CHAPTER 1
TECTORNIC SETTING OF INDONESIA AND REGIONAL GEOLOGY OF SULAWESI

It has long been recognized that the Indonesian archipelago is one of the most enigmatic areas in Southeast Asia in terms of its geological and tectonic evolution (Hall, 1996, 2002; Hall & Wilson, 2000; Hamilton, 1979; Harris, 2003; Hinschberger et al., 2005; Katili, 1971; van Bammelen, 1949). It is a place where evidence of complex collision processes between tectonic elements can be observed. Understanding the geology of this area is, therefore, vital for reconstructing the overall geological history of the region.

Geological investigations on this archipelago have been conducted since the start of the 20th century by numerous workers from European countries, and have continued until the present by local and international workers. The first comprehensive investigation of Indonesian geology was the book “The Geology of Indonesia” (van Bammelen, 1949). This was the first comprehensive report on the regional geology, but described the geological evolution of the archipelago in terms of the pre-plate tectonic theory; known as “Undation theory”. Later studies by Katili (1971) and Hamilton (1979) interpreted the evolution of Indonesia in terms of plate tectonics.

1.1 TECTONIC SETTING OF THE INDONESIAN ARCHIPELAGO

The Indonesian archipelago was formed by interaction of at least three major plates, namely the Indian-Australian, the Pacific and the Eurasian (Daly et al., 1991; Hall, 1996; Hamilton, 1979), and many smaller plates (Charlton, 2000; Hamilton, 1988). The region is bounded to the northwest by the Eurasian Plate, to the west and south by the Indian-Australian Plate which is moving northward, and to the east by the Pacific and Phillipine Sea Plates, which are moving west–northwestward (Fig.1.1). The most up to date tectonic model of the Indonesia region is that published by Hall & Wilson (2000) and Hall (2002), based on computer simulations from various reported data.
The archipelago can be simply divided into two major tectonic settings: western and eastern Indonesia, separated by the Makassar Strait (Katili, 1971; Tjia, 1981). Katili (1971) noted that these two major regions had experienced different tectonic histories.

The western region, also known as the Sunda shelf or “Sundaland”, occupies the partially submerged southeastern part of the Eurasian continental mass, the large islands Sumatera, Java and Kalimantan which share its continental shelf, the Java Sea and the southern part of the South China Sea. The detailed tectonic setting has been reviewed by Katili (1971), Hamilton (1979) and Hall (1996). This region shows tectonic features including extinct and active subduction zones, volcanic arcs and volcanic plateaus, and foreland basins, all surrounding the continental mass. The major active volcanic arc now runs along the length of Sumatera and Java but continues eastward beyond west Indonesia, into Bali, Lombok, Sumbawa, Flores and small islands in the Banda Sea. Some back-arc basin extension due to subduction rollback has occurred in Sumatera, Java, South China and Kalimantan (Daly et al., 1991).

The eastern region, also called the Sahul shelf, extends from Sulawesi through the east part of the archipelago including the Indian-Australian continental shelf, extends from Papua through the Arafura Sea and the southern part of Timor Sea. The tectonic setting of the region has been discussed by many workers (Charlton, 2000; Hinschberger et al., 2005; Katili, 1971; Nishimura & Suparka, 1986; Nishimura & Suparka, 1990). It is more complex than the western region (Charlton, 2000; Harris, 2003). There are no very large continental masses in this area, the crust being of mainly oceanic affinity. However, it is characterised by the occurrence of several microcontinental fragments which detached from their Australian source during the Mesozoic (Pigram & Panggabean, 1984), and complex interactions between these microcontinents, volcanic arcs and back-arc basins, and trapped remnants of older Pacific and Indian ocean floor. Much of eastern Indonesia constitutes the “Eastern Indonesia Collision Complex” of Charlton (2000), a collection of structures resulting from multiplate collision since the Oligocene. Wakita (2000) identifies an older set of “Central Indonesia Cretaceous accretionary-collision Complexes” extending SW-NE across the archipelago from Java through Sulawesi. These approximately mark the divide between west Indonesia and the younger, less consolidated structures to the East. There is geographical overlap between the Mesozoic and Tertiary collision zones, the older structures being partially disrupted and otherwise overprinted by the younger.
Sulawesi, the island hosting the basement complexes of this study, did not exist as a single entity before the Eocene. The paleomagnetic investigations of Haile (1978) show large differences in paleolatitude between the eastern and western halves of the island in the Mesozoic. Charlton (2000) reported considerable differential rotation between southwest and northwest portions of the island since then. Tectonic reconstructions place south Sulawesi (including the field area of this study) against the southeast coast of Kalimantan prior to the opening of the Makassar Strait in the Eocene, while the eastern portions of the island formed hundreds of km to the south and east, on the Australian plate (Hall, 2002).

