TECTONIC AND VOLCANIC INFLUENCES ON THE DEVELOPMENT AND DIACHRONOUS TERMINATION OF A TERTIARY TROPICAL CARBONATE PLATFORM

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ABSTRACT: The demise of carbonate platforms has variously been related to factors such as tectonics, influx of clastic material, and environmental stress, sometimes in combination with eustatic fluctuations. However, the precise controls on foundering of platforms are often poorly understood. In Sulawesi, Indonesia, the extensive syntectonic Tonasa Carbonate Platform, of Eocene to middle Miocene age, developed to the west of a volcanic arc and is overlain by middle to upper Miocene volcanics. These carbonates provide a unique opportunity to study the effects of tectonic and volcanic activity on the development and subsequent demise of a carbonate platform.

Detailed field and laboratory analysis of the Tonasa Formation reveal that the shallow-water deposits of the Tonasa Carbonate Platform had their greatest areal extent in the late Eocene. Although a variety of factors influenced platform development, tectonics and volcanism were particularly important, influencing platform evolution and diachronous termination in four main ways: (1) During the Paleogene, calc-alkaline volcanic activity limited the eastward lateral extent of the platform but had little effect on carbonate sedimentation in western South Sulawesi. (2) Faulting in the latest late Eocene resulted in segmentation of the platform and caused localized drowning in hanging-wall areas and subaerial exposure on adjacent footwall highs. (3) A further phase of faulting in the early to middle Miocene, just prior to and during the early stages of renewed volcanism in western South Sulawesi, resulted in reactivation of faults, localized tilting of fault blocks, formation of new graben, and subaerial exposure of faulted footwall highs. (4) In the middle Miocene, the influx of volcaniclastics close to volcanic centers rapidly buried most of the few remaining areas of shallow-water carbonates and inhibited renewed carbonate production. However, carbonate production contemporaneous with volcanism occurred in more distal, or localized, areas shielded from volcaniclastic input.

INTRODUCTION

The interplay of factors controlling the spatial and temporal termination of carbonate production is poorly understood. It has been questioned what quantifiable factors could cause the foundering of carbonate platforms and whether there were any global trends in these events. Results indicate that the drowning of most healthy tropical carbonate platforms, related just to relative sea-level rise, is possible only by regional downfaulting or global rises due to desiccation of small ocean basins, submarine volcanic outpourings, or glacio-eustasy. In addition to relative sea-level changes, factors such as anoxia, clastic and nutrient input, climatic changes, platform-margin collapse, variations in salinity, and changes in carbonate producers are often instrumental in the demise of carbonate platforms (cf. Schlager 1981, 1989, 1998; Hallock and Schlager 1986; Schlager and Camber 1986; Vogt 1989; Erlich et al. 1990; Erlich et al. 1993; Enos et al. 1998). However, there is a general paucity of good case studies quantitatively documenting in detail the factors affecting the demise of individual carbonate platforms. In addition, there is a lack of data analyzing how an interplay of factors can result in different reasons for termination of carbonate production through time and space for individual carbonate successions.

Southeast Asia has been an area of extremely active tectonics and volcanism throughout the Cenozoic (Fig. 1). Cenozoic tropical carbonate production in this region was extensive and diverse, and developed in a range of tectonic settings, such as on microcontinental blocks, around the margins of extensional back-arc basins, or in forearc or intra-arc settings. The development and demise of many of these carbonate platforms was influenced by tectonics and volcanism or clastic input, and Southeast Asia is one of the best areas of the world to study these effects on Cenozoic carbonate platforms. This research on the well exposed Eocene to middle Miocene Tonasa Formation of South Sulawesi (Fig. 2) allows an excellent opportunity to assess the variable tectonic and volcanic influences on the development and demise of a tropical carbonate platform. Facies models, sedimentary evolution, and controls on sedimentation of this syntectonic carbonate platform were constrained from extensive facies mapping, logging, and petrographic and biostratigraphic work, and more details can be found in Wilson and Bosence (1996, 1997), Wilson (1999), and Wilson et al. (2000).

This paper first introduces the tectonostratigraphic setting of the carbonate platform and associated igneous lithologies. The next section details the nature of the contact between the carbonates and volcaniclastics in order to evaluate the reasons for the demise of the platform. The influences of tectonics and volcanism on the development and particularly the diachronous termination of the platform are outlined before the discussion. The reader is referred to Wilson et al. (2000) for details of facies models, controls on deposition, and initiation and evolution of this syntectonic platform.

The question of demise of carbonate platforms is not merely a semantic problem or one of just local interest. Many carbonate platforms form stratigraphic traps for hydrocarbons, yet the reservoir potential of carbonate platforms can be fully evaluated only with a knowledge of the factors affecting platform demise and the sealing capabilities of the overlying lithologies (cf. Erlich et al. 1990). The large-scale foundering of carbonate platforms can also drastically influence the global organic calcium carbonate budget (cf. Schlager 1981). A quantitative and better understanding of the factors influencing the demise of ancient carbonate successions may also help to safeguard the future of these unique and valuable ecosystems.

TECTONOOSTRATIGRAPHIC SETTING OF SOUTH SULAWESI

The geological history of Sulawesi is inextricably linked to the accretion of microcontinental and oceanic material onto the eastern cratonic margin of Eurasia, and to the resultant development of volcanic arcs (Fig. 1; Sukamto 1975; Hamilton 1979; van Leeuwen 1981; Wilson and Moss 1999). South Sulawesi, where outcrops of the Tonasa Formation occur, was accreted onto Eurasia in the Late Cretaceous and then separated from mainland Asia in the early Paleogene by widespread extensional basin development centered on the Makassar Straits (Fig. 1; van de Weerd and Armin 1992; Wilson and Moss 1999).

