Cretaceous tectonostratigraphy and the development of the Cauvery Basin, southeast India

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ABSTRACT: The late Jurassic to early Cretaceous rifting between India/Australia and India/Antarctica resulted in the formation of a number of NE–SW-trending basins in the Indian Precambrian crystalline basement. The Cauvery Basin is the southernmost basin along the eastern margin of the Indian Sub-Continent, covering much of this part of India and extending a considerable distance offshore. The basin comprises several 'depressions', or sub-basins, with the Ariyalur–Pondicherry Depression in the north. The exposed successions are in the southern part of this sub-basin.

The result of fieldwork (1994–8) has been a reassessment of the lithostratigraphy and the tectonostratigraphic history of the Ariyalur outcrop. Three major sedimentary groups were identified: the syn-rift Gondwana Group (of early Cretaceous age), the syn-rift Uttatur Group (of Albian to Coniacian age) and the post-rift Ariyalur Group (of Santonian to Maastrichtian age). Both microfaunal and macrofaunal information were used to develop a biostratigraphic framework for the basin and a new tectonostratigraphic model. This new model for the development of the basin is significantly different to that used by the Oil and Natural Gas Commission of India. Structures exposed onshore, which have been interpreted as Albian reefs, are interpreted here as irregularly shaped limestone olistoliths/olistostromes produced by intra-Cretaceous rifting and slumping within the basin. The paper discusses this model for the basin history which is calibrated by updated foraminiferal (and macrofossil) biostratigraphy.

KEYWORDS: *Southeast India, Cauvery Basin, Cretaceous stratigraphy, foraminifera, sequence stratigraphy*

BACKGROUND

The late Jurassic–earliest Cretaceous age rifting between India and Australia/Antarctica resulted in the formation of a number of NE–SW-trending basins in the Precambrian crystalline basement of the Indian Sub-Continent (Powell *et al.* 1988; Reeves & de Wit 2000; Li & Powell 2001; Behera *et al.* 2004; Parson & Evans 2005). These basins are the sites of oil and gas production and ongoing exploration (Bastia 2006). The Cauvery Basin is the southernmost basin along the eastern margin of India (Fig. 1a). The basin is segmented into several 'depressions' or fault-controlled sub-basins with intervening inter-basinal highs (Fig. 1b) (Ramanathan 1968; Sastri *et al.* 1973, 1979, 1981; Prabhakar & Zutschi 1993; Hart *et al.* 2001, fig. 1; Sundaram *et al.* 2001, fig. 1). The Ariyalur–Pondicherry Depression is the northernmost sub-basin (Fig. 1b) which contains three important outcrops at Ariyalur (Fig. 1c), Vridhachalam and Pondicherry. This work describes only the Ariyalur outcrop; the other two outcrops have been described recently by Sundaram *et al.* (2001).

Because part of their basin fill is exposed at outcrop, the sedimentary basins of the southeastern continental margin of India (Cauvery Basin, Pennar–Palar Basin, Krishna–Godavari Basin) can provide important stratigraphic, structural and sedimentological information which can help to better constrain the tectonostratigraphic evolution of southeast India. This outcrop-derived data can be applied in future petroleum exploration and production in both existing continental shelf and emerging deep-water plays.

The Cretaceous sedimentary basin fill of the Cauvery Basin has been the subject of intensive research since the early studies of Blanford (1862), Stoliczka (1870–3) and Kossmat (1897). The memoir of Blanford remains the fundamental description of the area, including geological maps and a wealth of palaeontological and stratigraphical information. Stoliczka and Kossmat produced comprehensive monographs on the macropalaeontology of the basin, although many of their localities are difficult to locate in the field as the place names have changed over the years. More recently there have been a number of important regional stratigraphical studies of the area (e.g. Rama Rao 1956; Tewari & Srivastava 1965; Bhatia & Jain 1969; Srivastava & Tewari 1969; Sastry & Mamgain 1971; Banerji 1973, 1982; Sastri *et al.* 1973, 1977; Nair 1974; Jain 1976; Rasheed & Ravindran 1978; Banerji & Sastri 1979; Sundaram & Rao 1979, 1986; Rasheed 1981; Chiplonkar 1985; Ramasamy & Banerji 1991; Tewari *et al.* 1996; Govindan *et al.* 1998; Sundaram *et al.* 2001), the majority of which have been published in the