Most previous work has concentrated on reconstructing the Tertiary evolution of east Indonesia, since the record is more complete and the present-day structures are of interest for hydrocarbon exploration. However, the basement complexes of the current study are preserved remnants of the older, Cretaceous structures, and hence provide some insight into the processes and tectonic environments that prevailed at the margin of Sundaland in the late Mesozoic.

1.2 GEOLOGY OF SULAWESI

Sulawesi Island, formerly called Celebes, is located in the central part of the Indonesian archipelago (Fig.1.1). The geological complexity of Sulawesi has attracted many Earth scientists over the years. The distinctive multi-armed shape of the island suggests that it is a complex assemblage of tectonic terranes, the details of which are still not fully elucidated (Katili, 1975; Helmers et al., 1989; Hall & Wilson, 2000; van Leeuwen & Muhardjo, 2005).

Investigations on the geology of Sulawesi were conducted initially by Dutch scientists in the early 19th century. Since then, numerous investigations by local and international Earth scientists have accumulated much data on the geology of Sulawesi. Like other regions, Sulawesi has had its field geology interpreted in different ways over the years. A consequence of this is that a historical review of the geology of Sulawesi must be divided into two stages: work according to the pre-tectonic geosynclinal paradigm, and plate tectonic interpretations. Before 1960, investigations on this island were dominated by Dutch geologists (van Bammelen, 1949) working within the geosynclinal paradigm whereas after 1960, the description of the geology of the island is based mainly on the tectonic model.
Fig. 1.1. The tectonic setting of the Indonesian Archipelago. (after Katili, 1971; Hamilton, 1979; Hall & Wilson, 2000; Hall, 2002).

The boundary line between west and east Indonesia is derived from Katili (1971).
1.2.1. Geosynclinal model

In the geosynclinal approach, Sulawesi was divided into a series of troughs and highs (or rises) that migrated in time and space (van Bammelen, 1949) (Fig. 1.2). Van Bammelen (1949) introduced the orogeny concept to the geology of Sulawesi, and defined three major orogenies: the northern Sulawesi orogeny which extends between the Sulawesi Trough and the Banggai Archipelago, the central Sulawesi orogeny which includes the region from the Makassar Trough to the Gulf of Tolo, and the southern Sulawesi orogeny, which is composed of the south and southeast arms of the island.

![Fig. 1.2. Geosynclinal elements of Sulawesi (Simplified after van Bemmelen, 1949)](image)
However, the geosyncline model failed to explain the various disparate geological terranes which can be described in the tectonic model as corresponding to different tectonic environments such as mid oceanic ridge, passive continental margin, island arc and mélangé occurrence. Diverse examples of such tectonically distinct units are widely distributed in Sulawesi.

1.2.2. Plate-tectonic model

The first plate tectonic interpretations on Sulawesi date from the early 1960s, and placed Sulawesi in a typical west Pacific setting involving either a single subduction system or multiple arc/subduction systems (Audley-Charles et al., 1972; Elburg & Foden, 1999; Hamilton, 1979; Katili, 1978; Miyashiro, 1961; Sukamto, 1982).

Miyashiro (1961) applied his idea of paired metamorphic belts to Sulawesi. A Miyashiro pair is composed of outer arc and inner arc belts, with respectively low-temperature high-pressure and high-temperature low-pressure metamorphism. These are now interpreted in the tectonic model as respectively a subduction/accretion complex and the associated volcanic arc. According to Miyashiro, the east arm, the southeast arm, the central arm and eastern part of central Sulawesi represented the outer arc of Sulawesi, consisting of a high-pressure metamorphic belt which formed beneath a trench zone. The north arm, the western part of central Sulawesi and the south arm constitute the inner arc, comprises a low-pressure metamorphic belt formed beneath a volcanic chain in the adjacent island arc or continental margin. He inferred that these components of a paired metamorphic belt were present, but dismembered by a great fault. This model was based on the similarity of the metamorphic rock assemblages to some in the Japanese archipelago and in other localities of the circum-Pacific region.

Katili (1971, 1978) was the most influential early worker to apply the plate tectonic framework to the geology of the island. He described a comprehensive model for the tectonic evolution of Sulawesi, with a series of reconstructions. He concluded that Sulawesi resulted from the interaction and collision of Eurasian, Indian-Australian and Pacific Plates. This origin was supported by the complex physiographic as well as the structural and stratigraphic successions on the island, including features such as the deformed tectonic belt, an inverted island arc and the development of reversed polarity in a small subduction zone.
Sukamto (1975) conducted geological investigations in Sulawesi and described the major structural patterns as well as the stratigraphy of the island. He recognized that each arm of the island appears to be a different terrane with a different tectonic origin. He later introduced the concept of tectonic provinces to distinguish and classify the tectonic differences between the regions of the island.

