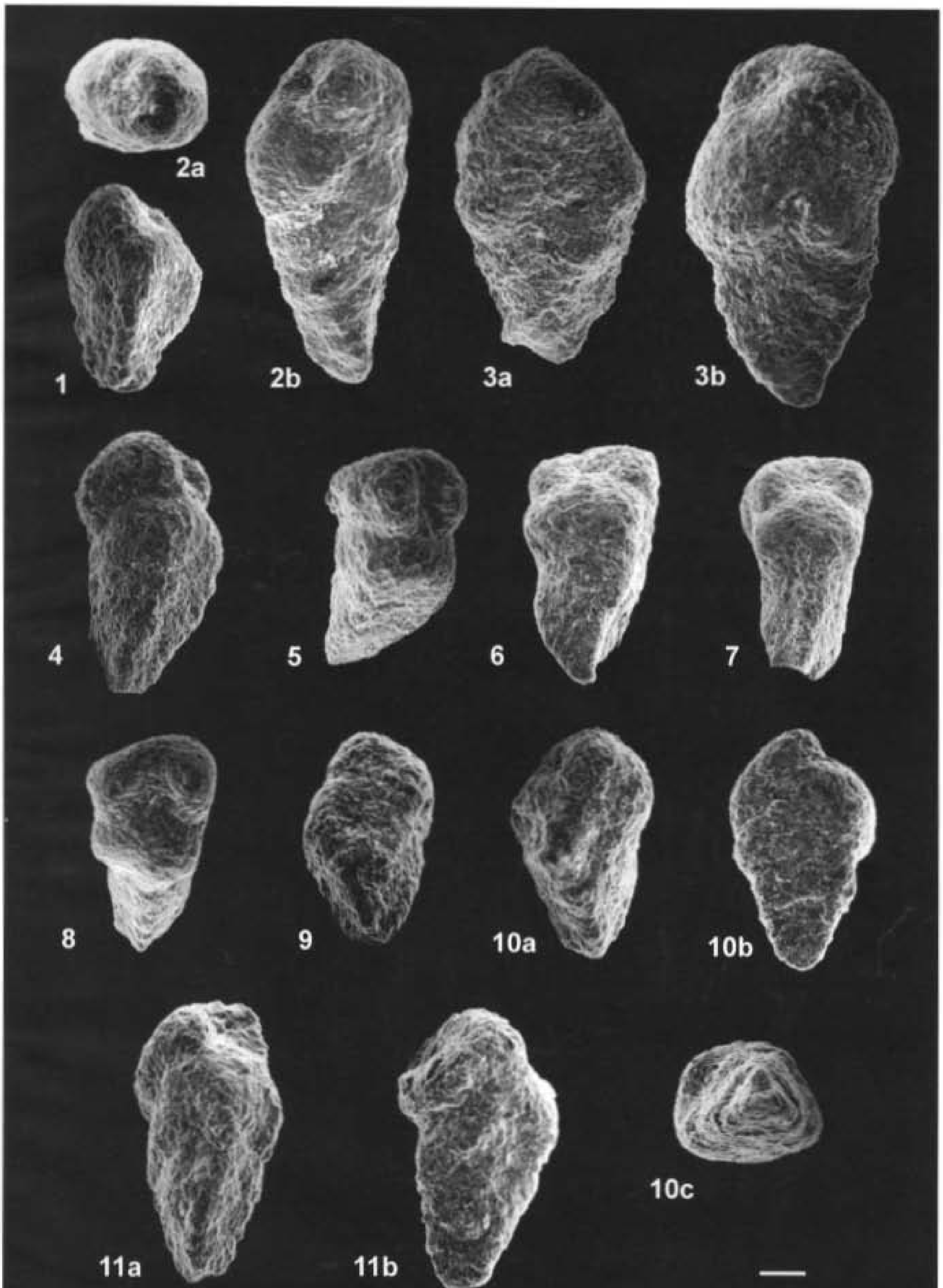

Plate 1. Scale bar is 100 μm. **1-11.** *Gaudryina hayasakai* Chang

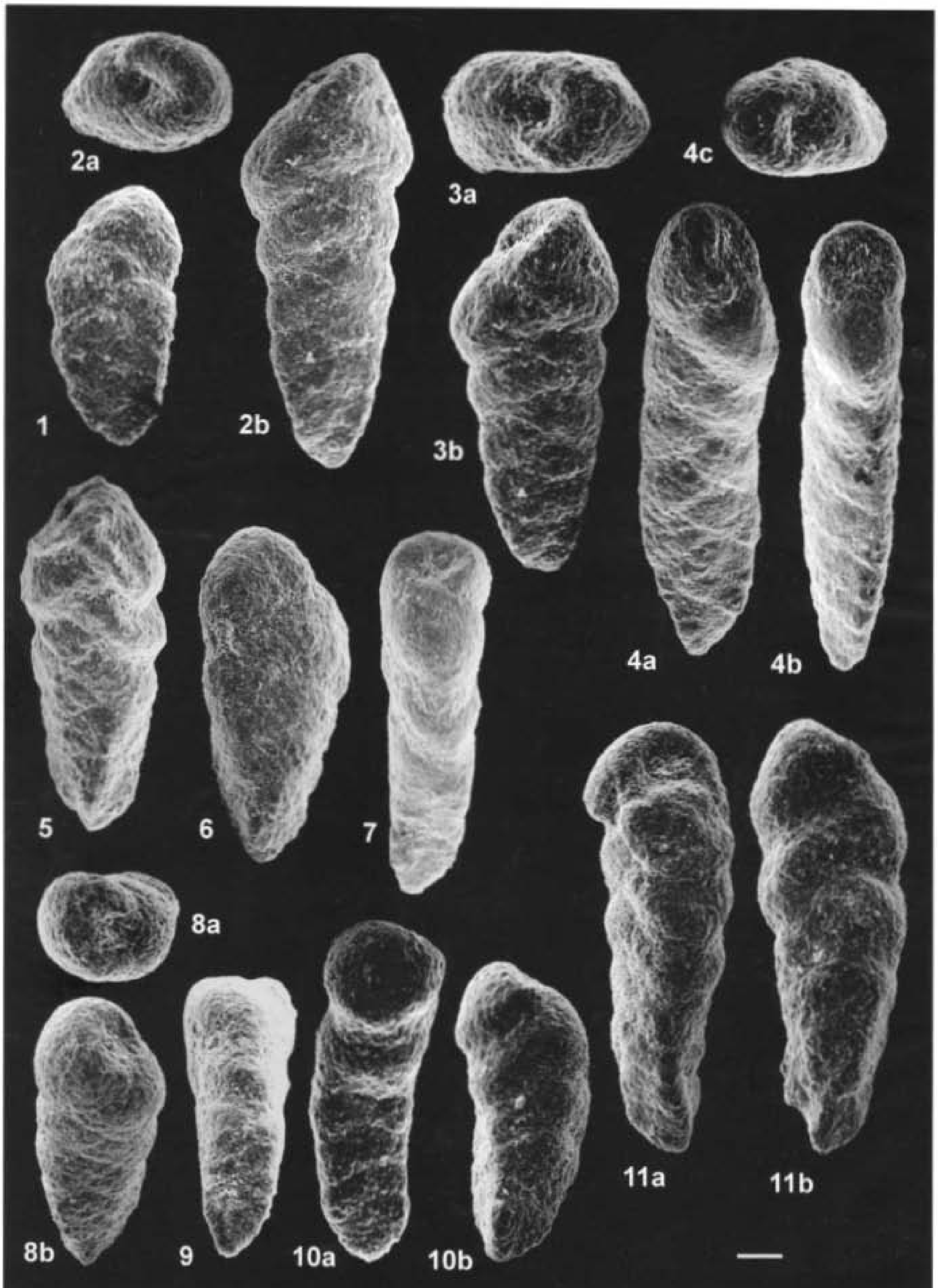

Plate 2. Scale bar = 100 µm. **1-4, 6-11.** *Gaudryina pseudohayasakai* Chang. **5.** *Gaudryina collinsi elongata* Chang