ABSTRACT

Bone Bay separates the South and SE Arms of Sulawesi. It is one of several enigmatic basins around this unusual K-shaped island and has been interpreted as rift-, collision- or arc-related and underlain by either oceanic or continental crust. Evaluating different interpretations has been hindered by lack of data. New insights into Bone Bay are based on a seismic stratigraphic study of regional 2D grid and seabed bathymetry data, both acquired in 2007.

Bone Bay has multiple depocentres and structural highs. A major basin trend, orientated approximately N-S, is divided into three depocentres by the Kolaka Fault zone in the north and by a W-E Basa basement high in the south. The two northern depocentres contain a thick sedimentary succession in a narrow basin. In places the acoustic basement can be traced below the 8 second TWT cut-off. Accommodation was produced by extensional displacement on major basin-bounding faults. The southern depocentre is characterised by basement-involved domino fault blocks with extensional growth-strata visible in some half graben. There is onlap and burial of post-extension topography with development of a large N-S submarine canyon system visible from 4 seconds TWT to the seabed. Two other depocentres formed later than the central basin: a small depocentre between the island of Kabaena and the SE Arm, and a narrow N-S orientated extensional basin located adjacent to the island of Salayar.

Early growth strata are interpreted to have been deformed by strike-slip movement along the western margin of the central basin. Deformation was followed by development of a widespread carbonate shelf on the eastern margin of Bone Bay displaying at least one phase of progradation.

Stratigraphically higher, a regional unconformity is interpreted to correspond to a latest Miocene event seen in two wells: Kampung Baru-1 and BBA-1X. This marks a brief tectonically-induced regional shallowing, followed by a phase of basin-wide subsidence causing drowning of local shallow water carbonates producing pinnacle morphologies that are interpreted to step back to topographic highs. Subsidence was accompanied by an increase in sediment supply.

INTRODUCTION

Bone Gulf is located between the South and SE Arms of Sulawesi and occupies an area of approximately 50,000km² (Fig. 1). It opens into the Flores Sea to the south which joins with the Banda Sea to the southeast. Active hydrocarbon exploration blocks are shown on Fig. 2. Proven petroleum plays include gas fields in stratigraphic traps in the East Sengkang Basin on the South Arm and oil shows and discoveries in and around the island of Buton at the tip of the SE Arm from Australian-origin continental crust. Interest in Bone Gulf remains high with two exploration blocks currently located on the west and east margins of the bay (Fig. 2). No wells have been drilled beyond the shelf and only two have been drilled offshore highlighting the difficulty in assigning ages and “ground truths” observations.

The South Arm is considered the eastern margin of Sundaland and formerly part of the Argo tectonic block: a continental fragment or fragments rifted from Australia in the Mesozoic that accreted to Sundaland by the Late Cretaceous with a Paleogene to Neogene volcanic overprint (Hall et al., 2009; Hall, 2012). The South Arm is bisected by the Walanae Fault trend (Fig. 3) which is often interpreted as a sinistral strike-slip fault (Sukamto, 1975) reported to show vertical displacement (Grainge & Davies, 1985; van Leeuwen et al., 2010). To the west of the fault zone, a Paleogene volcanic succession is diachronously overlain by the
extensive Tonasa carbonate platform which is succeeded by volcanics and volcaniclastics of the Camba Formation that contributed to drowning of the platform in the Miocene (Wilson, 2000). To the east of the fault zone, marine volcanics and volcaniclastics of Middle Eocene to Early Miocene age (van Leeuwen et al., 2010) are unconformably overlain by the Middle Miocene Camba Formation and then covered by Middle Miocene to Recent shallow marine carbonates and clastic sediments. The stratigraphy to the east of the Walanae Fault zone is a probably a direct analogue for the seismic units of Bone Gulf, at least in its western part (Yulihanto, 2004).

The SE Arm and the islands of Kabaena, Muna and Buton are a complex area containing Mesozoic sedimentary rocks, blueschists, metamorphic Mesozoic or Palaeozoic rocks and ultramafics of possible ophiolitic origin (Hamilton, 1979) although problems exist with this interpretation (Milsom, 1999). The lower units are unconformably overlain by Miocene to Recent clastic and carbonate sedimentary rocks (Surono, 1994, 1998). The origin of the SE Arm is complex. A “bacon-slicer model” model was proposed by Smith & Silver (1991). A common view interprets a series of approximately E-W collisions involving multiple microcontinents with the volcanic arc of the South Arm in the Neogene (Fortuin et al., 1990). However, recent publications have cast doubt onto this view (Hall, 2002, 2011; Satyana & Purwaningsih, 2012) suggesting that structures and vertical movements may not be simply collision-related. Strike-slip movement has been identified on many approximately NW-SE lineaments including the Palu-Kolo, Matano and Lawanopo Faults, thought to accommodate strain from active subduction beneath the North Arm. This interpretation is supported by relative movement acquired from GPS data (Socquet et al., 2006) and earthquake focal solutions (Beaudouin et al., 2003).

Bone Gulf is a geologically enigmatic region and has been variously postulated to be an extensional region of Eocene (Yulihanto, 2004) or Miocene (Hamilton, 1979) age, a contracted forearc basin (Sudarmono, 2000) or an intermontane basin (Bergman et al., 1996). Only Yulihanto (2004) and Sudarmono (2000) were assisted by the interpretation of 2D seismic lines across the Gulf.

This paper reports the results of a study of Bone Gulf based on new seismic and multibeam data, complemented by insights from our field studies on land, which integrated with previous studies provides new insights into the history and development of this enigmatic inter-arm basin. Some stratigraphic control can be established from onshore outcrops and wells from the East Sengkang Basin (Grainge & Davies 1985; Suyono & Kusnana, 2010) field studies in the South Arm (van Leeuwen et al. 2010), and field studies in the SE Arm (Surono, 1994) and nearby islands (Fortuin et al., 1990) and well BBA-1X (Sudarmono, 2000) located in the north of the Bone Gulf.