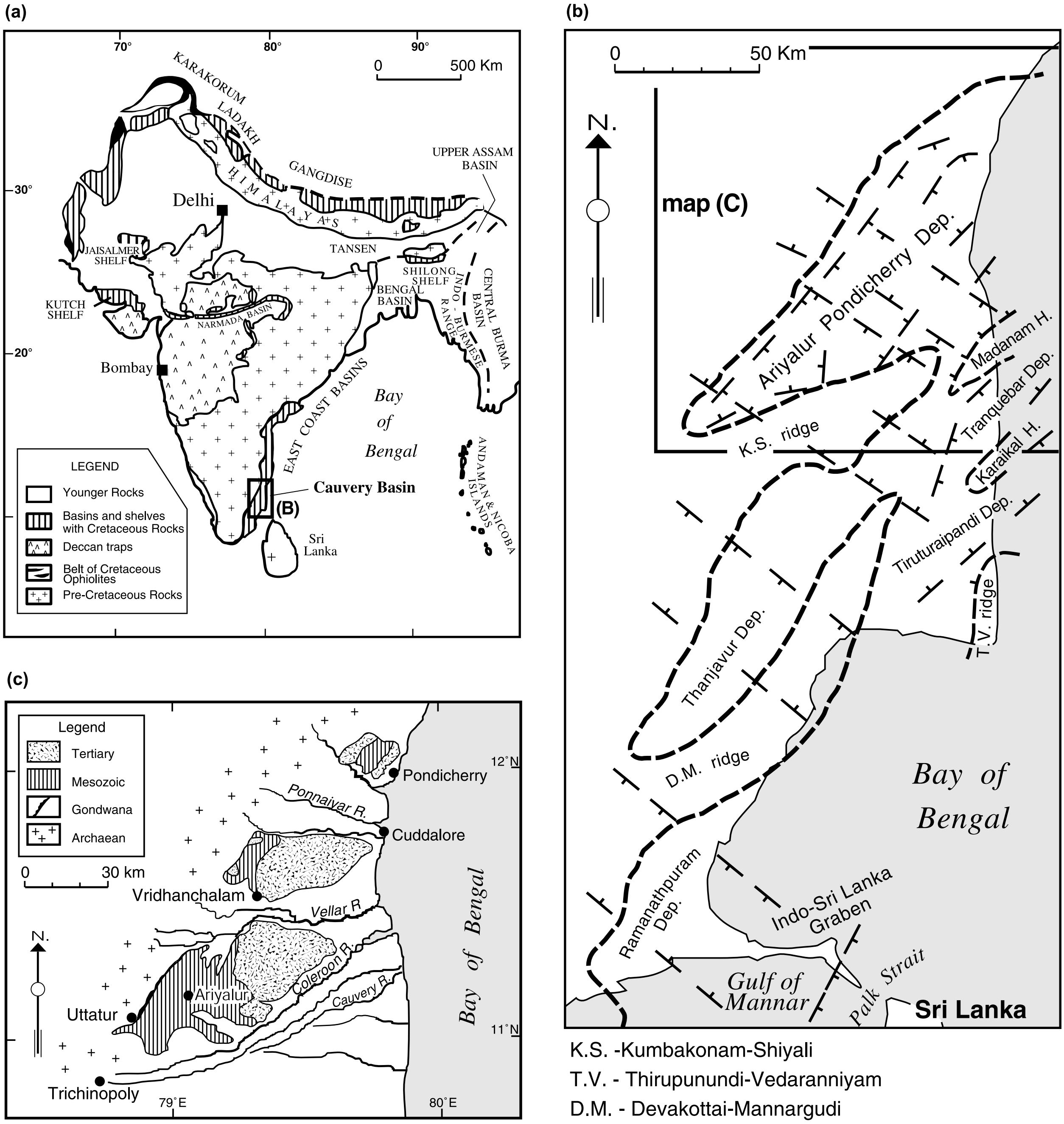

Fig. 1. The geological setting of the Cauvery Basin. (**a**) Distribution of Cretaceous rocks in the Indian Sub-Continent (after Acharyya & Lahiri 1991). The position of the Cauvery Basin is shown in the box. (**b**) Basement configuration map of the Cauvery Basin (after Sastri *et al.* 1979). (**c**) Geological map of the Ariyalur–Pondicherry Depression showing the onshore outcrops near Pondicherry, Vridhanchalam and Ariyalur (after Sastry & Rao 1964).

Indian literature (some of which can be quite difficult to access).

In many cases, those working in the Cauvery Basin have proposed new terms and age ranges for the rock succession, but have failed to acknowledge any of the previously published information. As a result, a plethora of confusing and often contradictory stratigraphical terms are in current usage, with some authors continuing to prefer their own classification schemes, or continuing to follow the initial work of Blanford (1862). There are four key reasons for this state of affairs.

First, whilst major facies changes have been identified within the Cauvery Basin, there is a reluctance to include these in the lithostratigraphic classifications employed. Evidence of this is seen in the diagram of Sundaram *et al.* (2001, fig. 5), which describes a number of 'layer-cake' lithological units abutting directly against the (?)faulted margin of the basin with no perceptible change in facies (with one notable exception).

Secondly, there has been the lack of a coherent understanding of the mid-Cretaceous extensional faulting seen at numerous localities in the basin. This is especially true at the western end of the Kovandakuruchchi quarry-2 at Kallakudi (Figs 2, 3), where the Archaean basement is juxtaposed against mid-Cretaceous calcareous sandstones and in the Kallakudi quarry-2 where the outcrop of the pink limestone is cut through by a significant number of faults. The resulting irregular outcrop pattern is, therefore, not a product of a reefal structure (as has

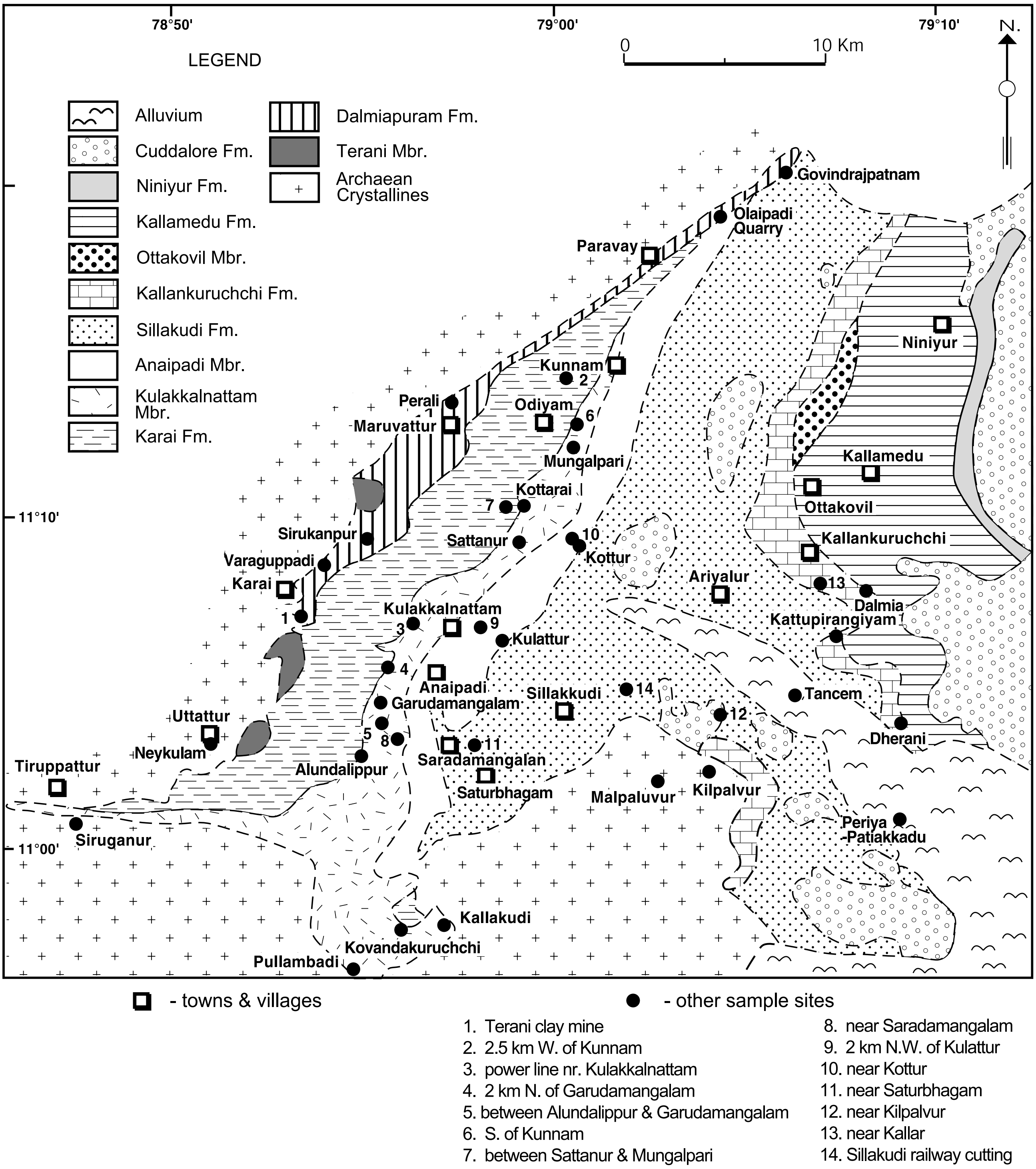

Fig. 2. Geological map of the Ariyalur area, with the key localities identified (based on Sundaram & Rao 1986, Ramasamy & Banerji 1991, Tewari *et al.* 1996 and the Geological Survey of India).

been suggested in the recent literature) but a combination of faulting and massive displaced blocks (many of which can be shown to be inverted by the presence of geopetal structures). Around the margins of the basin, it is contended that syn-sedimentary mid-Cretaceous faulting is associated with a large number of massive debris deposits. These contain exotic blocks of pink limestone (e.g. in the quarries at Olaipadi, Neykulam and Tiruppattur; Fig. 2) together with rare (and much smaller) blocks of Archaean basement. In other localities (e.g. Kovandakuruchchi quarry-2), massive conglomerates composed exclusively of boulders and cobbles of Precambrian basement mark the base of the sedimentary fill of the basin (Fig. 3).