South Sulawesi has a thick, almost complete upper Cretaceous to present-day stratigraphy, with carbonate and igneous lithologies spanning much of the Tertiary (Figs. 2, 3; Sukamto 1975; van Leeuwen 1981). By Eocene times west-dipping subduction was occurring to the east, and marginal marine siliciclastics of the Malawa Formation, which pass transgressively upwards into carbonates of the Tonasa Formation (Fig. 4A) were deposited over western South Sulawesi. During the deposition of these sedimentary rocks, volcaniclastic and igneous lithologies of the Salo Kalupang, Langi, and Kalamiseng Formations dominated in eastern South Su-
The Eocene and Oligocene lithologies formed as a calc-alkaline volcanic arc thought to be due to west-dipping subduction, whereas the Kalamiseng Formation may be an ophiolitic sequence, accreted during the Oligo-Miocene (Yuwono et al. 1987). Paleogene oceanic spreading is inferred for the northern Makassar Strait from gravity data (Cloke 1997). There was considerable extension in the South Makassar Strait (β factor 2.5), and highly attenuated continental crust occurs in western South Sulawesi. However, a thick succession of flat-lying strata seen on seismic and gravity data from the South Makassar Strait suggest that Tertiary oceanic crust did not form in this area (Situmorang 1982; Dürbaum and Hinz 1982). Therefore the Tonasa Formation was deposited initially as part of a transgressive sequence on an area of attenuated continental crust behind an arc, but probably not in a true back-arc setting (Fig. 5; cf. Kearey and Vine 1996). The Tonasa Formation is overlain by volcaniclastic deposits of the Camba Formation, which were derived from a volcanic arc that developed in western Sulawesi in the middle to late Miocene, perhaps related to microcontinental collision to the east (Figs. 4B–D; Sukamto and Supriatna 1982; Yuwono et al. 1987; Bergman et al. 1996).

### THE TONASA CARBONATE PLATFORM

The Tonasa Formation crops out mainly in western South Sulawesi and was deposited as a widespread area of shallow-water carbonate production, known as the Tonasa Carbonate Platform, during the early or middle Eocene to middle Miocene (Figs. 2, 3; Wilson et al. 2000). Detailed facies mapping and logging (81 measured sections, totaling about 7 km of section), together with petrographic (~ 500 thin sections and acetate peels) and biostratigraphic analysis was undertaken throughout the outcrop area of the Tonasa Formation. Larger benthic foraminifera dominate lithologies of this platform, which were deposited within the photic zone. Other bioclasts include coralline algae, echinoid fragments, small benthic foraminifera, and rare corals.

The Tonasa Formation includes up to 600 m of shallow-water carbonates (Fig. 4A) deposited in the main platform area (Pangkajene area, Fig. 2; Wilson et al. 2000). Shallow-water carbonates overlain by basinal lithologies, totaling over a kilometer, were deposited to the north (Barru area) and south (Jeneponto area) of this platform. The Tonasa Carbonate Platform had a north–south extent of about 100 km. The main platform had a tilt-block morphology from late Eocene times (Wilson et al. 2000) and was bounded by a segmented, faulted northern platform margin (Wilson and Bosence 1996) and a gently dipping ramp-type southern margin (Wilson and Bosence 1997). Areas of more complex block faulting lay to the east (Western Divide Mountains area) and west (Segeri area) of the main tilt-block platform (Fig. 2; Wilson et al. 2000). A variety of factors, including tectonics, volcanism, carbonate producers, climate, and oceanography influenced the development of the platform. Although a eustatic sea-level fall in the Oligocene may have been a contributing factor in localized subaerial exposure of the platform, the effects of eustasy are difficult to discern on this platform strongly influenced by tectonics (Wilson et al. 2000). Detailed analysis of platform and surrounding basal deposits reveal that the Tonasa Carbonate Platform was affected by a number of phases of syndepositional tectonic activity (see below and van Leeuwen 1981; Wilson and Bosence 1996; Wilson 1999; and Wilson et al. 2000). This paper concentrates on the factors controlling the diachronous demise of this Tertiary platform, evaluating the relative roles of tectonics and volcanism.

### VOLCANICS AND VOLCANICLASTICS OF THE CAMBA FORMATION

Middle to upper Miocene volcanics and volcaniclastics overlie the Tonasa Formation and older formations, locally with an angular unconformity (Figs. 2, 3). These volcaniclastic sediments, igneous extrusives, and associated intrusives constitute the Camba Formation (Sukamto 1982; Sukamto and Supriatna 1982; Yuwono et al. 1987). The Camba Formation was de-
Fig. 2.—Geological map of South Sulawesi (after van Leeuwen 1981, Sukamto 1982, Sukamto and Supriatna 1982, Wilson et al. in press), showing the locations of the five main outcrop areas of the Tonasa Formation and the location of mentioned measured sections.

The lower member of the Camba Formation (Camba I Formation; Yuwono et al. 1987) is composed of tuffaceous sandstones interbedded with tuffs, sandstones, claystones, volcanic conglomerates/breccias, marls, limestones, and coal and is dated as middle to late Miocene (N9–N15; Sukamto 1982; Sukamto and Supriatna 1982). The dominantly volcanic upper member of the Camba Formation is also dated as middle to late Miocene on the basis of foraminifera (Sukamto 1982) and K–Ar and fission-track dating of igneous rocks (Yuwono et al. 1987; van Leeuwen 1981). This member includes volcanic breccias/conglomerates, lavas, and tuffs and is described here as the Camba Volcanics. Intercalated with the volcanic lithologies are marine sediments including tuffaceous sandstones, calcareous sandstones, and claystones containing disseminated plant remains (Sukamto 1982; Sukamto and Supriatna 1982). The lower part of the Camba Volcanics contains more volcanic breccia and lava of basaltic and andesitic composition.
SUKAMTO AND SUPRIATNA 1982) and is thought to be equivalent to the Sopo Volcanics described from near Biru (Fig. 2; van Leeuwen 1981). The upper part of the Camba Volcanics probably corresponds to the Pammesurang Volcanics, which disconformably overlie earlier successions near Biru and includes ignimbrites, lavas, tuffs, marls, and volcaniclastics (van Leeuwen 1981).

**CONTACT BETWEEN, AND DEPOSITIONAL ENVIRONMENTS OF, THE UPPERMOST CARBONATES AND OVERLYING VOLCANICS**

The contact between the carbonates of the Tonasa Formation and the volcaniclastics of the overlying Camba Formation is extremely variable, reflecting differing reasons for diachronous carbonate platform termination. This contact was studied, where accessible, in 22 sections distributed across western South Sulawesi (Figs. 2, 6). To evaluate factors influencing carbonate platform demise, sections crossing the contact were subdivided into those with conformable or angular unconformable contacts, and for the latter there may be a major or minor (intra-Miocene) hiatus. Lithological and chronostratigraphic correlations of selected sections that cross this contact and simplified cross sections across the platform are shown on Figures 6 and 7.

**Conformable Contacts**

A conformable contact between shallow-water deposits of the Tonasa Carbonate Platform and the overlying volcanics of the Camba Formation was studied in the Patunuang Asue section in the Pangkajene area (Figs. 2, 6). Along the rest of the eastern periphery of the Pangkajene Area the contact between these two formations is a fault contact or is poorly exposed. Conformable contacts between deep-water deposits of the Tonasa and Camba Formations occur in many sections in the Barru and Western Divide areas (Figs. 2, 6).