Dataset and Methods

In 2007, TGS acquired and processed a widely spaced 2D dataset over Bone Gulf shot broadly below shelf which provides improved resolution over vintage lines. The area of interest is covered by 16 time-migrated, 2D lines covering an area of approximately 43,000 km², with line spacing ranging from 25 km to 40 km. This provides a dataset with a combined length of c. 2419 km and a processed TWT limit of 8 seconds. High resolution seabed multibeam data (Orange et al., 2009) acquired at the same time covering approximately 37,500 km² were also incorporated in the study and provide exceptional details of the seafloor topography, sedimentary features and active structures. This coverage was acquired using a Kongsberg Simrad EM120 Multibeam Echo Sounder using 191 beams at equidistant spacing. Positioning control used a C-Nav Starfire DGPS. During processing, positioning, tidal and calibration corrections were applied, random noise and artefacts were removed, and a terrain model using a 25 m bin size was gridded and exported to ESRI format. Multibeam data were further processed in ER Mapper to remove voids and generate a digital elevation model (DEM).

Seismic Stratigraphy

The Bone Gulf dataset covers a large, geologically complex area and the subsurface has been divided into areas of interpreted similar geological history marked on Fig. 2. Three Sub-basins lie on a north to south axis; Bulupulu Sub-basin, Padamarang Sub-basin and the Kabaena Sub-basin. The Bulupulu and Padamarang Sub-basins are separated by the Kolaka High and the Padamarang and Kabaena Sub-basins are separated by the Basa High. The shoulders of the basins are broadly parallel the central Sub-basins with the Bone Platform and Bunerate High on the west and the Maniang and Kabaena Highs on the east. There are also three additional Sub-basins identified; the Saleyar Trough and Liang-Liang Sub-basins to the west of the Bunerate High and the
The Tulang Sub-basin located between the SE Arm and Kabaena. On the seabed, a canyon system runs southwards, within the Bulupulu, Padamarang and Kabaena Sub-basins and is identified here as the Bone canyon. The southern limit of this study has been taken at the northern edge of a contractional region with broadly north to northeast verging structures near the Bonerate islands.

An integrated seismic stratigraphy (Fig. 4) has been produced with attempts to link the seismic units to onshore lithostratigraphy. Lithostratigraphy from well BBA-1X (Sudarmono, 2000) can be correlated into the offshore area by extrapolating the interpretation of Yulihanto (2004) to the northern edge of the survey (Fig. 5). No direct ties were established from onshore localities to the survey. However, based on the stratigraphy of the South Arm east of the Walanae Fault, (van Leeuwen et al. 2010; Grainge & Davies 1985) a possible correlation is proposed in the discussion below. Similarly, based on studies of the SE Arm (Surono, 1994; 1998) the stratigraphy on land can be tentatively correlated with the Maniang High and Tulang Sub-basin. Figs. 6 to 10 illustrate the interpreted structure and stratigraphy of different parts of Bone Gulf.

**Unit X**

The top of Unit X is the base of the lowest coherent seismic package. Where a clear response is visible this surface is frequently irregular and rugose and becomes onlapped or overlain by younger units (Figs. 6, 9 and 10). In zones of poor reflectivity the top marker cannot be clearly picked (Fig. 6), for example beneath interpreted carbonates (Fig. 6 - box c). Unit X varies in seismic character. On many lines (e.g. Figs. 6 and 7) it is structureless and has an irregular locally diffuse top. However, in other areas some internal reflectors can be traced within the unit (Fig. 8 and 10).

At the northern end of Bone Gulf only a single line crosses the Bulupulu Sub-basin where the basement is interpreted at 6.4-7.7 seconds TWT. The top of Unit X cannot be traced across the Kolaka Fault zone and is not visible in the Padamarang Sub-basin further south, indicating that the top of Unit X is deeper. Even further south, the top of Unit X is visible across the Basa High and can be traced to the southern limit of the study area. In the Kabaena Sub-basin, discontinuous to chaotic bright reflectors can be seen within Unit X often with a curved shape. They may represent deformed layered strata within Unit X (Fig. 7).

At the southern end of Bone Gulf, at its western side, on the seismic section crossing the Bonerate High, the top of Unit X is difficult to pick (Fig. 4). To the east, on the eastern side of the Kabaena Sub-basin, Unit X displays a wavy top reflector and internally bright discontinuous, chaotic to sub-parallel reflections which become obscured as they are traced onto the Maniang High. The top of Unit X crossing the Maniang High is irregular and appears erosional with high relief (up to 200ms) which may be due to development of a drainage network during or after tilting and prior to the deposition of younger units. Still further to the east, Unit X underlies the Tulang Sub-basin and its top appears to be tilted at approximately 11-22° to the east. The seismic character is poorly resolved beneath a bright, irregular top reflector that is interpreted to represent erosional truncation of overlying carbonates prior to or during tilting.

Unit X is likely to correspond to different lithologies in different parts of the region in and around Bone Gulf. On the west side of the region Unit X may correspond to Paleogene volcanic rocks seen in the Bone Mountains (van Leeuwen et al., 2010) or lowermost East Sengkang Basin (Grainge & Davies, 1985). On the SE Arm there are peridotites, Palaeozoic and/or Mesozoic metamorphic rocks, and low grade metamorphosed sandstones of Triassic age in the SE Arm (Surono 1994; Ferdian et al. 2012).

**UNIT A**

Seismic Unit A is confined to the central N-S axis of the Sub-basins (Bulupulu, Padamarang and Kabaena) and is characterised by persistent, continuous, parallel reflectors onlapping Unit X. The top of the unit is an unconformity over highs and in the Kabaena Sub-basin but is observed to be a conformable reflector in places in the Padamarang Sub-basin.

In the Padamarang Sub-basin, Unit A is up to 2 seconds TWT thickness and is confined between two bounding faults, oriented approximately N-S, about 40 km apart. Unit A is poorly imaged in this Sub-basin with may be caused by faults (Figs. 8 and 10) or fluid effects. In the north, the unit cannot be traced clearly over the Kolaka Fault zone, although a probable time equivalent is interpreted on its northern side.