Thirdly, there has been a general lack of sedimentological analysis and interpretation, including the correct identification of different sedimentary facies. Trace fossil assemblages have been ignored largely.

Finally, there has been a general lack of adherence to accepted stratigraphical procedure (Hedberg 1976; Holland *et al.* 1978; Whittaker *et al.* 1992; Rawson *et al.* 2002). Many

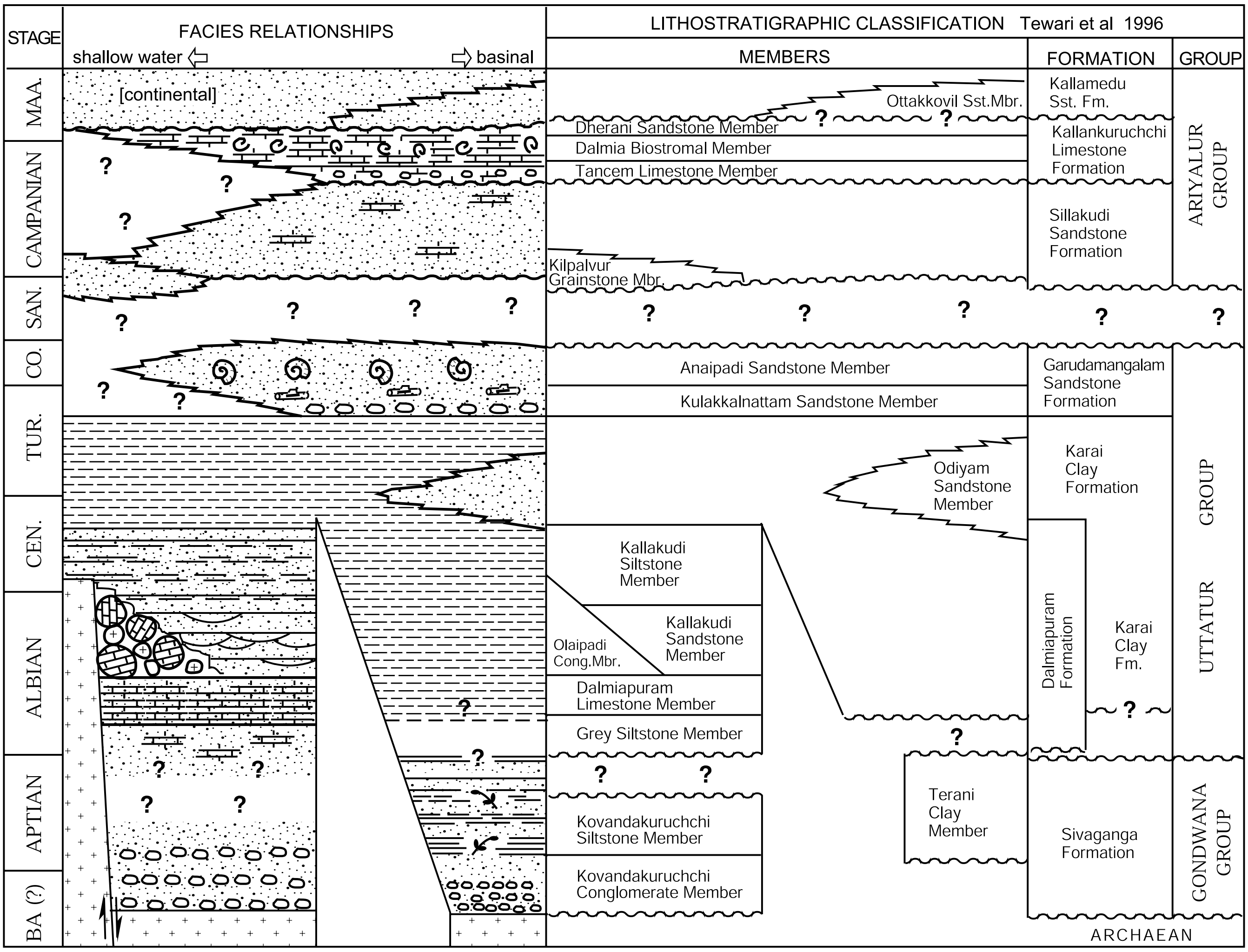

Fig. 3. Lithostratigraphy and facies relationships proposed by Tewari *et al.* (1996). The positions of the stage boundaries follow current European usage, including some of the decisions taken at the meeting of the International Sub-Commission on Cretaceous Stratigraphy when it met in Brussels (September 1995) and Neuchâtel (September 2005).

workers, in the past, have used (and published) casual descriptive terms that may have served a purpose at the time but have not helped in the understanding of the basin. This has led, partly, to the development of a multiplicity of terms, many of which are redundant. In recent years however, Sundaram & Rao (1979), Ramasamy & Banerji (1991), Tewari *et al.* (1996) and Sundaram *et al.* (2001) have defined their lithostratigraphical units more in keeping with modern practice and identified type sections wherever possible, although this paper may not agree with all of their conclusions (see below).

LITHOSTRATIGRAPHY OF THE CAUVERY BASIN (ARIYALUR OUTCROP)

Over the more than 140 years of research on the Cauvery Basin a number of stratigraphic 'units' have become well established, many by historical precedent. The research papers in which this stratigraphy is described are numerous and reviewed fully by Tewari *et al.* (1996) and Sundaram *et al.* (2001). As indicated above, this paper may not agree with all the units used and/or named by Sundaram *et al.* (2001), but it is clear that the two versions of the lithostratigraphy are fairly close (see Figs 3, 4). A further review of the lithostratigraphy is in preparation, with this present contribution focusing more on the rift to drift tectonostratigraphic evolution of the basin and the interpretation of the sequence stratigraphy.