The upper part of the carbonate succession in the Patunuang Asue section was deposited under moderate-energy, shallow-water conditions, inferred from fragmented corals and alveolinids (Wilson and Bosence 1997). *Flosculinella sp.* indicates an early Miocene (Te₅) or younger age for the up-
permost beds of the Tonasa Formation, and there is no evidence for subaerial exposure of the carbonates. Slightly abraded euhedral feldspars constitute a few percent by volume of a limestone bed ten meters below the first bed of the Camba Formation. Therefore the early stages of volcanic activity are inferred to be contemporaneous with the last stages of carbonate production on the platform top. Fragmented plant matter is also common in these uppermost beds of the Tonasa Formation, indicating proximity to a marginal marine or terrestrial habitat where vegetation could grow. After a 3 m gap, a 2.3-m-thick coal bed, with the same attitude of bedding as the Tonasa Formation, is the first exposed bed of the lower Camba Formation. Overlying this coal are poorly exposed pink and brown mottled claystones, interpreted as soils, interbedded with volcaniclastic siltstones. It is unclear if there was a relative sea-level fall during the early deposition of the Camba Formation in this area, or whether volcaniclastic material passively infilled the available marine accommodation space. A heavily altered mafic sill or lava flow and coarse volcaniclastic conglomerates of the upper Camba Formation, thought to be deposited as sheet-flood deposits, crop out above the soils.

Conformable contacts between the Tonasa and Camba Formations were studied along the eastern side of Barru area (Rala, Bangabangae, Doi-doi, and Salupura sections) and in the Bua, Birau Menge, Malawa East, and Biru South sections in the Western Divide area (Figs. 2, 6). The upper part of the Tonasa Formation in all these sections is composed of deep marine marls of early to middle Miocene age (NN4–NN5), containing abundant planktonic foraminifera, interbedded with redeposited carbonate facies. In the Rala, Doi-doi, Salapura, Birau Menge, and Bua sections, extremely thick, texturally and compositionally immature redeposited carbonate units dominate the uppermost part of the Tonasa Formation (Fig. 8A). These sections are all proximal to faulted footwall highs, and carbonates and material from the underlying formations were reworked into adjacent hangingwall depocenters during periods of block faulting (Fig. 9; Wilson and Bosence 1996; Wilson et al. 2000). The lower member of the Camba Formation, conformably overlying the Tonasa Formation, is composed of interbedded dark gray bioturbated mudstones, tuffs, and fine to gravel-grade volcaniclastics. The volcaniclastic beds often have erosional bases, fine upwards, and contain Bouma sequences characteristic of turbidites. The dark shales are laminated and include centimeter-scale randomly oriented burrows and a few planktonic foraminifera. Deposition occurred in deep marine environments, into which there was episodic influx of volcaniclastic material.

Where the conformable contact between deep marine carbonates and volcaniclastic is seen to within a few meters it is either sharp or gradational to interdigitating. In the Bangabangae and Birau Menge sections, sharp conformable contacts occur, with interbedded bryalshales and fine volcaniclastic units directly overlying marls or redeposited carbonates. Planktonic and benthic foraminifera, rare shallow-water carbonate clasts, and...
deeper-water marls are reworked into volcaniclastic sandstones and conglomerates in the lower few tens of meters of the Camba Formation. In the basal 35 m of the Camba Formation in the Bangabangae section, conglomerates, of a few meters thickness, containing rounded marl clasts in a shale matrix are interbedded with the shales and volcaniclastic siltstones. The reworking of abundant marl clasts into these units suggests slope instability, perhaps related to tectonics. The contact in the Salapura and Rala sections are gradational, because dominantly carbonate beds in the upper few tens of meters of the Tonasa Formation contain up to 20±30% euhedral feldspar crystals.

In the North Biru section, there is an angular unconformity between Paleogene shallow-water limestones of the Tonasa Formation and the Miocene Camba Formation (or Sopo Volcanics; van Leeuwen 1981). However, although the Camba Formation has been eroded south of this contact, interbeds occur between deep-water Neogene carbonates deposited in a fault-bounded graben and the volcaniclastics. In this South Biru section, tuff beds, euhedral feldspars, and igneous clasts occur in redeposited carbonates interbedded with marls at least 80 m below the base of the Camba Formation. These beds have been dated as lower middle Miocene (van Leeuwen 1981) and indicate early volcanic activity contemporaneous with the late stages of carbonate production.

**Angular Unconformable Contact with Minor Intra-Neogene Hiatus**

Angular unconformable contacts with an intra-Neogene hiatus occur in the Jeneponto Area, the Padanglampe section (Segeri Area), and the Camba section (Western Divide area, Figs. 2, 6). Miocene carbonates of the Tonasa Formation were deposited in shallow water in the Padanglampe and Camba sections and under bathyal conditions in the Jeneponto area.

At Camba, the lower marine member of the Camba Formation is a few tens of meters thick, has bedding dipping 20° to the northeast, and consists of dark claystones interbedded with conglomerates and graded volcaniclastic sandstones, packstones, and rudstones. The claystones contain well preserved gastropods and oysters, indicating shallow depositional depths. The sandstones, conglomerates, packstones, and rudstones contain dominantly euhedral feldspars, pyroxenes, opaque minerals, volcanic clasts, and up to 50% un lithified carbonate material. Reworked bioclasts include corals, shell fragments, coralline algae, and foraminifera. In comparison, the Miocene (Te5 or younger) Tonasa Formation dips 20° to the west, indicating an angular unconformity of about 40°. The Tonasa Formation is lithified, in some places recrystallized, and does not contain corals. These facts suggest that the shallow marine bioclasts in the Camba Formation were derived from nearby carbonate-producing areas contemporaneous with volcanic activity and after the deposition of the Tonasa Formation. Karstic cavities in the Tonasa Formation, containing laminae of ostracods, cave pearls, and volcaniclastic material, are linked by small-scale faults, indicating tectonic tilting and karstification prior to volcanic activity (Fig. 8B; see below).