In the Kabaena Sub-basin, fanning geometries characterise Unit A and can be traced through several lines, and are interpreted as extensional
growth strata produced by east-dipping normal faults (Fig. 6 and 9). Low angle onlap surfaces divide periods of stratal growth and periods of tectonic quiescence. To the south, the Kabaena Sub-basin gradually widens from approximately 40 km to 70 km and the unit thins to only 0.2 seconds TWT, where it is characterised by an absence of growth strata and with a low angle upper onlap surface that is hard to pick. In the widest part of the Sub-basin, domino fault blocks show earliest growth strata in the east-most compartment with a “fill and spill” of sediment to the west showing that dominant sediment input was from the east and north (Fig. 9). Substantial tilting of the unit to the west to a maximum of 9.5° (using migration velocities) occurred during or shortly after deposition due to fault-controlled subsidence perhaps augmented by uplift of the eastern margin.

In places Unit X appears to interfinger with Unit A (Fig. 8), which could be due to poor imaging or a lateral transition from non-deposition into shallow marine carbonate or volcanic strata. Near the base of Unit A in the Kabaena Sub-basin are two bright positive amplitude events that can be traced for 140 km and may correspond to condensed sections of marine origin (Fig. 6).

Near the margins of the Kabaena and Padamarang Sub-basins, the seismic character changes; to the west, reflectors become disrupted as they approach the western bounding fault (Fig. 6 – box b). Although this probably has a tectonic origin, it may also be caused by poor imaging of the interfingerung of basinal facies with high energy mass transport complexes sourced by material eroded from the Bonerate High producing a “pseudo-unconformity” (Vail, 1977; Schlager, 2005). On the eastern margin of both Sub-basins, Unit A onlaps or interfingers with Unit X. At the eastern margin of the Padamarang Sub-basin Unit A is progressively obscured under the clearly defined clinoform belt of Unit B. Reflector geometries in Unit A steepen beneath Unit B’s clinoform belt, perhaps corresponding to tilting visible further south.

Unit A is interpreted to be predominantly marine siliciclastic sediments, probably relatively deep marine, which may have shallow marine carbonates at the base. In the SE Arm there are possible Lower Miocene shallow marine carbonates (Rusmana et al., 1993) and in the East Sengkang Basin there are planktonic limestones and calcareous mudstones of Early Miocene age (Grainge & Davies, 1985) which could be the equivalent of Unit A.

Unit B

Unit B is a succession of seismic packages that display downlap (Fig. 8) and onlap (Fig. 6) with respect to the top of Unit A. The unit is present in the Bulupulu, Padamarang and Kabaena Sub-basins and corresponds to the development of an extensive carbonate platform over the Maniang High. The unit is thickest in the Kabaena Sub-basin and thins to the south. The top of the unit is chosen at the top of the Bone carbonate platform; a drowning surface, and at a bright amplitude truncating event present over the Basa High which can be traced into the basins. This surface is clearly erosional over highs and probably marks the end of widespread carbonate deposition. Unit B is thought to be time equivalent of Unit B1 on the Bonerate High (Fig. 6) but a direct tie across the western margin of Kabaena Sub-basin remains ambiguous (Fig. 8).

The character of Unit B changes from the highs into the deeper parts of the Sub-basins. In the Kabaena Sub-basin, Unit B downlaps onto Unit A, younging to the south. E-W seismic sections reveal mild wedging geometries to the west against the West Bone Fault system. This indicates that while displacement terminated on faults in the east, it continued on the western-most fault producing the strongly asymmetrical half-graben geometry seen in Figs. 6 and 9. Internal reflectivity is largely parallel and continuous with laterally extensive zones of disrupted reflectors interpreted as soft-sediment deformation related to gravitational collapse. Parallel continuous reflectors show steepening and thickening towards the West Bone Fault in places indicating that the dominant sediment supply came from the west, perhaps along depressions similar to the present-day Walanae Fault zone, supplying sediment from the south arm. The largest collapse unit can be traced across several lines for up to 50 km, and reaches a maximum 200ms TWT thickness near the Bonerate High with thrust duplexes and folding of c.10 ms scale most clearly visible on W-E lines (Fig. 9). Initiation may have occurred by oversteepening of the Bonerate High margin produced by carbonate build-up or differential subsidence. Smaller gravity deposits are also present near the eastern margin of the Kabaena Sub-basin.

In the Padamarang Sub-basin, Unit B is the distal equivalent of the carbonate platform situated to the east. Seismic character is largely parallel and continuous with disrupted units only present near the margins reflecting small-scale mass transport complexes. Unit B onlaps Unit X on the western
margin of the Padamarang Sub-basin at a gentler angle than in the Kabaena Sub-basin with minor thickening towards the western margin.

The eastern carbonate platform (Figs. 6 and 10) shows a phase of progradation, in which clinoforms steepen upwards. This is followed by possible downstepping with an associated exposure surface. Finally, a backstepping and drowning trend is seen at least over part of the platform (Fig. 10). The top surface of Unit B displays a complex relationship with the overlying Unit C, in some places appearing truncated, in others onlapped and in others gradational. One interpretation is that the platform was drowned by relative sea level rise, producing pinnacle reefs as platform growth became restricted to highs. Backstepping broadly moved the shoreline east towards the SE Arm and the Basa High but became complicated by the three dimensional nature of pinnacle building with talus aprons building over older carbonate locally in addition to a eastwards stepping trend. After the platform drowned, deposition stopped, producing a type three unconformity (Schlager, 1999) or slowed. Hemipelagic drape deposited over topography may have been punctuated by gravity flows from the SE Arm. Gravity flows may have caused localised submarine erosion along transport routes, perhaps enhancing relief on the drowning surface. Marine onlap of Unit C diachronously buried the lower parts of the carbonate platform.

Unit B is interpreted as platform carbonates at the basin margin highs and deeper water carbonates in the Sub-basin centres. It is suggested to be equivalent to the calcareous claystones and thin limestones of well BBA-1X (Sudarmono, 2000) and calcareous mudstones with lithic sandstones of the Camba Formation in the East Sengkang Basin (Grainge & Davies, 1985) all of Middle to Late Miocene age.