BIOSTRATIGRAPHY OF THE CAUVERY BASIN (ARIYALUR OUTCROP)

Early studies of the Cauvery Basin used the macrofauna (Blanford 1862; Stoliczka 1870–3; Kossmat 1897) as a basis for all of the stratigraphy and inter-basinal correlation. In recent years information on the microfauna and microflora has increased substantially (see, for example, Narayanan 1977; Raju *et al.* 1991; Kale & Phansalkar 1992; Govindan 1993; Govindan & Ramesh 1995; Ravindran *et al.* 1995; Ventkatachalapathy & Ragothaman 1995*a*; Raju & Mishra 1996; Govindan *et al.* 1996). The history of this research has been reviewed by Tewari (1996), Tewari *et al.* (1996) and Hart *et al.* (2001). The current work, including that of Tewari (1996), is based on independent work in the 1990s and quite extensive sampling of the Ariyalur Outcrop (Fig. 2). The revised lithostratigraphy proposed by Tewari *et al.* (1996) was set against the authors' interpretation of the stratigraphy based on foraminifera, ammonites, rudistid bivalves, palynology and, to a lesser extent, other fossil groups. During the course of the field studies, Venkatachalapathy (1993, 1996) and Venkatachalapathy & Ragothaman (1995*a*, *b*, 1996*a*, *b*) published a number of useful papers on the

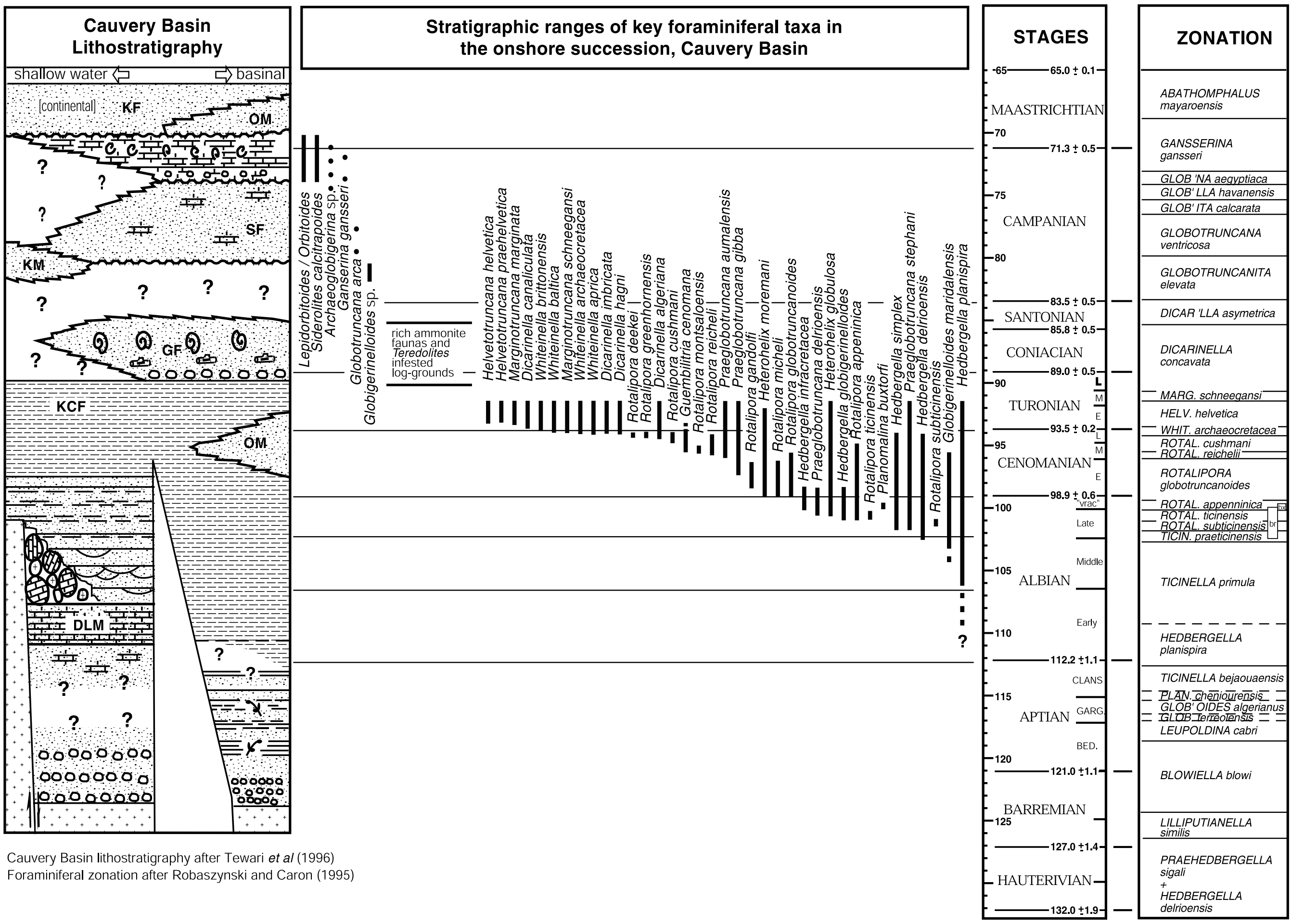

Fig. 4. The distribution of planktic foraminifera (and some other taxa) in the onshore succession of the Cauvery Basin. The lithostratigraphy is that of Tewari *et al.* (1996) and the foraminiferal data are after Hart *et al.* (2001). The zonation based on planktic foraminifera follows that of Robaszynski & Caron (1995) and this is essentially that adopted by Ogg *et al.* (2004). Abbreviations used are as follows: KF, Kallamedu Sandstone Formation; OM, Ottakkovil Sandstone Formation; KM, Kilpalvur Grainstone Member; GF, Garudamangalam Formation; KCF, Karai Clay Formation; OM, Odiyam Sandstone Member; DLM, Dalmiapuram Limestone Member.

foraminifera of the Ariyalur sedimentary succession. A review of the Cretaceous stratigraphy of India by Raju & Mishra (1996) also includes a section on the Cauvery Basin, although the detailed stratigraphy is somewhat unresolved by the regional super-stage and stage nomenclature used to calibrate this and other successions.

Some parts of the succession are characterized by extremely abundant foraminifera, including planktic taxa (Hart *et al.* 2001). This is especially true of the Karai Clay Formation which can be subdivided using the standard microfaunal zonation that is normally applied to Tethyan areas (Fig. 4). All of the zones are present and can be identified across the outcrop. The only problem is in the interval of the Aptian/Albian boundary where the *Hedbergella planispira* Zone is indicated by a lack of other taxa, rather than the definitive appearance of the nominate taxon. For this reason the date of the onset of marine clay sedimentation in the basin remains vague, but may well be earliest Albian. Other, more sandy, parts of the succession (e.g. Anapaidi Sandstone Member, Sillakudi Sandstone Formation) contain only sparse microfaunas with very few planktic foraminifera being recorded. In the Kallankuruchchi Limestone Formation (Tewari 1996; Tewari *et al.* 1996; Hart *et al.* 2001; Nagendra *et al.* 2002) there are smaller benthic foraminifera, some planktic foraminifera and abundant larger foraminifera (e.g. *Siderolites calcitrapoides*, *Orbitoides* spp. and *Goupillaudina daguini*). This assemblage is typical of the very latest Campanian and the Maastrichtian, although *Omphalocyclus macroporus* (another marker species at this stratigraphic level) has yet to be found in eastern India.