At Padanglampe the lower member of the Camba Formation is less than ten meters thick and consists of interbedded volcaniclastic siltstones and sandstones. These lithologies unconformably (angular unconformity 10°-40°) overlie bioclastic packstones of the Tonasa Formation. The limestones contain fragmented echinoids, coralline algae, whole and fragmented *Leptidocyolina sp.*, *Spiroclypeus sp.*, *Heterostegina sp.*, *Miogypsina sp.*, and small benthic foraminifera. Well preserved planktonic foraminifera in the packstones, including *Globigerinoides sacculifer*, indicate an early to middle Miocene age (N7–8) and an open oceanic influence. Subaerial exposure...
North-South correlation of sections crossing the contact between the Tonasa and Camba Formations and schematic cross section prior to volcanism

Key to lithologies on measured sections:
- Shallow-water carbonates
- Redeposited facies predominant
- Marl predominant
- Angular unconformity
- Substantial exposure or karstification surface

Camba Formation:
- Coarse volcanioclastic facies predominant
- Terrigenous-marine clays predominant
- Deep marine shale predominant
- Ignimbrite and volcanioclastic material

Scale for measured sections is in meters. Cross sections are at 20 m spacing. Complete sections of the Tonasa Formation are not shown. Thicknesses for the Tonasa Formation are given from the base of the carbonate succession. For descriptions of the measured sections see text.

For the foraminiferal zones see Figure 3.
and colonization by plants just prior to the deposition of volcaniclastics is inferred from alveolar structures and fine sediment infilling karstic disolution cavities in the upper few meters of the limestones.

In the Jeneponto area the contact with the overlying Camba Formation was logged in the Tabatingea section and the Sungai Allu 1 and 2 sections (Fig. 10). In these sections, marls and planktonic foraminifera wackestones/packstones of early to middle Miocene age (NN4–NN5) dip more steeply (15°–25°) than the overlying shales and volcaniclastics of the Camba Formation (10°–12°). Twelve kilometers to the east, near Sapang there is a small decrease in the angle of dip between the Tonasa Formation (310°/15°) and the Camba Formation (310°/12°). These differences in bedding angle (3°–15°) may indicate a low-angle unconformity between the two formations or a change in depositional slope (cf. Schlager and Camber 1986). The change to noncarbonate facies of the Camba Formation is relatively sharp, with only one bed (NJ76, Fig. 10) showing significant mixing of carbonate and noncarbonate grains (up to 50% volcaniclastic grains).

The lower Camba Formation in the Jeneponto Area is composed of interbedded dark marine shales and volcaniclastic siltstones, sandstones, and conglomerates (Fig. 10). Submarine deposition is inferred from abundant burrows, rare planktonic foraminifera, climbing ripples in the siltstones (NJ69), and load structures (NJ69, Fig. 10). Normal grading in the volcaniclastic beds suggests deposition under waning current. The coarse sediments are dominantly composed of subangular clasts of heavily altered volcanic lithologies. Minerals, such as feldspar, pyroxene, and opaques, and rip-up clasts of dark shales are also present. Volcaniclastic beds cannot be correlated within the Camba Formation (Fig. 10), suggesting channelization.

Angular Unconformable Contact with Major Hiatus

In the southwest Barru area and the Ujunglamur, Malawa West, and Biru North (van Leeuwen 1981) sections in the Western Divide area the Camba Formation unconformably overlies the Tonasa Formation and there is a significant hiatus in the timing of deposition between these two formations (Figs. 2, 6). In all these sections, shallow-water Paleogene deposits of the Tonasa Formation are unconformably overlain by the Camba Formation. Uplift, tilting, and periods of nondeposition or erosion during block faulting are inferred for all these sections prior to volcanism (see below).

In the southwest Barru area, the upper volcanic member of the Camba Formation overlies the Tonasa Formation or older formations with an angular unconformity, and the lower member of the Camba Formation is absent (Wilson and Bosence 1996). In the Lisu and Bulo Bentjeng sections (Fig. 2), upper Eocene (Tb) shallow-water carbonates of the Tonasa Formation are overlain by volcaniclastics. In the Rumpio section (Fig. 2), upper Eocene (Tb) shallow-water limestones are overlain by 40–50 m of poorly exposed redeposited carbonate units, containing Eocene and Oligo-Miocene shallow-water biota. Where volcaniclastic conglomerates occur in the basal few meters of the Camba Formation, they contain up to 40% limestone clasts (Fig. 8C). However, much of the periods of erosion and nondeposition on these footwall highs occurred prior to volcanism (Wilson and Bosence 1996; Wilson et al. 2000).

In the Western Divide area, on the western limb of the anticline close to the village of Ujunglamur, 60 m of upper Eocene (Tb) limestones are unconformably overlain by coarse volcaniclastics. On the eastern limb of this anticline the volcaniclastics, including a basal conglomerate containing subrounded clasts of igneous lithologies, marls, and packstones, unconformably overlies claystones and sandstones of the Eocene Malawa Formation. Four hundred meters to the east, horizontally bedded coral framework limestones of the Miocene Tacipi Limestone (Fig. 3) overlie the Malawa and Tonasa Formations with an angular unconformity. These relationships indicate that the Malawa and Tonasa Formations were tilted prior to the deposition of the Camba Formation. Further tilting then occurred prior to the deposition of the Tacipi Limestone. In the Malawa section, 32 m of shallow-water limestones of the Tonasa Formation overlie coals and clastics of the Malawa Formation. The limestones contain abundant miliolids, suggesting they were deposited in a restricted shallow-water setting, and although no age diagnostic fossil were found an Eocene age is inferred. The upper 14 m of these carbonates has been karstified and is unconformably overlain by volcaniclastics of the Camba Formation.

TECTONIC AND VOLCANIC CONTROLS ON THE DEVELOPMENT AND DEMISE OF THE PLATFORM

The initiation and development of the Tonasa Carbonate Platform occurred contemporaneously with tectonic activity, and with volcanic activity to the east, yet shallow-water carbonate production continued unabated on many areas of the platform throughout much of the Tertiary. The final demise of this “long-lived” platform was related to a combination of tectonic activity and volcanism in the immediate vicinity of the platform, with the precise timing and causes for demise varying locally. The sections below explore what level of volcanic and/or tectonic activity the Tonasa Carbonate Platform could withstand and the reasons for the final extermination of the platform.