Unit B1

Unit B1 corresponds to the deepest visible units above Unit X on the Bonerate High. Its top surface is marked by a bright positive amplitude reflector which is an angular unconformity that represents the termination of widespread carbonate deposition over the Bonerate High, and onset of easterly downlapping to onlapping reflectors produced by clastics of Unit C.

The Bonerate High accumulated significant carbonate deposits after the creation of accommodation space in the Kabaena Sub-basin. Build out phases of carbonate can be seen to infill earliest visible accommodation (Fig. 6 box A) and are overlain by a later onlap. Several build-up structures are observed, reaching heights of up 1.2 seconds TWT at or near the seabed which suggests diachronous carbonate growth where some build-ups were able to keep up with rising sea level. The largest carbonate build-up is at least 35 km in length and displays a raised-rim visible on seabed bathymetry. Clastic drape has been restricted to the carbonate build-ups centre by a moat around the edge of the feature (Fig. 7). Shallow water carbonate morphologies interfinger and are locally onlapped by continuous, parallel to chaotic reflections of moderate to bright amplitude interpreted to show emplacement of gravity deposits along the margins of the platforms and low energy onlap after or during drowning.

On the western footwall of the Kabaena Sub-basin an apron is interpreted to have been produced by mass wasting. The apron has built over early fault growth strata in the Kabaena Sub-basin, obscuring the west Bone Fault system to the south (Fig. 9 compared with Fig. 6). Adjacent to the fault zone, Unit A (Fig. 6) shows local reverse faulting and folding. This complicates interpretation near this structure and may be due to reactivation of a moderate angle normal fault with strike-slip movement. A similar feature may be present in on the western margin of the southern Padamarang basin (Fig. 10).

Unit B1 is interpreted as the age equivalent of Unit B and possibly part of Unit A and is probably a mixture of shallow marine carbonates and deeper marine claystones.

Unit C

This unit has been deposited throughout Bone Gulf and corresponds to an increase in clastic sediment supply in the Early Pliocene (Fig. 5). It records a variety of depositional processes and complex geometries that hamper regional internal correlation.

Unit C is proposed to broadly correlate with the various formations corresponding to the “Celebes Molasse” described from the South Arm and SE Arm (e.g. Surono, 1994; Grainge & Davies, 1985). In the Bulupulu Sub-basin, this corresponds to a change in seismic character from Unit B: low frequency, parallel, continuous reflections to higher frequency, highly continuous events with local incisions (up to several km in width) and disrupted
zones representing the processes of erosion and deposition of mass transport complexes (Fig. 5). The unit thins over the Kolaka Fault zone and thickens to 2.4 seconds TWT in the Kabaena Sub-basin. A large submarine canyon of c.10 km width is visible on the multibeam bathymetric map (Fig. 3) with multiple infill channel packages with thicknesses of c.100ms TWT. This canyon can be traced for 310 km on the seabed but its origin is uncertain beyond the northern edge of the multibeam coverage. It has undergone many phases of avulsion and aggradation, with more than four phases of incision and infilling visible in W-E seismic lines. The stratigraphic depth of the lowest canyon “cut and fill” event is lower in the Padamarang Sub-basin compared to the Kabaena Sub-basin (Fig. 10) and the total width of the stacked cut and fill belt is wider in the north (approximately 30 km) compared to the south (<10km). This canyon system developed in response to high sediment supply events from the north which caused southward progradation and later bypass, of Unit C. Outside the axis of canyon incision, reflections are relatively continuous with bright amplitude horizons. These are basin floor turbidites that have been interbedded with pelagic sediments. Excellent imaging of lobe fan channels and levees can be seen in Kabaena Sub-basin (Fig. 9) indicating that smaller systems existed, perhaps fed by canyons transporting sediment through the Polaeng Strait separating the SE Arm from islands further south.

Unit C intersects the seabed and this allows the multibeam data to inform interpretation of submarine processes. At the seabed, upward-migrating sediment waves (Lee et al., 2007) with 0.5-2 km wavelength and up to 30 ms amplitude formed by repeated turbidite flows from adjacent submarine canyons and are visible on the eastern and western sides of the Padamarang Sub-basin. Sediment-wave cross-beds are observed at 2.9 to 3.65 seconds TWT beneath the present day surface waves on both sides of the basin. This suggests that the depositional environment, sediment flux and slope gradient (approximately 1°) may have been similar to the present day during formation.

Unit C displays marked thinning over the Bonerate and Maniang Highs (Figs. 4 and 5) suggesting that palaeo-topography produced by basinal subsidence became infilled. Older parts of Unit C are confined to the basin centre and younger parts cover the platforms. Seabed canyons cut into Unit C over highs displaying 100’s metres of relief showing that sediment has bypassed the slope to the active depocentres in the basins.

Unit C is considered to be dominated by siliciclastic sediments transported from Central Sulawesi with contributions from the South and SE Arms. Judging from the stratigraphy recorded in well BBA-1X (Sudarmoyo, 2000), and the East Sengkang Basin (Grainge & Davies, 1985), it is likely that Unit C begins with coarse clastics, including conglomerates, and/or limestones, and possibly mass transport complexes (Fig. 5) and is interpreted here to be of Pliocene age.

Unit D

Unit D is a mounded feature of uncertain origin located in the south part of the eastern margin of the Kabaena Sub-basin (Fig. 9). The unit shows relief of up to 1.5 seconds with a bright, irregular to chaotic top reflection. Internal character is mostly reflection free with some bright patches which may simply be seismic noise. Where visible, the internal seismic character shows parallel or hummocky to sigmoidal reflections. The irregularity of the top surface has two wavelengths. First, those from one to tens of kilometres highs and lows (100’s ms amplitude) that are interpreted as incision of canyons or division by faults. Second, the unit has surface variation with wavelengths of 100’s of metres and amplitude of up to 100ms. This larger variation may be related to its internal structure. This unit may be equivalent to the top of Unit X beneath the Maniang High that has been exposed, eroded and onlapped during the deposition of Unit C. The most convincing evidence for erosion is a high amplitude apron adjacent to Unit D, extending for up to 25 km westwards into the Kabaena Sub-basin in Box a Fig. 9. The internal structure of Unit E suggests shallow water carbonates but it may have experienced several phases of erosion and renewed growth, perhaps during tectonic tilting. Alternatively, the unit may correspond to previously emergent basement rocks similar to those seen in Kabaena or the SE Arm, or it could be a volcanic feature.