SEQUENCE STRATIGRAPHY

The early Cretaceous to Maastrictian succession of the Cauvery Basin can be subdivided into megasequences (*sensu* Hubbard *et al.* 1985) representing episodes when distinctly different tectonic regimes were in operation. The **Syn-rift Megasequence** spans the Barremian to upper Turonian part of the sedimentary basin fill and corresponds to the Gondwana Group, Dalmiapuram Formation and the Karai Clay Formation (Fig. 5). The **Post-rift Megasequence** is a relatively attenuated succession. This includes the Garudamangalam Sandstone Formation and the Ariyalur Group of late Turonian to Maastrictian age in which there are major hiatuses in the sedimentary record.

Overall the Cretaceous sedimentary succession displays a retrogradational deepening of facies in the lower, Syn-rift Megasequence, with the Post-rift Megasequence displaying a punctuated regressive character. The origins of these deepening and regressive trends are discussed later.

Syn-rift Megasequence

The deposition of continental, lacustrine and marginal marine sedimentation in the Barremian or Aptian in the Cauvery Basin

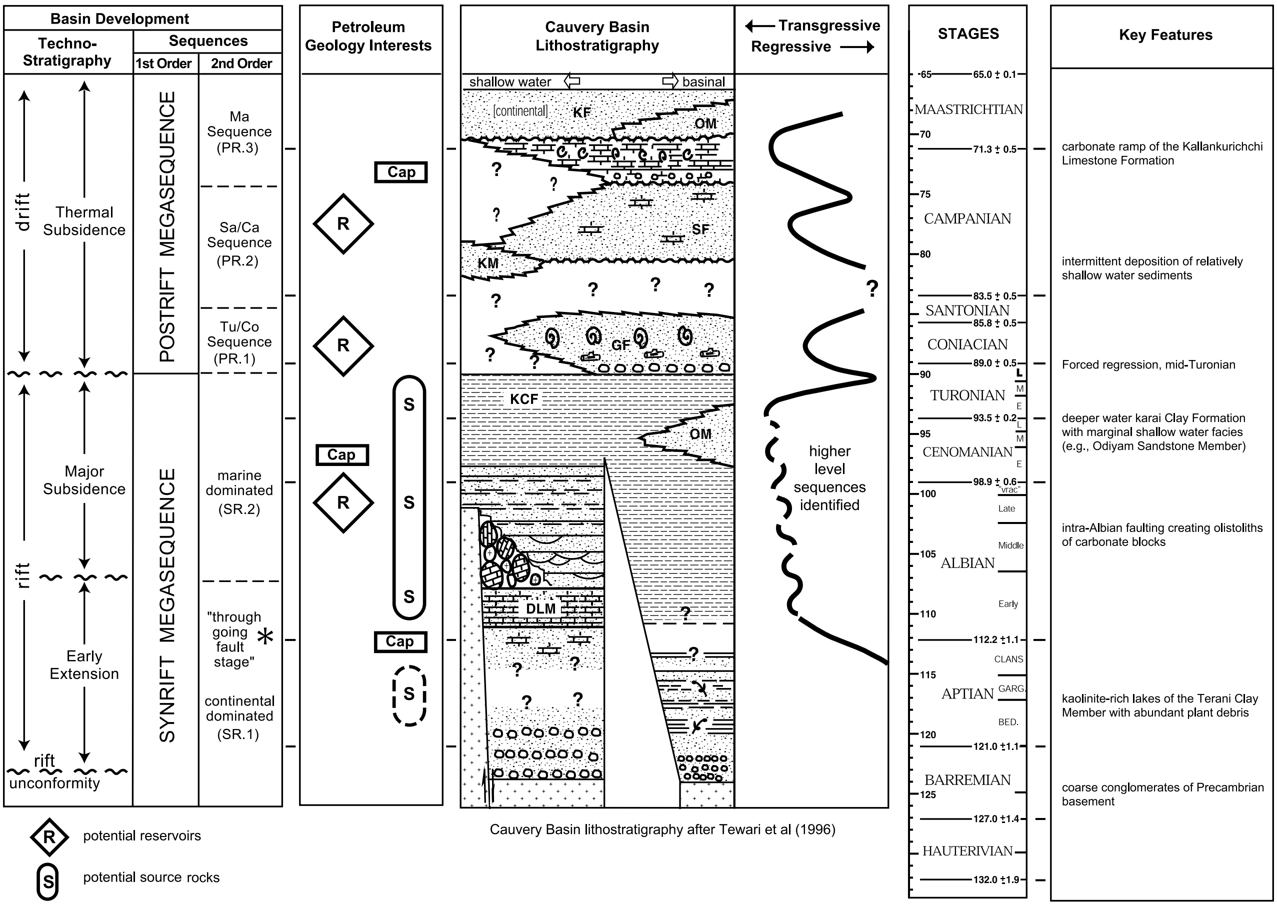

Fig. 5. The Cretaceous succession of the Cauvery Basin (based on Figs 3 and 4), showing the major transgressive/regressive events, key features in the development of the basin, sequence stratigraphy and the petroleum geology interest. The potential source rock of the Karai Clay Formation is overlain by two major sandbodies of reservoir potential. These two prospects are those identified recently as targets in the offshore part of the Cauvery Basin (www.oilvoice.com, 'Hardy begins offshore Cauvery Basin drilling programme', 24 July 2006). Abbreviations used are as follows: KF, Kallamedu Sandstone Formation; OM, Ottakkovil Sandstone Formation; KM, Kilpalvur Grainstone Member; GF, Garudamangalam Formation; KCF, Karai Clay Formation; OM, Odiyam Sandstone Member; DLM, Dalmiapuram Limestone Member.

is interpreted to be the result of rift-related extension. This early syn-rift phase appears to have generated a series of linked half-graben basins (see Venkatarengan 1987), which includes the Ariyalur–Pondicherry Depression (see Fig. 1b).