Hamilton (1979) later described Sulawesi as an active plate boundary and initially proposed incipient segmentation of Sulawesi based on the diverging north, south, east and southeast arms of the island. The differences between the eastern and western parts of the island led him to divide the island into two arcs, western and eastern, similar to the division of Miyashiro (1973). The western arc consists of the north arm, south arm and western part of central Sulawesi. This was interpreted to be subduction complexes overlain by sediments deposited in an outer-arc basin. The eastern arc consisted of the east and southeast arms and the eastern part of central Sulawesi, comprised of fragments of ophiolites and younger subduction complexes.

After the 1970’s, numerous workers continued to conduct a series of studies on the arms of this island in isolation. Sukamto (1982) and Sukamto & Supriatna (1982) published the first systematic geological map of the southern part of the island. Davies (1990), Kadarusman et al. (2004) worked on its east arm whereas Priadi et al. (1994), Elburg et al. (1998) and van Leeuwen et al. (2007) worked on north arm of the island. Helmers et al. (1990), Parkinson (1998) and Villenueve et al. (2002) worked on the central part of the island while Wilson & Bosence (1996), Wakita et al. (1996), Bergman et al. (1996), Coffield et al. (1993), and Elburg et al. (1999a, 1999b, 2002) worked on the western arm of the island and Smith et al. (1991) worked on the southeast arm and Buton Island. The overall geological model of Sulawesi did not change significantly despite the various additional local data and reconstructions by those workers.

The Neogene orogeny in Sulawesi was discussed by Simandjuntak and Barber (1996). They concluded that the Neogene orogeny in this island was initiated by the collision of the eastern part of the island with two microcontinental blocks of Australian origin; Tukang Besi and Banggai-Sula. This collision was followed by a series of regional tectonic events including the obduction of the East Sulawesi Ophiolite, the formation of the Central Sulawesi Thrust Belt and development of the Palu–Koro sinistral transcurrent fault (Fig.1.3).
Paleomagnetic investigations carried out by Haile (1978), Sasajima et al. (1980), Otofuji et al. (1981), Surmont et al. (1994), Mubroto et al. (1994) and Wensink (1997) also contributed to our current understanding of the evolution of the island. Differences of paleoaltitude between western Sulawesi and the eastern arc suggest significant geographical separation before colliding in the Miocene.

Based on the overall geological framework that has emerged from these studies, lithotectonic Sulawesi can be divided into four (4) tectonic provinces, namely (1) the Western and North Sulawesi Pluto-Volcanic Arc, (2) the Central Sulawesi Metamorphic Belt, (3) the East Sulawesi Ophiolite Belt and (4) the Banggai-Sula and Tukang Besi continental fragments (Fig.1.4). The detailed description is as follows:

1. **West and North Sulawesi Pluto-Volcanic Arc**

   This province can be subdivided into two segments:

   (i) the West region, which consists of a continental margin segment with metamorphic basement rocks of pre-Tertiary Sundaland origin (including Bantimala and Barru Complex) (Wakita et al., 1996; Parkinson et al., 1998) and overlain by Upper Cretaceous and Cenozoic volcanic-sedimentary sequences. This region, including part of the south arm, was part of east Sundaland during the Mesozoic (Elburg et al., 2002; Hamilton, 1979) prior to the opening of the Makassar Strait in the Eocene (Guntoro, 1999; Hall, 2002). Paleomagnetic studies show that it rotated through 35-50° as a rigid block with Malaya and west Kalimantan between the Cretaceous and then (Haile, 1978). After separation from Kalimantan, the north part of this province has undergone a clockwise rotation of approximately 20-25° since the Miocene (Surmont et al., 1994).

   (ii) the North region, which consists of a Late Miocene to Recent subduction-related volcanic arc (Elburg & Foden, 1998), resulting from the west-dipping subduction of the
Molucca Sea Plate (Jezek et al., 1981). This region is built on an oceanic substrate in most of the north (Kavalieris et al., 1992; van Leeuwen et al., 2007), and a Paleozoic microcontinental block, the Malino Metamorphic Complex which was derived from the New-Guinea-Australian margin of Gondwanaland (van Leeuwen et al., 2007).