STRUCTURE AND DEFORMATION HISTORY

Basin defining structures have been mapped in Fig. 11. Many of the structural features are similar to those identified by Yulihanto (2004) who recognised basin-bounding faults with normal displacement in the Padamarang Sub-basin. This study supports earlier interpretations (Yulihanto,
2004) of strike-slip movements on the West and East Bone Fault systems.

**Basement-involved normal faults**

East dipping normal faults containing growth strata are interpreted in the northern part of Kabaena Sub-basin (Figs. 6 and 9). A possible network of major faults is shown in Fig. 11 with the basin bounding faults striking approximately N-S and smaller faults NE-SW or NW-SE. In the southern part of Sub-basin, there is no direct evidence of normal faulting (Fig. 7). Seismic character and the irregular top surface of basement inhibit the interpretation of faults without overlying growth strata or direct fault plane imaging. Only the upper parts of Unit A onlap Unit X in the southern part of the basin resulting in a lack of growth strata. Alternatively, displacement may diminish to the south suggesting that an alternative mechanism would be required to produce accommodation. The East Bone fault system (Yulihanto 2004) can be clearly seen in the Padamarang and Kabaena Sub-basins marked by a change in thickness of Unit C and by abrupt changes in seabed relief implying very recent normal displacement (Fig. 6).

Substantial normal fault-driven relief is present on the seabed east of Saleyar showing recent normal fault displacement cutting Unit C. An escarpment with a maximum of 1.5 km height with a maximum slope of 17°. The faults rim a NNW-SSE striking, deep narrow basin at least 100 km in length and approximately 30-40 km wide. This basin is interpreted to represent the offshore continuation of the onshore Wulanae Fault zone. At depth, reflections are curved and disrupted in places interpreted to indicate strike-slip displacement in addition to normal displacement.

**Shallow faults**

Numerous, well imaged normal faults which have maximum displacements of 50 ms that can be traced vertically for up to 3 seconds TWT are visible in Units A to C with many extending from the top of Unit X to the seabed (Figs. 6 to 10) showing active displacement. These faults often concentrate over areas with significant relief in Unit X or at the margins of basins where a slope is present in underlying Unit X. They may be caused by a change in stress orientation preventing strain accumulation on existing faults causing new faults to develop Unit X.

Irregularity and truncation of seismic reflectors at the seabed in all areas other than basin centres show erosion and deformation associated with subsidence is presently occurring (Figs. 6 to 10). Thinning of Unit C over the shoulders of the Kabaena and Padamarang Sub-basins demonstrates differential subsidence of up to a 1 second TWT which implies that extensional faults at depth were recently active. Seafloor gradients caused by such subsidence resulted in localised gravity spreading in the form of minor listric faults detaching on the mechanical boundary between Unit C and underlying carbonates shown in Figs. 6 to 8.

**Strike-slip faults**

The Kolaka Fault zone extends offshore NW from the SE Arm bounding the Padamarang Sub-basin and it intersects the seismic lines at a low angle. Onshore, the fault zone separates ultramafic rocks from metamorphic rocks (Simandjuntak et al., 1993) and we have observed fault gouges intruded by acid igneous rocks. Fault bounded ultramafic rocks (including Padamarang Island) and granites outcrop within the fault zone along the western coast of the SE Arm. Surono et al. (1997) interpreted offsets of streams and alluvium to indicate young left-lateral movement on the Kolaka Fault. On seismic lines Units B and C are seen to be deformed into a broad, faulted anticline interpreted as transpressional in origin (Fig. 8) with uplift in the wide fault zone (Fig. 11). An interpreted onlapped transpressional pop-up is shown in Fig. 8 and the presence of at least two angular unconformities mark episodes of uplift and erosion along the fault zone. Unit C thins across the fault zone and there are examples of onlap of reflectors onto older reflectors within Unit C implying that the Kolaka High was relatively elevated as Unit C was deposited. The oldest movements on the fault can be correlated with the angular unconformity at the base of Unit C (Fig. 5) which represents deformation of Unit B followed by the change to conglomerates and sandstones of Unit C (Fig. 5). Movements on the fault are interpreted to be linked to development of the Bone canyon system which initiated at the same time as the fault, with episodes of uplift influencing controls on canyon incision such as seabed gradient, basin morphology, sediment supply or grain size (Kolle et al., 2007).

In the southern part of the Padamarang Sub-basin, strike-slip fault activity can be seen in Units A and B with a faulted anticline located at the northern margin of the Basa High (Figs. 8 and 10). The anticline shows a reduction of amplitude upwards,
accompanied by onlap of reflectors onto the fold within Unit B. This shows that the last phase of transpression occurred during the deposition of Unit B. The location of the anticline adjacent to Unit X suggests reactivation of a former normal fault. Disrupted reflectors in Unit A suggest a series of faults cut it shortly after deposition. Similar disruption is present along the West Bone Fault system indicating strike-slip movement occurred during deposition of the upper part of Unit A and Unit B.

The Tulang Sub-basin (east end of Fig. 6) formed and filled during the deposition of Unit C (Pliocene to Recent). The Sub-basin is underlain by a major listric fault dipping east at 10-20° and contains about 4 km of Unit C sediment (Fig. 6). In the footwall carbonates of Unit B with a thin drape have been faulted and tilted after deposition. Listric normal faults detached in drape that covers the carbonates. In the Sub-basin itself there is an early phase of syn-kinematic deposition in which sediments thicken towards the fault, overlain by parallel onlapping strata. Tracing marker reflectors in Unit C show that there was a later phase of deposition of syn-kinematic growth strata with tilting of the early basin fill. Finally, channel “cut and fill” deposits concentrated in the hangingwall mark sedimentary bypass of the basin. The seabed across the basin at approximately 200m truncates the uppermost reflectors of Unit C indicating active or recent uplift that could be related to terraces in many localities in the SE Arm and islands. Kabaena Island and the Rumbia Mountains expose metamorphic rocks at up to 1500m and 900m above sea level respectively only 15 km from the deep Tulang Sub-basin. If these form the basement to the Sub-basin, which is probable, the basin must have subsided rapidly and shows an approximate average gradient of 23°.