Syn-rift Sequence 1 The syn-rift megasequence can be subdivided further into two major sequences or sequence sets. The first is of latest(?) Barremian to mid-Albian age (Kovandakuruchchi Conglomerate Member to top Dalmiapuram Limestone Member). The basement-derived boulder and cobble conglomerate of the Kovandakuruchchi Conglomerate Member (=Arogyapurum Formation of Sundaram *et al.* 2001) is almost invariably faulted against the Precambrian basement and no *in-situ* stratigraphical boundary has been seen. In the quarries near Kallakudi, this grades upwards into a succession of grey sandstones and grey siltstones, the upper part of which (the Grey Siltstone Member) includes rare, poorly preserved foraminifera and rare dinoflagellates. This change from terrestrial conglomeratic sediments to marginal marine siltstones appears gradational and a detailed description is hampered by a lack of suitable exposures. Along the western edge of the basin the Terani Clay Member is represented by basement-derived kaolinite-rich claystones with interbedded coarse sandstone beds that display sharp, planar to erosive bases. Mudtsone rip-up clasts are also present in these sandstones. The setting of these deposits appears to be comparable to that of the Tertiary Bovey Basin in South Devon (Edwards & Freshney 1982). In the earlier literature these were often described as the Terani 'plant beds' as they contain abundant dispersed plant remains (including *Ptilophyllum*). These sediments have been described variously as being of Jurassic (Pascoe 1959), Neocomian (Mamgain *et al.* 1973), Aptian (Sastri *et al.* 1977; Ramasamy & Banerji 1991) or Albian (Sundaram *et al.* 2001) age. The current study favours an Aptian age on stratigraphical, rather than palaeontological, grounds as they are overlain (almost conformably) by the Karai Clay Formation. The outcrop pattern of the Terani Clay Member appears fault controlled and the working quarries display numerous, relatively small, syn-sedimentary normal faults that are parallel, and at right angles, to the western margin of the basin. Lacustrine shales are reported to have been drilled in Lower Cretaceous syn-rift succession in the offshore Krishna–Godavari Basin to the northeast (Bastia 2006).

The base of the Karai Clay Formation in the basin is probably earliest Albian in age (Kale & Phansalkar 1992). Hart *et al.* (2001, p. 219) have given a long discussion of the evidence, and recent work (A.S. Gale, pers. comm.) appears to confirm this conclusion. This marine flooding of the basin is, therefore, the combined effect of the major flooding event after Ap6 (de Graciansky *et al.* 1998, chart 6) and augmented by continued tectonic subsidence of the basin.

At the margins of the basin the Dalmiapuram Limestone Member represents a shallow-marine carbonate platform with rare solitary corals, bryozoans, algae and other shallow-water benthos.

Syn-rift Sequence 2 Shallow-marine carbonates of the Dalmiapuram Limestone Member are overlain by clastic sediment gravity flow deposits and olistoliths containing boulders of the carbonate platform and significantly smaller clasts of the Precambrian basement. The Dalmiapuram limestones were dissected by normal faults and fractures at this time and it is probable that the Precambrian basement was also uplifted and exposed on footwall highs. This continued faulting in the mid-Cretaceous is evidence for ongoing syn-tectonic activity (as indicated in Fig. 4). The deepening seen in the basins, where shallow platform carbonates are overlain by slope clastics (e.g. in the Kallakudi and Kovandakuruchchi quarries), was coeval with basin margin uplift and erosion of both basement and Albian carbonate platform material. Relative deepening within this basin continued throughout the Cenomanian, with the gradual establishment of open-marine, deep-water conditions and the deposition of the Karai Clays across the whole basin. The mid-Albian to early Turonian assemblage of abundant planktic foraminifera indicates a water depth in the basin in excess of 150–200 m, based on experience elsewhere (Hart & Bailey 1979). The shallow-marine Odiyam Sandstone Member may represent either an initial pulse of regression within this highstand succession, or the relatively restricted distribution of this facies may also be the result of local tectonic activity. Within the Odiyam Sandstone Member, and the contemporaneous Karai Clay Formation, Gale *et al.* (2002) have recognized a number of sequence boundaries that appear to match those of the European Basin. This would imply that during the latest Albian and Cenomanian global signals are detectable in the sea-level changes recorded in the basin, even when a local tectonic overprint may also be present. Rift-related extension ceased at some point in the Cenomanian or Turonian and the main subsidence mechanism after this time was dominantly thermal re-equilibration of the lithosphere.

Post-rift Megasequence

Throughout the Post-rift Megasequence, facies changes are more gradual and normal faulting is both localized and on a small scale. The base of this megasequence is placed at the major sequence boundary indicated by an abrupt shallowing of facies at the very top of the Karai Clay Formation (Tewari *et al.* 1998). This forced regression (Type-1 Sequence Boundary: Posamentier *et al.* 1988, 1992) is almost certainly coeval with a major, global sea-level fall in the mid-Turonian (Hancock 1976, 1989; Hancock & Kauffman 1979; Hart & Bailey 1979; Haq *et al.* 1987, 1988; Raju *et al.* 1993; de Graciansky *et al.* 1998, chart 6; Fig. 5).

The Post-rift Megasequence is composed of generally shallow-marine and fluvial sandstones and sand-rich carbonates, with numerous hiatuses. There is little evidence for regionally extensive lowstand systems tract deposits. Where they are exposed, successions interpreted as lowstand systems tracts are aerially restricted fluvial and marginal marine deposits that may have been deposited within incised valleys. Three post-rift sequences can be identified, although detailed investigation is made difficult by poor, to non-existent, exposure. It is likely that these sequences actually represent sequence sets (*sensu* Van Wagoner *et al.* 1990), which may be subdivisible into higher-order sequences. The limitations of exposure and equivocal dating mean that further sequence resolution is not possible at this stage of the analysis.

Post-rift Sequence 1: Upper Turonian to (?)base Santonian Post-rift Sequence 1 coincides with the Garudamangalam Sandstone Formation and is interpreted to represent the transition from the Syn-rift Megasequence to the Post-rift Megasequence.

The sequence boundary at the base of Post-rift Sequence 1 is defined at the sharp boundary between the Karai Clay and Garudamangalam Sandstone formations. The claystones at the top of the Karai Clay Formation are exposed 1.5 km south of the village of Kulakkalnattam (Fig. 2). The top of the formation here contains a diverse assemblage of foraminifera, dominated by deep-marine planktic taxa (Tewari 1996). The overlying basal Garudamangalam Sandstone Formation is characterized by an abrupt change to siltstones, which contain a high abundance, low diversity fauna dominated by agglutinated taxa. The Kulakkalnattam Sandstone Member is composed of fine to medium, locally pebbly sandstones. Exposure quality is not good enough to observe sandstone body geometries. The base of this member is made up of several 1.5–2 m thick cycles composed of massive, bioturbated sandstones overlain by horizontally laminated sandstones. The horizontally laminated sandstones contain horizons of (up to 1.5 m wide) carbonate concretions, often surrounding *Teredolites*-infested log-grounds (Hart *et al.* 1996; Tewari *et al.* 1998). Each of these sedimentary cycles is capped by either (i) planar erosive surfaces overlain by coarse, sometimes pebbly sandstones with *Thallassinoides* burrows; or (ii) omission surfaces with vertical dwelling traces (*Diplocraterion, Ophiomorpha* and *Skilithos*) that are overprinted by *Thallassinoides* burrows that extend down from overlying fine sandstones.