Paleogene Volcanism Limited the Eastward Lateral Extent of the Platform

Calc-alkaline arc volcanism was active in eastern South Sulawesi during the Paleogene, and was contemporaneous with carbonate sedimentation on the Tonasa Platform to the west (van Leeuwen 1981). Volcanogenic units of the Langi Formation are interbedded with the basal part of the carbonate section close to Biru. In other areas, rare arkosic packstones are intercalated with the carbonate succession. The Langi Formation consists of highly altered lavas, volcanic breccias, and tuffs of andesitic to trachyandesitic composition (van Leeuwen 1981). Near the top of the Langi Formation close to Biru, intercalations of limestone, a few meters thick, contain abundant larger benthic foraminifera and up to 50% volcanogenic grains. These limestone units are interpreted as foraminiferal shoals, which developed on the flanks of the volcanic arc during periods of relative volcanic quiescence (Fig. 5). To the west of the Walanae Depression, rare carbonate interbeds in the Salo Kalupang Formation and the limited occurrence of the Tonasa Formation in eastern South Sulawesi also suggest that carbonate sedimentation was localized in areas near to volcanic activity. Therefore in areas close to the volcanic arc, 5–15 km from the volcanic centers, volcanogenic input commonly hindered shallow-water carbonate production. However, foraminiferal shoals were able to develop, albeit for short periods of time, when rates of input of sand-size volcaniclastic grains were about equal to, or less than, rates of carbonate production (Fig. 5).

The Tonasa Carbonate Platform developed up to 40–50 km to the west of the main inferred volcanic arc (Fig. 5). Except for limiting the eastward
Fig. 7.—Chronostratigraphic correlation among, and environmental interpretation of, selected sections through the Tonasa Formation (after Wilson et al. in press).

Fig. 8.—A) Coarse, immature redeposited carbonates derived from the northern faulted margin of the main tilt-block Tonasa Carbonate Platform and resedimented into an adjacent hangingwall depocenter in the Barru Area. B) Photomicrograph of Miocene fissure-fill sediment from the uppermost part of the Tonasa Formation in the Camba section. Scale bar is 500 µm. Laminae of micrite and cave pearls constitute most of the fissure fill. A fracture infilled with fine volcaniclastic sediment postdates the carbonate fill of the cavity. C) Limestone clasts reworked into the basal few meters of the volcaniclastics on faulted footwall highs (Rumpio section, Barru area).
Fig. 9.—Paleogeography of western South Sulawesi and the Tonasa Carbonate Platform during the middle Miocene just prior to the beginning of volcanic activity.

Paleogene Faulting Caused Localized Foundering of the Platform

Faulting and tectonic subsidence contemporaneous with carbonate deposition strongly controlled the development of the Tonasa Platform from the latest Eocene onwards. The greatest lateral extent of the shallow-water platform was during the earliest late Eocene (Wilson et al. 2000). During the latest late Eocene, fault segmentation resulted in localized foundering of the platform (Fig. 7; Wilson and Bosence 1996; Wilson 1999). In the Barru and Segeri areas, subsidence of hangingwall areas and graben formation caused rapid drowning of shallow-water carbonates. Footwall uplift of fault blocks adjacent to these graben in the northern Pangkajene and Segeri areas resulted in localized subaerial exposure and erosion of the platform top. Footwall uplift, emergence, and tilting of fault blocks in the Western Divide Mountains area may have also affected the Malawa West and Ujunglamuru sections at this time (Fig. 7).

Accumulation rates for the shallow-water larger benthic foraminifera dominated carbonates on the Tonasa Platform, ignoring the effects of compaction, vary between 0.07 and 0.3 m/ky, surprisingly low for Cenozoic tropical carbonates (Wilson et al. 2000). Subsidence of hangingwall blocks during faulting, with rates of 0.5 m/ky, was therefore usually more than sufficient to cause rapid drowning of the shallow-water carbonates (Wilson 1999).

Regional tectonic subsidence, after removing the effects of block faulting, for these carbonates, was about 0.02 m/ky (Wilson et al. 2000). This would not have been sufficient to cause drowning of the shallow-water carbonates but may have resulted in areas previously uplifted by block faulting being submerged below sea level. The resurgence of shallow-water carbonate production on the northern part of the main tilt-block platform probably occurred as a result of regional subsidence. Computer modeling of the main Tonasa tilt-block platform showed that during faulting the combined effects of regional subsidence and subsidence related to lateral extent of the platform and the interdigitation and minor volcanioclastic input to the east, volcanic activity had little overall tangible effect on the development of the carbonate platform in western South Sulawesi. Paleocurrent data from cross-bedding in the platform carbonates (Wilson and Bosence 1997) suggests that western South Sulawesi was located on the lee side of the volcanic arc, and it is therefore unsurprising that fallout of fine-grained volcanogenic detritus did not affect the platform. Coarse-grained volcanic debris and the extent of lava flows was limited to within about 15 km of the main volcanic arc and therefore affected only the eastern part of the platform. Paleogene deposits are not exposed in the Walanae Depression (Figs. 2, 3), and one possibility is that shallow-water carbonates of the Tonasa Carbonate Platform extended across this area (Fig. 5). Alternatively, a basinal area, located along the present-day Walanae Depression, between the western and eastern parts of South Sulawesi may have acted as a trap for volcanioclastic debris. This is likely if the main development of the Tonasa Carbonate Platform occurred on faulted highs separated from the main volcanic arc, as is seen behind other volcanic arcs (cf. Fulthorpe and Schlanger 1989; Marsaglia 1995). It is inferred from the Biru and Malawa sections that basinial fault-bounded graben did not develop along the western flank of the Walanae Depression until the early Miocene. The size of the Tonasa Carbonate Platform, about 100 km across, is unusual for a carbonate platform developed behind a volcanic arc. Most carbonate platforms close to volcanic arcs are a few kilometers to tens of kilometers across, because of high subsidence rates and the localized and limited occurrence of faulted highs (Fulthorpe and Schlanger 1989; Watkins 1993; Busby and Ingersoll 1995). Western Sulawesi is composed of material much of which is microcontinental in origin (Hamilton 1979). Basement lithologies and structures strongly influenced which areas subsided or were uplifted, and the relatively buoyant nature of the crust in western South Sulawesi allowed the development of an extensive carbonate platform.
F I G . 10.—Diagram to show measured sections crossing the low-angle unconformable contact between the Tonasa and Camba Formations in the Jeneponto Area. All deposition occurred in bathyal environments. Correlation between beds is not possible.
block rotation could have caused the observed rapid drowning and “step back” of the southern ramp-type margin. During phases of tectonic quiescence, middle-ramp to outer-ramp deposits were able to prograde southwards again (Wilson et al. 2000). Minor early to late Oligocene normal faulting may have caused shedding of coarse, immature redeposited facies in the Barru area and localized subaerial exposure, although a eustatic sea-level change may also have influenced sedimentation at this time (Wilson and Bosence 1996; Wilson et al. 2000).