DISCUSSION

Bone Gulf is one of the enigmatic inter-arm basins of Sulawesi whose age and origin have been uncertain because of the lack of any data from the basins themselves. The new data used in this study offer some important new insights into Bone Gulf despite the absence of well control on ages of events.

Nature of basement

Hamilton (1979) suggested the Saleyar Trough was a recently inactive trench and that Bone Gulf was probably the result of Neogene extension, shown as due to counter-clockwise rotation of the SE Arm relative to the South Arm. He speculated that the gulf likely had oceanic basement in its deeper portion. Harris (2003) suggested a Paleogene age and showed Bone Gulf as floored by 35-25 Ma age oceanic crust. Sudarmono (2000) suggested the Bone Basin probably occupied a forearc position during the Paleogene and it formed a major Neogene depocentre following Middle Miocene collision and eastward rotation of SE Sulawesi. Bergman et al. (1996) and Milsom et al. (2001) suggested Bone Gulf could be result of a collapse of the Sulawesi orogen implying a Neogene age for its formation. Yulihanto (2004) interpreted Bone Basin to be the result of Eocene rifting with little modification of the basin due to Miocene collisions to the east.

We see no evidence to support the suggestion that Bone Gulf is underlain by oceanic crust. The deeper parts of the basins (Figs. 7 and 9) lack the strong reflectors characteristic of the top of oceanic basement, the central deeper parts of the deepest Sub-basins show rifting features, and packages of strong reflectors interpreted as shallow marine carbonates can be traced well out into the deeper parts of basins, where they are seen beneath up to 3 seconds TWT of sediments.

The WNW-ESE orientation of lineaments juxtaposing lithologies on both Kabaena Island (Sukamto, 1975) and in the Rumbia Mountains broadly matches the orientation of lineaments in the Kolaka and Lawanopo Fault zones suggesting a transtensional origin for the Sub-basin. A fault on the north side of the Sub-basin south of the SE Arm is very probable, but a parallel fault on the south side is less certain. An alternative explanation is that the Sub-basin is the result of extension broadly parallel to the strike-slip faults which occurred at the same time as subsidence in the main axial Bulupulu, Padamarang, and Kabaena Sub-basins.

The South Arm of Sulawesi experienced extensive volcanism in both the Paleogene and Miocene. The older volcanic rocks of the Bone Mountains are calc-alkaline and MORB-type (van Leeuwen et al., 2010) whereas the Miocene phase has an extension-related character with potassium-rich products (Priadi et al. 1994, Polvé et al., 1997; van Leeuwen et al. 2010). The Bonerate islands have previously been interpreted as volcanic islands but within the study area no clear evidence of volcanism has been identified. Parts of Unit X are interpreted to be
equivalent to the older volcanic rocks of the Bone Mountains.

In the south part of the Padamarang Sub-basin there is an extensive basement high (Fig. 8) which is overlain by carbonates interpreted to display a karstic morphology. At approximately 6-7 seconds TWT, a bright continuous reflector that appears to broadly follow the eroded top surface can be traced for 120 km. This bright reflector is also visible on intersecting W-E lines although typically only continues for a few kilometres before background noise obscures it. It lies within Unit X and is broken in places, perhaps disrupted by fault strands from the West Bone Fault system. The feature could have a lithological origin, such as serpentinite over peridotite, a volcanic edifice over metamorphic basement, or even carbonate over a denser lithology or a tectonic origin, where a formerly layered sequence has been modified by faulting. A lithological change seems most likely. For example, the variation in Paleogene volcanic and volcanoclastics rocks reported from the south Arm east of the Walanae Fault zone (Wilson, 2000; van Leeuwen et al. 2010) or exhumed ultramafics modified by surface waters produce a mineral phase boundary which are known from fault zones elsewhere (pers. comm., I. Deighton, 2012).

The collision and stacking of different fragments between West and East Sulawesi yielded a diverse and variable basement. Unit X may include metamorphic rocks or ophiolites in places but may also have a volcanic origin, particularly along the western margin of Bone Gulf.

**Well BBA-1X and basin age**

Well BBA-1X at the north end of Bone Gulf penetrates approximately 3200 m of section (Fig. 5) and penetrates a major unconformity illustrated by Sudarmono (2000) and Yulihanto (2004). Sudarmono (2000) interpreted the unconformity to be Early Pliocene and the section beneath the unconformity to be Middle to Upper Miocene. Yulihanto (2004) interpreted the section beneath the unconformity to be Paleocene or older rocks. A re-evaluation of the time-depth relationship in well BBA-1X shows the interpreted basement of Yulihanto (2004) to be more than 1280m of Middle to Upper Miocene calcareous claystones, limestones and sandstones, as suggested by Sudarmono (2000).

The unconformity marks an important change in depositional environment from open marine calcareous mudstones to a 150m thick conglomerate overlain by shelf sandstones and claystones. The flat angular unconformity suggests subaerial exposure and we suggest the conglomerates are probably fluviatile or marginal marine deposits. This abrupt change to significant clastic input is seen in many parts of Sulawesi at the end of the Miocene (Grange & Davies, 1985; Davies, 1990; Calvert 2000; Cottam et al., 2010; Pholbud et al., 2012). The oldest package (Fig. 5) the Bulupulu Sub-basin above the unconformity is interpreted as multiple mass transport complexes. The seismic reflectors appear disrupted in contrast to the more continuous reflectors of the packages above and below, and the unit terminates abruptly against the Kolaka High. The establishment of a prograding clastic shelf correlates with the development of prograding submarine fan systems (Unit C) over a phase of carbonate build up (Unit B) in the Padamarang and Kabaena Sub-basins.