The top of the Kulakkalnattam Sandstone Member is poorly exposed, but is composed of poorly cemented, fine sands with horizons of *in situ* shell beds containing an exclusively molluscan fauna of bivalves (including oysters) and gastropods. The Kulakkalnattam Sandstone Member is interpreted to have been deposited in shallow-marine sub-tidal to intertidal environments. The most likely settings are low-energy shoreface and foreshore environments, or sand-flats within estuaries. The 2 m thick sedimentary cycles are shallowing-up parasequences capped by erosion (ravinement) or non-deposition marine flooding surfaces. The log-grounds are interpreted to have been stranded on sand-flat/foreshore environments during transgressions. Where present, xylic material acted as nuclei for concretion growth in a similar way to that described by Huggett (1994) and Hugget & Gale (1995). The concretion growth is, however, interpreted to have been the result of long residence times in sulphate reduction or methanogenic zones during times of sediment starvation associated with marine flooding surfaces (Curtis 1987; Taylor *et al.* 2000).

The overlying Anaipadi Sandstone Member is composed of burrowed medium-grained sandstones, calcite-cemented sandstones and siltstones. The basal part of the member contains further log-ground horizons. These are overlain by a horizon (or horizons) rich in large Coniacian ammonites. The remainder of the Anaipadi Sandstone Member contains oysters, brachiopods and nautiloids.

The abrupt shallowing and coarsening of facies at the top of the Karai Clay Formation is interpreted as a sequence boundary resulting from forced regression. This can be dated as mid-Turonian on the basis of planktic foraminifera (Tewari *et al.* 1998, fig. 13; Hart *et al.* 2001; Fig. 4). The Kulakkalnattam Sandstone Member is interpreted to be a transgressive parasequence set deposited during the late transgressive infilling of estuarine valley system and corresponds to the lowstand and transgressive systems tract of this sequence. The most open-marine conditions at the top transgressive systems tract are represented by the preservation of the cephalopod-rich horizon near the base of the Anaipadi Sandstone Member (Coniacian). This is interpreted as the maximum flooding surface. The overlying Anaipadi Sandstone Member coarsens upwards and is regressive in character. It is, therefore, interpreted to represent the HST (highstand systems tract) of this sequence.

Post-rift Sequence 2: Santonian to end-Campanian The base of this sequence is marked by an important hiatus over much of the field area that is picked out by regional mapping (Sundaram & Rao 1986). Localized fluvial sandstones are present at the basin margins (e.g. Saturbhagam) and are interpreted to represent incised valley fill deposits. The initial transgression (transgressive surface) occurs at the base of the marine Sillakudi Sandstone Formation and Kilpalvur Grainstone Member. The latter is an oolitic grainstone facies developed within shallow-marine successions on the remaining basement highs. The upper parts of the Sillakudi Sandstone Formation contain poor assemblages of planktic foraminifera and may represent deeper-shelf facies (Srivastava & Tewari 1969; Rasheed & Ravindran 1978; Ravindran 1980; Tewari 1996; Govindan *et al.* 1996). At the top of the Sillakudi Sandstone Formation there is a marked erosion surface and the base of the Kallankuruchchi Limestone Formation displays a basal conglomerate (with quite angular blocks of basement and large pink feldspar clasts) that has been seen only in an exposure in the Kallar River (Lat. 11°08′24″: Long. 79°06′10″E) and within an exploratory borehole drilled in the Dahrani Mines (Tewari 1996; Nagendra *et al.* 2002).

Post-rift Sequence 3: Maastrichtian The uppermost Post-rift Sequence is represented by the Kallankuruchchi Limestone Formation (see Tewari *et al.* 1996). This limestone succession is characterized by bioclastic to sandy bioclastic packstone-grainstone, composed mainly of larger foraminifera, bryozoa, echinoids and massive inoceramid and rudist bivalves. Towards the upper parts of the succession the limestone is a foraminiferal grainstone, with other levels dominated by gryphaeids (10–15 cm diameter) and *Alectronia/Lopha*. There are a number of parasequences delineated by minor non-sequences within the carbonate succession, each marked by the development of a weak or 'incipient' hardground. The maximum flooding surface would appear to be within, or at the top of, the major bivalve concentrations within the Dalmia Biostromal Member. This concentration of inoceramid and other bivalves is also associated with a concentration of larger foraminifera (including abundant orbitoids: see Fig. 4). The Dherani Sandstone Member is an orbitoid-rich sand and this marks the change from a carbonate ramp to the marginal marine and continental clastic facies of the Kallamedu Sandstone Formation. The basal, and only locally developed, Ottakkovil Sandstone Member represents the most marine part of this succession, containing a diverse macrofauna of ammonites, echinoderms and rudistid bivalves, together with a diverse foraminiferal assemblage. The rest of the sequence is regressive in character and represents the progradation of an alluvial plain (with dinosaurian remains). These stratigraphic relationships suggest that the basal sequence boundary is also a transgressive surface, and that most of the preserved part of this sequence corresponds to the highstand systems tract.

DISCUSSION

The Cauvery Basin developed as a result of rift-related extension between India and Sri Lanka during the fragmentation of Eastern Gondwanaland (Katz 1978). Pre-rift basement is formed of the Archaean rocks typical of this part of Southern India. This Precambrian basement forms the exposed hinterland that borders the Ariyalur–Pondicherry Depression (Figs 1c, 2). Recently, Narasimha Chari *et al.* (1995) have provided a burial history for the evolution of the Cauvery Basin. They concluded that tectonic subsidence profiles conform more to those of extension of an intracratonic basin than would be expected on a passive margin. Their interpretation of data from Well VG-2, within the Ariyalur–Pondicherry Depresssion, suggests that the major subsidence of the basin occurred between 108 Ma and 85 Ma (Albian to Coniacian). The stratigraphical information here would suggest an earlier onset of rift-related tectonic subsidence (Barremian–Aptian, 120 Ma), with an earlier (Turonian, 90 Ma) transition from the Syn-rift to Post-rift Megasequence. The plate rotation model of Reeves & de Wit (2000, figs 3, 4) infers that in the 140 Ma time slice (Valanginian) the margin remained unrifted and only by early Albian (112 Ma) had the rifted margin developed. This reconstruction is broadly consistent with the current interpretation of major extension of border faults in the earliest Albian (*c.* 108 Ma).

The SW–NE-orientated 'depressions' that characterize the Cauvery Basin are an en-echelon array of rift basins offset by basement highs. This pattern is probably the result of dextral transtension resulting from the SSW–NNE relative separation of eastern Antarctica and southeast India in the early Cretaceous (see Powell *et al.* 1988; Reeves & de Wit 2000; Parson & Evans 2005). Confirmation of this hypothesis will require a detailed analysis of high-resolution seismic and additional field structural data.

The current work constrains the onset and duration of rifting to the period spanning the late Barremian to early Turonian (approximately 120–90 Ma), with the main rifting phase occurring in the Albian–Cenomanian. One cannot be precise about the exact stratigraphic age of the onset of rift-related extension as a result of the paucity of biostratigraphic data at this level. However, a Barremian–Aptian (*c.* 125 Ma) date corresponds well with recent estimates published elsewhere in the region (Behera *et al.* 2004; Parson & Evans 2005).