**Neogene Faulting Prior to Volcanism Radically Altered the Morphology of the Platform and Caused Localized Drowning**

A period of early to middle Miocene faulting prior to and partially during the earliest stages of Neogene volcanism strongly affected much of the Tonasa Carbonate Platform. Tectonic activity caused reactivation of some of the Paleogene faults, resulting in new graben formation, renewed localized uplift of footwall blocks (below), and shedding of very immature redeposited carbonates into hangingwall depocenters (Fig. 7; Wilson and Bosence 1996). The ramp-type southern margin of the main tilt-block platform also “stepped back” at this time, inferred to be related to periods of fault-block rotation similar to that during the Paleogene (Wilson et al. 2000). Interbedded with basinal marls in the Jeneponto area are planktonic foraminifera wackestones, which may be the distal deposits of redeposited carbonate facies. If these deposits are distal redeposited facies, this suggests the Jeneponto area was more unstable during the Miocene than during the Paleogene. The possible unconformity between the Tonasa and Camba Formations in this area may also indicate tectonic tilting prior to volcanism.

New normal faults became active in the Western Divide area, forming graben and resulted in the drowning of shallow-water carbonate sections such as in Biru and Bua. Footwall areas adjacent to these graben either continued to accumulate shallow-water carbonates or became locally emergent, and there was considerable reposition of lithified carbonates into hangingwall depocenters (Fig. 8A). Accumulation rates for Oligo-Miocene shallow-water carbonates dominated by larger benthic foraminifera on the platform were between 0.03 and 0.05 m/ky, ignoring the effects of compaction. Subsidence rates in hangingwall blocks are inferred to have been at least an order of magnitude greater than this. Rapid drowning of shallow-water successions, as evidenced by marls and redeposited carbonates directly overlying shallow-water carbonates, resulted directly from this subsidence.

Neogene faulting altered the Paleogene morphology (Fig. 5) of the Tonasa Carbonate Platform, and a paleogeographic map of the platform just prior to volcanism is shown in Figure 9. The combined effects of Paleogene and Neogene faulting, causing basinal graben formation and exposure of footwall highs, had greatly reduced the area of shallow-water carbonate production. Just prior to Neogene volcanism, shallow-water carbonates were restricted to the Pangkajene area and small parts of the Western Divide area (Fig. 9), compared with the original platform, which extended across western South Sulawesi in the earliest late Eocene.

**Neogene Faulting Prior to Volcanism Caused Localized Emergence and/or Tilting**

Angular unconformable contacts between the Tonasa and Camba Formations, in about half the sections studied, indicate tectonic tilting of a number of areas prior to volcanism. Many of the angular unconformable contacts occur in sections above commonly karstified shallow-water carbonates, where there was a hiatus of variable duration before volcanism (Fig. 7).

The difference in dip angle of bedding between the shallow-water carbonates and the volcanics may be as much as 40°, and dip directions vary, indicating localized tectonic tilting associated with block faulting prior to volcanism, rather than a change in depositional slope angle. Tilting did not affect most of the graben successions, inasmuch as conformable contacts are located mainly between the deep-water marls and volcanics. It is not clear whether the minor angular unconformity in Miocene bathyal deposits in the Jeneponto area (Fig. 10) was related to tectonics or to a change in depositional slope.

Evidence for subaerial exposure comes from karstic dissolution cavities, in places coated in speleothem cements and infilled by fine laminated sediments, cave pearls, or crystal silts. Microcodium, alveolar structures, and rootlets provide further evidence for subaerial exposure. Miocene shallow-water carbonates in the Camba and Padanglampe sections have been tilted and karstified and are directly overlain by the Camba Formation. Karstic cavities, formed along linked systems of fractures, in the uppermost carbonates in the Camba section are infilled with laminated carbonate and volcanlastic material (Fig. 8B). Offsets of a few centimeters are seen across later minor normal faults, often containing volcanlastic sediment, which cut the lithified carbonates and cave-fill sediments but do not pass upwards into the overlying volcanlastics. Tilting, causing subaerial exposure, and fracturing of the carbonate succession is therefore inferred prior to, or during, the very early stages of volcanism.

Much of the evidence for in situ karstification of shallow-water carbonates deposited on footwall highs has been removed by erosion, or sections are covered by volcanastics. Indirect evidence for localized subaerial exposure of footwall highs prior to volcanism can be found in karstified limestone clasts reworked from footwall highs (Wilson and Bosence 1996). Reworked shallow-water limestone clasts indicate that the Barru Block was subaerially exposed during the late Eocene and Miocene, whereas the Bantimala Block was probably not exposed until the latest Oligocene (Figs. 2, 5; Wilson and Bosence 1996). Upper Eocene to middle Miocene redeposited facies in the Segeri Area contain reworked shallow-water limestone clasts with karstic cavities, suggesting that adjacent areas were subaerially exposed. Localized uplift and subaerial exposure of the carbonate succession on footwall highs is therefore inferred during the Cenozoic and particularly during the Miocene prior to the onset of volcanism. Although a Miocene eustatic sea-level fall may have been a contributing cause in localized subaerial exposure, it is inferred from the evidence of tilting and contemporaneous deep-water sedimentation that block faulting was the main cause of termination of carbonate production.

The Camba Formation, and older formations, are commonly folded, and intraformational angular unconformities occur close to Biru (van Leeuwen 1981), Ujunglamur, and other areas in western South Sulawesi. Tectonic folding and after the deposition of the volcanastics is related to further block faulting and folding.

**Effects of Neogene Volcanism on the Carbonates**

Fresh volcanlastic debris is present in the upper few tens of meters of some shallow-marine and deep-marine successions of the Tonasa Formation. This indicates that some carbonate production and accumulation was contemporaneous with the early stages of volcanism. In many areas where carbonate production had already ceased, such as karstified footwall highs, volcanlastic influx prevented renewed shallow-water carbonate production if the blocks subsided below sea level. In the few remaining areas of shallow-water carbonate production, such as the Patuung Asue area, it is difficult to ascertain whether the influx of volcanlastic material and/or relative sea-level change caused the final demise. However, for many shallow and bathyal sections the contact is sharp or the transition/interdigitation occurs over a few meters, suggesting a rapid change from carbonate-dominated to volcanlastic-dominated deposits. The influx of volcanlastic debris therefore strongly hindered and/or probably caused the demise of carbonate production in the remaining shallow-water areas proximal to volcanism. Minor erosion and reworking of carbonates during the early stages of volcanism is inferred from fragmented bioclasts or lithified carbonate clasts in overlying basal conglomerates of the Camba Formation. In deep-
water successions this may be related to slope instability caused by tectonics.