Similarly, re-interpretation of the basement of Yulihanto (2004) as Middle to Upper Miocene leads to the conclusion that a significant part of the section in the Bulupulu and Padamarang Sub-basins was deposited in the Miocene. This idea is not new. Hamilton (1979) suggesting a rotational opening of the Bone Gulf in the Miocene, Sudarmono (2000) suggested much of the sequence was Pliocene to Recent syn-orogenic or post-collision sediment.

**Stratigraphic correlation**

We suggest that all of the seismic units above Unit X are likely to be Miocene and younger. Many studies link the presence of a widespread Early Miocene unconformity with a collision between the SE Arm and the western volcanic arc (e.g. Surono et al., 1997; Silver & Smith, 1991; Bergman et al., 1996). Unit X is likely to correspond to collision-related lithologies as previously suggested by Sudarmono (2000) and is probably varied in lithology and character. On the west side of Bone Gulf Unit X probably corresponds to Paleogene volcanic rocks seen in the Bone Mountains (van Leeuwen, 2010) and East Sengkang Basin (Grainge & Davies, 1985) or ophiolites and metamorphic rocks of the Latimojong Mountains (Bergman et a., 1996). On the east side of Bone Gulf there are peridotites, metamorphic rocks, and metamorphosed Triassic sandstones in the SE Arm (Rusmana et al., 1993; Surono, 1994; Surono & Bachri, 2002).

Unit A is interpreted locally to include shallow marine carbonates at the base overlain by relatively deep marine siliciclastic sediments. The limestones are possible equivalents of Lower Miocene shallow
marine carbonates (Rusmana et al., 1993) in the SE Arm and the East Sengkang Basin (Grainge & Davies, 1985) where they are overlain by deeper marine Lower Miocene planktonic limestones and calcareous mudstones. Unit A shows growth strata interpreted to have formed by early extension of the Kabaena Sub-basin and probably also the Padamarang Sub-basin. Unit A has been tilted to the west and possibly locally eroded prior to deposition of Unit B. Previous interpretations (Sudarmono, 2000; Yulihanto, 2004) dated this unit as Middle-Upper Eocene or older. Extension in the Early Miocene was reported in the South Arm by Wilson et al. (2000).

In the east part of the South Arm is the Tacipi Limestone of Middle Miocene to Pliocene age (Ascaria, 1997). Up to 700m of Tacipi Formation is interpreted from seismic data by Grainge & Davies (1985). Several phases of carbonate growth can clearly be seen on the Bonerate High which may match the growth history reported further west. On the SE arm, Miocene-Pliocene limestones (Eemoiko formation) and Miocene to Recent clastics (Langkowala and Boepinang Formations) cover metamorphic and ultramafic rocks unconformably. These seem the most logical units to assign to the cover of the Maniang High and Tulang Sub-basin. The back-stepping carbonates of Unit B are interpreted to initiate in the Miocene with the possibility of the drowning surface with diachronous character and backstepping continuing to the Pliocene in places. The infilling sediments of the Tulang Sub-basin above tilted Miocene carbonates of Unit B suggest correlation with the clastic units of Miocene to Pliocene age of the Langkowala or Boepinang Formations.

Unit C is interpreted to be of different character to the older units. It represents the beginning of significant clastic input to Bone Gulf from Central Sulawesi and in parts from the South and SE Arms. Unit C begins with coarse clastics, including conglomerates, and/or limestones, and locally mass transport complexes and is interpreted as Pliocene.

PETROLEUM POTENTIAL

Yulihanto (2004) recognised petroleum potential based on an interpretation of an Eocene age rifting event with the synrift containing source rocks of Eocene age (Maraja/Tonasa Formations). In this paper we consider the lowest parts of the Bulupulu, Padamarang and Kabaena Sub-basins (Unit A) are more likely to contain pelagic carbonates. These sediments may have source rock potential, particularly in the central axis of Sub-basins where thick accumulations are present. The Bonerate High and Liang-Liang Sub-basin are thought to be stratigraphically similar to the East Sengkang Basin and therefore may have dry gas potential. Dispersed source material may be present in the Pliocene to Recent clastics of Unit C that have covered Bone Gulf. The Tulang Sub-basin and the North of the Bonerate High show thick sections of Pliocene cover.

The Bone Canyon system is expected to have coarse deposits preserved at the base of canyon fills, which could reservoir hydrocarbons with stratigraphic seal. Interpreted shallow water carbonates located on the Maniang high, Kabaena High and Bonerate High provide excellent stratigraphic traps, although in many places the sedimentary cover is relatively thin. Extension (figure 9) and strike-slip (figure 8) features have produced possible structural traps, although recent tectonic uplift and faults cutting the seabed suggest active fault movement in many places, which may have caused breach of some traps.

CONCLUSIONS

The new seismic and multibeam survey contributes to an improved understanding of the complex history of Bone Gulf and Sulawesi. The gulf can be divided into several Sub-basins and highs, some identified by Yulihanto (2004) and others not described previously.

We suggest the highs are important strike-slip fault zones trending roughly WNW-ESE. These fault zones segment Bone Gulf into the different Sub-basins. Structurally, the basins are complex with additional early basin-bounding faults oriented NNW-SSE. In the Padamarang Sub-basin there was transpressional strike-slip movement of Middle to Late Miocene age over a very wide zone seen in deeper parts of the section (Fig. 8). The Basa High appears to have been bounded by faults which were active and ceased activity relatively early in the basin history. It seems in part to be basement high which has a similar orientation to the known strike-slip fault zones. The Kolaka Fault zone has many features indicating Pliocene and younger activity which can be traced on land. It appears that the different fault zones were active at different stages with the Kolaka Fault zone being the youngest seen in the study area.

A change in seismic character, traceable over much of the Gulf can be dated as the base of the Pliocene
from well BBA-1X. The deeper section of BBA-1X shows a significant thickness of Middle and Upper Miocene marine sediments that can be traced southwards to the Kabaena Sub-basin and are time equivalent to shallow carbonates deposited on the intrabasinal highs.