The initial phase of rifting in the Barremian–Aptian (125 Ma) is recorded by the onset of fluvio-lacustrine deposition, probably in relatively low relief half-graben basins (Venkataregan 1987, figs 4, 6). This rift initiation phase (see Gawthorpe & Leeder 2000) culminated in a marine transgression in the earliest Albian that is marked by the deposition of the Dalmiapuram Limestone Member. By this time, the rift system had become inundated and individual sub-basins linked. This facilitated a marine incursion from the Tethys Ocean to the north (as evidenced by the cosmopolitan nature of the assemblage of planktic foraminifera). It is likely that this event represents the lateral propagation of major through-going basin-bounding faults that developed interconnected transfer zones between the various sub-basins (Gawthorpe & Leeder 2000).

The main extensional phase commenced in the mid-Albian (*c.* 106 Ma) as recorded by a sudden deepening in the Ariyalur–Pondicherry Depression. This was coeval with the break-up of the stable Lower–Middle Albian, shallow-water carbonate platform by the propagation of extensional normal faults. This phase of deformation led to uplift and erosion of the Dalmiapurum Limestone Member, together with Precambrian crystalline basement at the basin margins. They were reworked by sediment gravity flows into the half-graben and deposited as proximal fault-scarp conglomerates – not the 'mud mounds' proposed by Venkatarengan (1987, figs 4, 6). From the evidence seen in the field it is suggested that these are proximal footwall-derived coarse-grained apron facies and tectonically derived Albian carbonate olistoliths. The presence of coarse-grained sand-rich turbidites located downdip of marine shales, locally rich in marine organic matter, clearly presents a potential petroleum exploration play for some southeast Indian sedimentary basins. Rapid generation of accommodation space resulted in siliciclastic turbidites being confined to basin margin settings, while marine mudstone deposition dominated the basin centre. This tectonic phase is analogous to Gawthorpe & Leeder's (2000) through-going fault stage. Major extension on basement faults had ceased by the mid-late Turonian, as evidenced by a relatively condensed succession of marginal marine and continental siliciclastic and carbonate rocks containing numerous hiatuses. This major facies change records the transition from the Syn-rift Megasequence to the Post-rift Megasequence.

It is likely that the stratigraphy for the syn-rift sequences of the onshore Cauvery Basin are a direct analogue for linked half-graben basins offshore. The presence of karstified shallow-marine carbonates, marine mass-flow systems and overlying marine shales provides significant potential for stratigraphic traps. Normal fault-bounded basins have been identified from seismic lines from offshore basins of the southeast Indian continental margin (Bastia 2006). Basin restriction, coupled with deposition during two Oceanic Anoxic Events (late Barremian to Albian, late Cenomanian to early Turonian), led to the deposition of over 90 m of organic-rich marine black shales within the Karai Clay Formation (Govindan 1982, 1993; Tewari *et al.* 1996). These represent the main petroleum source rock for the Cauvery Basin, and syn-rift reservoirs could be expected to charge directly through expulsion, or following short distance secondary migration.

The younger of the Post-rift Megasequences are unlikely to be a direct analogue for similar-aged deposits in the offshore Cauvery Basin, which will have been deepening following the formation of the southeast Indian continental margin during the late Cretaceous. One can, however, expect that the times of sequence boundary formation were times of siliciclastic sediment bypass into deeper-water plays to the east. Recent exploration has targeted deep-water sands of Turonian and Campanian age (www.oilvoice.com, 'Hardy begins offshore Cauvery Basin drilling programme', 24 July 2006).

It is interesting to note that more recent models of the tectonic evolution of this region place the location of the Cauvery Basin between India and Antarctica (e.g. Reeves & de Wit 2000, fig. 3). Some Indian geologists (e.g. Sastri *et al.* 1981, fig. 15) have argued that the East Coast Basins of India would be better juxtaposed against the basins of Western and Northwestern Australia. The evidence for this is based largely on the stratigraphic similarity of the Cauvery Basin in India and the Carnarvon Basin in Australia.

While there are some similarities within parts of these two successions, it is clear that the Carnarvon Basin has a marine succession that extends into the Barremian or even the uppermost Hauterivian (McLoughlin *et al.* 1995). The oldest marine succession with an identifiable fauna of foraminifera is the Muderong Shale Formation, and this appears to be Barremian in age (Taylor & Haig 2001). Similarities higher in the succession (e.g. the latest Cenomanian 'anoxic event' and the apparent equivalence of the Kallankuruchchi Limestone Formation and the Korojon Calcarenite) are almost certainly related to global highstands and not a common basin history. Comparative biostratigraphical work on the Cauvery and Carnarvon basins remains ongoing in the Palaeontology & Palaeoenvironments Research Group of the University of Plymouth.

CONCLUSIONS

The Cretaceous of the onshore Ariyalur–Pondicherry Depression (Cauvery Basin) provides insights into the timing and nature of tectonostratigraphic evolution of the southeast Indian continental margin, and formally conjugate margins in Northwest Australia and offshore Antarctica. Syn-rift and Post-rift Megasequences can be differentiated, within which a number of higher-order sequences are present. The timing of rift-onset, rift climax and post-rift phases help constrain the timing of the separation of southeast India from northern Australia during the Cretaceous.

The initiation of this sedimentary basin was associated with a first phase of rift-related extension during the latest(?) Barremian to mid-Albian (Syn-rift Sequence 1). In this rift initiation phase, continental lacustrine and alluvial sedimentation was restricted to a number of small half-graben basins. With continued extension, a through-going fault stage enabled inundation of marine waters into the most landward parts of the Cauvery Basin, and the establishment of marine carbonate platforms. The second Syn-rift Sequence (mid-Albian to Turonian) was marked by faulting, uplift and erosion of older sequences and basement rocks by normal faults. In this rift climax, or through-going fault phase, olistoliths, clastic turbidites and capping marine shales were deposited into a marine extensional fault-controlled basin, characterized by rapid deepening resulting from accelerated normal-fault controlled subsidence. The juxtaposition of black marine shales with syn-rift shallow-marine carbonates and siliciclastic turbidites has significant potential for future petroleum exploration in southeast Indian basins.

The Post-rift Megasequence (latest Turonian to late Maastrichtian) is characterized by significantly less deformation by normal faults, sub-horizontal and more consistent dips, reduced thickness compared to the syn-rift sequences, and a number of basin-wide hiatuses. This megasequence can be subdivided into three sequences composed of marginal marine siliciclastics and carbonates, with locally developed fluvial facies. The sequences are dominated by transgressive and highstand systems tracts. The regressive phases associated with the post-rift sequence boundaries (latest Turonian, late Santonian to early Campanian, early Maastrichtian) are likely to be times of siliciclastic sediment bypass into the offshore Cauvery Basin to the east.

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