The timing of the start of Neogene volcanism and the main influx of volcaniclastic debris was diachronous across western South Sulawesi. Tuffs in the upper part of the Tonasa Formation in the Biru section are earliest middle Miocene in age (Tf1), whilst for other sections the earliest record of volcaniclastic debris is during the later part of the middle Miocene (NN8 at the earliest). During the main influx of volcaniclastic debris, average sedimentation rates were on the order of at least 0.5 m/ky. This is the same order of magnitude as the maximum accumulation rates for the shallow-water carbonates. It is therefore not surprising that in areas close to initial volcanic centers the final demise of the few remaining areas of carbonate production was rapid, as indicated by the sharp contacts. However, carbonate production was coeval with the early stages of volcanism in distal areas, as evidenced by the presence of volcaniclastic debris in the upper few tens of meters of the Tonasa Formation in some sections. Carbonate beds close to the contact with the Camba Formation may contain up to 40% volcaniclastic material along with well preserved shallow marine bioclasts. In comparison, beds in the basal part of the Camba Formation contain less than 50% shallow marine bioclasts, which are fragmented and reworked, or if conglomeratic, less than 40% lithified carbonate clasts. It is therefore suggested that for foraminiferal-dominated carbonates, termination of carbonate production occurs when the rate of influx of volcaniclastic debris is equal to or greater than the rate of carbonate production.

In the Camba locality, after tilting, fracturing, and karstification of the Miocene Tonasa Formation (above), the lower member of the Camba Formation was deposited in a marginal to shallow marine setting. Interbedded with these volcanioclastics are packstones and rudstones containing abundant unliothfied shallow-water bioclasts. These bioclasts were derived from nearby shallow-water carbonate-producing areas, which developed contemporaneously with volcanic activity and after deposition of the Tonasa Formation. The middle to upper Miocene carbonates of the Tacipi Formation in eastern South Sulawesi also developed contemporaneously with volcanism. Therefore, carbonate production occurred in shallow-water areas sufficient-ly distal from volcaniclastic influx or during periods of volcanic quiescence, as in other arc settings (see below).

DISCUSSION: TECTONICS VERSUS VOLCANISM AS THE CAUSE OF DEMISE OF THE PLATFORM

Tectonostratigraphic Setting and Factors Leading to Termination of the Tonasa Carbonate Platform

The Tonasa Carbonate Platform developed less than 60 km to the west of a volcanic arc and was strongly affected by tectonics. Arc volcanism inhibited shallow-water production close to volcanic centers and limited the eastward lateral extent of the platform but had little effect on Paleogene carbonate sedimentation in western Sulawesi. Paleogene and Neogene faulting resulted in segmentation of the extensive shallow-water platform, causing localized tilting, drowning of downfaulted blocks, and subaerial emergence on some football highs. In areas that drowned, shallow-water carbonate production was never able to recover, whereas some of the emergent highs became sites of renewed carbonate production if they subsided below sea level. Rapid subsidence rates, subsidence below the photic zone, fault reactivation, and slow accumulation rates of the carbonates dominated by larger benthic foraminifera, all contributed to the terminal nature of the drowning. Faulting radically altered the morphology of the platform and drastically reduced the available areas habitable for shallow-water carbonate producers. The start of Neogene volcanism in western South Sulawesi was diachronous within the middle Miocene. Initial Neogene volcaniclastic sediments were deposited on an irregular surface with variable submarine and subaerial topography caused by block faulting. Near to volcanic centers, in the few remaining shallow-water areas, carbonate production rapidly ceased. In previously subaerially exposed areas the resurgence of shallow-water carbonate production was prevented by the massive influx of coarse volcaniclastic debris. In more distal areas, or those protected from volcaniclastic influx, carbonate production continued.

Comparison of Platform Termination in Other Volcanic Arcs or Tectonically Active Areas

The evolution and demise of the Tonasa Carbonate Platform is similar in many ways to other carbonates developed in back-arc, intra-arc, or other tectonically active settings with some clastic or volcaniclastic input. Carbonates fringe many active and recent volcanic islands, such as those along the north coast of Sulawesi. Misconceptions that carbonates are unlikely to accumulate and/or be preserved near active volcanic areas have been dis-pelled by a number of studies of carbonates in ancient arc settings (cf. Soja 1993 for review). In more distal areas, shielded from volcaniclastic debris, or during periods of volcanic quiescence, the flanks of volcanoes or nearby areas within the photic zone often become the sites of carbonate production (Blendinger 1986; Göktén 1986; Fulthorpe and Schlanger 1989; Soja 1990, 1993). Indeed, Fulthorpe and Schlanger (1989) showed that volcanic arcs in the tropics are often favorable sites for major carbonate development because of their isolation from continental sources of siliciclastics. Thick carbonate successions, such as those from the Philippines (Hawkins et al. 1985), Guam (Tracey et al. 1964), and the Silurian of Alaska (Soja 1990, 1993) may develop during periods of volcanic quiescence or on faulted highs shielded from volcaniclastic input.

Soja (1993, 1996) has suggested guidelines for the recognition of ancient arc-related carbonates. The Tonasa Formation fulfills a number of these criteria, namely the association with calc-alkaline volcanics and volcaniclastics, a great thickness of platform carbonates, evidence for crustal instability, and rapid vertical and lateral facies changes between carbonates and volcaniclastics and between shallow-water and deep-water limestones. Other criteria such as high levels of species endemism are not seen in the Tonasa Formation, perhaps because Sulawesi lies in an area where tropical carbonate development was extensive and local interchange of biota was possible. However, the abundance of larger benthic foraminifera and scarcity of “reefal corals” in Paleogene carbonates in Southeast Asia may be related to biogeographic isolation from other coral-rich regions at this time (Wilson and Rosen 1998). The dominance of these larger benthic foraminifera, and the resultant slow accumulation rates of the shallow-water carbonates, meant that fault-related subsidence invariably caused localized drowning of the Tonasa Carbonate Platform. Therefore another criterion, that of high carbonate accumulation rates, is also not met by the Tonasa Formation.

One of the most intense phases of tectonic activity to affect the Tonasa Platform occurred just prior to and/or during the early stages of volcanism in the early to middle Miocene. The timing of this tectonic activity may be related to the early emplacement of intrusives or to changes in plate tectonic stresses, caused by events to the east, preceding and ultimately causing volcanic activity in western South Sulawesi. Preexisting and re-activated faults cutting the Tonasa Formation may in turn have acted as lines of weakness, influencing the location of early volcanic centers.