The Sub-basins are not simply the products of extension and appear to have a more complex transtensional origin as suggested by Yulihanto (2004). Based on our observations on land in the SE Arm it seems likely that the orientation of the strike-slip faults is influenced by basement structures of pre-Neogene age. Therefore, during extension the basins developed in part a strike-slip character illustrated best at the western of the Padamarang Sub-basin where faults have a clear normal component but also show indications of strike-slip movements (Fig.10). The inferred ages of different units suggest that extension occurred since the Middle Miocene although may have started in the early Miocene. Early to Middle Miocene extension has received support from tectonic studies (Spakman & Hall, 2010; Hall, 2011) and studies of the South Arm (Grainge & Davies 1985; Wilson, 2000; van Leeuwen et al., 2010).

The Walanae Fault zone can be traced offshore, east of Saleyar, where it has a narrow, deep character and contains a disrupted basin fill. The fault on land has been interpreted as an important strike-slip zone (Sukamto, 1975; van Leeuwen et al., 2010). The west and east edges of the Walanae depression may step eastwards, offshore to the two bounding faults of the Saleyar Trough which have very significant normal displacements. However, the disrupted basin fill could indicate a component of strike-slip movement.

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Figure 1 - Location of Bone Gulf with key geographic features.
Figure 2 - The structural provinces of Bone Gulf discussed in the text. Current exploration licenses are shown in blue. Wells shown are BBA-1X at the north end of Bone Gulf and Kampung Baru-1 in the East Sengkang Basin. The Bentang-1 discovery well is located within the shaded block on Buton.
Figure 3 - SRTM and multibeam data showing detailed land elevation and sea floor bathymetry of Bone Gulf. The 2D seismic grid is shown and lines presented on later figures are shown in red.
Figure 4 - The seismic units interpreted in this study and their correlation between different structural provinces. Internal surfaces are highlighted although correlation between areas is problematic.
Figure 5 - Correlation panel showing the location of well BBA-1X modified from Yulihanto (2004) correlated with the northernmost seismic line used in the project. The interpreted basement of Yulihanto (2004) is shown as a black dashed line. The interpreted TD of this study has been traced at the same dip as overlying strata to produce the Middle Miocene age estimate shown and is suggested to form part of the wrench anticline shown in Sudarmono (2000) indicating that transpression occurred to the north of the study area before Pliocene deposition. Seismic units cannot be traced across the Kolaka Fault zone but this figure demonstrates that approximately 5 seconds of Middle Miocene or younger strata are likely to be contained within the Bulupulu and Padamarang Sub-basins.
Figure 6 - Uninterpreted and interpreted seismic line at the south end of Bone Gulf between the South and SE Arms with key horizons and faults. The section is vertically exaggerated to approximately 1:8. Box a shows detail with at least two phases of carbonate growth in Unit B1 and a further phase of carbonate growth in Unit C with an unconformable contact with downlapping clastics above. Box b shows two late phases of growth strata in Unit A, deposited just prior to the formation of the faulted anticline. Box c shows the top surface of Unit X which has an irregular contact with Unit B, possibly due to erosion. Drowning morphologies suggests Unit B may have briefly developed a rimmed shelf before backstepping and drowning of the platform.
Figure 7 - Uninterpreted and interpreted seismic line section at the south end of the study areas crossing the Saleyar Trough and Kabaena Sub-basin. There is thinning in Units A and B without growth strata or obvious extensional faults seen further north. Unit B thickens westwards towards the Bonerate High. Unit C thickens eastwards away from the Bonerate High. The narrow Saleyar Trough to the west shows significant normal displacement with obvious faults on the seabed. To the east, gradual backstepping of carbonates is interpreted, with a pinnacle of approximately 500 ms TWT height marking the last phase of carbonate production before drowning.
Figure 8 - Uninterpreted and interpreted N-S seismic line through Bone Gulf showing the Kolaka Fault zone in the north part of the section, a deep sedimentary package in the Padamarang Sub-basin and interpreted strike-slip faults disrupting deeper basin fill. The seismic line crosses a basement high to the south interpreted as Unit X. Within Unit X, a strong bright deep reflector can be traced over a distance of at least 60 km.
Figure 9 - Uninterpreted and interpreted W-E seismic line at the south end of Bone Gulf between the South and SE Arms and between sections shown in Figs. 6 and 7. This shows an interpreted intermediate stage in development. Fault blocks cutting Unit X are interpreted to produce growth strata in Unit A. Unit X shows a complex relationship with Unit A, with onlap, apparent interfingering and possible erosion. Blue arrow shows sediment direction for Unit A, red arrow for Unit B and yellow arrows suggesting sediment input for unit D. Purple shows the top of an MTC sourced from the south or east. Green and yellow lines mark phases of basin fill during Unit C. Box A shows the location of a bright reflection within Unit C that may correspond to a period of erosion of Unit E.
Figure 10 - Uninterpreted and interpreted W-E seismic line at the south end of the Padamarang Sub-basin along the northern margin of the Basa High. Offlapping strata are observed at the base of Unit A but becomes obscured and disrupted to the west. Disruption and tilting of Unit A may be related to transpressional fault movement along the western margin. Mounded reflections of Unit B are present over the western edge of the Padamarang Sub-basin which may mark shallow water carbonate build-ups. Unit C is interpreted to display carbonate build-up seismic character on the western edge of the basin. Protuberance of Unit X may correspond to a prograding apron of material, time equivalent to Unit A. The apron may have carbonate, siliciclastic or volcaniclastic sediment.
Figure 11 - Structural elements map showing a possible fault network based on the interpreted seismic, SRTM data and geological maps (Sukamto, 1975a; Rusmana et al., 1993). The Kolaka and Basa fault zones (FZ) are thought to correspond to old lineaments that are partly controlling more recent deformation. The Walanae fault zone is interpreted to step eastwards into the Saleyar Trough, although hard linkage of the East Walanae fault to the offshore eastern margin of the Saleyar Trough is unknown.