Controls on the Termination of Carbonate Platforms

This case study of the well exposed Tonasa Formation provides an insight into the precise controls on the demise of a carbonate platform. Four main factors have been identified as possible causes in the drowning of carbonate platforms, and these are equally applicable to the demise of carbonate platforms in general. These are relative sea-level changes (either tectonic or eustatic), environmental deterioration, oversteepening and self-erosion of platform margins, and burial by prograding clastics (Schlager 1981, 1989, 1998; Schlager and Camber 1986; Erlich et al. 1990). The
ultimate demise of the Tonasa Carbonate Platform, as with the demise of many carbonate platforms, was caused by a number of these factors, with the actual reasons for foundering varying spatially and temporally. Indeed the setting of the Tonasa Formation in a tectonically active area and over- lain by thick volcaniclastics suggests that its demise might have been related to all of these major factors. Certainly a combination of relative sea-level change, mostly caused by tectonic subsidence and uplift, burial by volcaniclastics, and fault-related collapse of the margins were all factors both regionally and locally instrumental in the demise of the platform. The role of environmental deterioration is more difficult to determine. However, given that during the Oligo-Miocene the platform was isolated from silici-clastic or nutrient input and that there is no evidence for major environmental change in platform-top facies, environmental deterioration seems unlikely. During the early stages of Neogene volcanism, carbonate production in areas near to volcanic centers quickly ceased because of burial by volcaniclastics. This is because sedimentation rates for the volcaniclastics were higher than accumulation rates for the carbonates dominated by larger benthic foraminifera. Lower accumulation rates of shallow-water carbonates on the platform also resulted in rapid local drowning caused by fault-related subsidence. Also, shallow-water carbonates were able to pro-grade out into deeper-water areas only when the slope angle was very low and there was no emergence on footwall highs along the platform margin. This differs from many Cenozoic and indeed Mesozoic carbonates, where higher shallow-water carbonate accumulation rates led to reestablishment of shallow-water carbonate production and/or to in-filling of adjacent basins (cf. Winker and Buffler 1988; Playford et al. 1989).

**Analogue for the Subsurface**

A cursory look at hypothetical seismic across the top of the Tonasa Platform and its overlying lithologies might suggest that the final demise of the platform was caused by burial under volcaniclastics and therefore that the reservoir potential of the top of the Tonasa Formation is likely to be poor. On a closer look, however, a number of features would indicate that faulting and associated variable block rotation, subsidence, and uplift played a major role in the demise of the platform. These features, potentially recognizable on seismic, include variously tilted fault blocks, localized subtle unconformities at the contact, perhaps a slightly irregular top to the carbonates, suggesting karstification, and the formation of fault-bounded graben and half-graben and associated collapse of faulted margins just prior to volcaniclastic input. Samples from selected wells, if available, would also indicate that the demise of the platform was not simply due to burial and could yield important information on the timing of tectonic activity. The revised interpretation of the nature of the top surface of the carbonates has important implications for reservoir potential. Enhanced secondary porosity would perhaps be associated with subaerial exposure or fracture zones and good primary porosity potentially preserved in redeposited facies in graben, abutting impermeable basement, as is the case for the Tonasa Formation. Also, on a seismic scale, unconformities and breaks in sedimentation and their role in the recognition of “drowning events” have been hotly debated in the literature (Schlager 1981, 1989, 1998; Schlager and Camber 1986; Erlich et al. 1990). In the case of drowned portions of the Tonasa Carbonate Platform related to fault subsidence, no breaks in sedimentation are recognizable. Minor angular unconformities do occur on the downdip parts of fault blocks, and breaks in sedimentation occurred on faulted highs that were subaerially exposed. This study suggests, as does that of Erlich et al. (1990), that “drowning events” are not always marked by drowning unconformities. Where unconformities are seen, their character must be carefully studied to reveal their true cause and the actual often complex reasons for the demise of carbonate platforms.

**CONCLUSIONS**

Carbonates of the Tonasa Formation in Indonesia allow a unique insight into the roles of tectonics and volcanism on the development and termi-

ation of a carbonate platform. This study quantitatively documents how an interplay of factors can result in different reasons for termination of carbonate production through time and space for an individual carbonate succession. The foundering of carbonate platforms has considerable implications for reservoir quality and hydrocarbon exploration.

The main factors influencing the demise of the Eocene to Miocene Tonasa Carbonate Platform were:

**Tectonics.**—Paleogene and Neogene normal-fault segmentation resulted in formation of basinal graben, subaerial exposure of footwall highs, and tilting of fault blocks. Subsidence in hangingwall areas invariably caused drowning, because rates of subsidence were higher than rates of accumulation for the shallow-water carbonates dominated by larger benthic foraminifera. Rates of regional tectonic subsidence were never sufficient to cause drowning of the shallow-water carbonates, but they resulted in submergence of footwall highs below sea level, thus allowing renewed carbonate production. Faulting had radically altered the morphology of the Tonasa Carbonate Platform and significantly reduced the available area for carbonate production just prior to Neogene volcanism.

**Volcanism.**—Paleogene initiation and development of the Tonasa Carbonate Platform occurred on attenuated continental crust within 60 km and on the lee side of a calc-alkaline volcanic arc. With the exception of limiting the eastward lateral extent of the platform, and interdigitation and minor volcaniclastic input to the east, arc volcanism had no tangible effect on development of the platform carbonates in western South Sulawesi. Close to Neogene volcanic centers the mass influx of volcaniclastic debris probably rapidly smothered carbonate-producing organisms in many of the remaining habitable shallow-water areas in western South Sulawesi. In more distal areas or during periods of volcanic quiescence, however, when the rate of influx of volcaniclastic debris was less than the accumulation rate of shallow-water carbonates, carbonate production occurred coevally with volcanism.

Although the extent of the Tonasa Carbonate Platform is unusual, the evolution and termination of the platform is similar to other carbonates developed in back-arc, intra-arc, or other tectonically active settings. Characteristic features include the association with volcanics and volcaniclastics, a great thickness of platform carbonates, evidence for crustal instability, and rapid lateral and vertical facies changes. The predominance of larger benthic foraminifera in platform deposits, perhaps related to biogeographic isolation, resulted in low accumulation rates for the Tonasa Formation, which is uncommon for carbonates in volcanic areas. Finally this study emphasizes that if we are to understand the termination of carbonate production on a global scale more information is required on the complex interplay of factors instrumental in the demise of individual carbonate platforms.

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