2. Central Sulawesi Metamorphic Belt

This belt is confined to the centre and part of the eastern arm of the island, and is assumed to have resulted from collision between fragments of Gondwana and the active Asiatic margin in the late Oligocene or early Miocene (Villeneuve et al., 2002). It consists of sheared metamorphic rocks including the Pompangeo schist complex and a mélangé complex (Parkinson et al., 1998), as well as a Miocene Ophiolite (Lamasi Complex) (Bergman et al., 1996). This region has been assumed to be an accretionary complex formed during Cretaceous and Paleogene time (Hamilton, 1979), or a suture between western and eastern part of Sulawesi (Villeneuve et al., 2002); the two are not exclusive. The major structures are a westward directed fold and thrust belt with a thrust front in the Makassar Strait (Coffield et al., 1993), and the sinistral strike-slip Central Sulawesi Fault System, which consists of the Palu-Koro Fault to the NNW and the Matano Fault to the SSE (Bellier et al., 1998). Radiometric dating suggested that this fold belt was developed about 13 – 5 Ma (Bellier et al., 2006).

3. The Eastern Sulawesi Ophiolite Belt

This belt extends from the central Sulawesi trough across the east and southeast arms, including Buton and Muna Islands. It consists of tectonically dismembered and highly faulted ophiolite associated with Mesozoic metamorphic rocks and sediments. These form a basement for this region, which is overlain by Cenozoic sediments (Kadarusman et al., 2004; Mubroto et al., 1994; Simandjuntak & Barber, 1996). The ophiolite series comprises residual mantle peridotite, mafic-ultramafic cumulate and gabbro, sheeted dolerites and basaltic volcanic rocks. The oceanic plateau component of the ophiolite has been interpreted as a product of the southwest Pacific Superplume (Kadarusman et al., 2004). Gravity data suggest that the ophiolite thickens westward and dips beneath schist along a major fault (Silver et al., 1978). The belt is interpreted as a Neogene accretionary complex formed by westward dipping subduction and by partial underthrusting of the Sula and Tukang Besi platforms.
4. The Banggai-Sula and Tukang Besi continental fragments

These continental fragments are located in the eastern and southeastern parts of Sulawesi, respectively. The Bangai-Sula microcontinent is represented above sea level by a group of islands, including Peleng, Banggai, Taliabu and Mangole Islands (Garrard et al., 1988) whereas the Tukang Besi microcontinent is comprised of Buton, Muna and smaller surrounding islands.

Banggai–Sula has a metamorphic basement which was intruded by Late Paleozoic granitoids and overlain by Triassic felsic to intermediate volcanic products (Pigram & Panggabean, 1984). The region is interpreted to have originated from New Guinea in the late Cenozoic (Pigram et al., 1985) and to have transported by extension on the Sorong Fault during the Neogene (Audley-Charles et al., 1972). The Buton Islands consist of metamorphic rocks associated with ophiolite, Mesozoic – Paleogene deep water limestone with minor terrigenous clastic rock (Smith & Silver, 1991), ultramafic and mafic rock and Neogene and Quaternary sediments, which rifted from the Australian-New Guinea Gondwana margin during the Mesozoic and collided with Sulawesi in mid-to-late Tertiary times (Davidson, 1991; Hamilton, 1979). Most of the Tukang Besi Platform is submerged; the exposed part of the platform is occupied by Upper Neogene and Quaternary reef limestone. Like other microcontinents in the region, Buton and the rest of the Tukang Besi platform are interpreted as an Australian continental fragment (Hinschberger et al., 2005). However, Fortuin et al. (1990) suggested that Buton Island and the Tukang Besi Archipelago represent different continental fragments which were formerly separated from each other by oceanic crust.

1.3 GEOLOGICAL SETTING OF SOUTH SULAWESI

The south Sulawesi terrane lies in the south arm of Sulawesi (Fig.1.4) and is made up of sediment and volcanic arc products overlying a pre-Tertiary basement complex. The present day tectonic system is dominated by two major NNW-SSE trending strike-slip faults, namely the West Walanae Fault (WWF) and East Walanae Fault (EWF). Movement on these is mainly sinistral (Berry & Grady, 1987), but an extensional component has resulted in opening of the Plio-Pleistocene Walanae Graben (Fig. 1.5) between them (van Leeuwen, 1981).
Fig. 1.4. Tectonic Setting of Geology of Sulawesi (modified after Hamilton, 1979; Hall & Wilson, 2000).
Various parts of south Sulawesi appear to have undergone significant (up to 80º) rotation in either clockwise or anticlockwise directions, which may be rotation of local blocks associated with movement on this fault system (Charlton, 2000).

Sukamto (1975, 1982) mapped throughout the area, and the results were compiled by Sukamto (1982) and Sukamto & Supriatna (1982) in the form of 1:250,000 Geological Maps in several sheets (Ujung Pandang, Benteng and Sinjai sheet and Pangkajene and Western part of Watampone sheet) and explanatory notes.

From previous investigations, the geology of south Sulawesi is depicted in Fig. 1.5 and described as follows:

1. **Pre-Tertiary Basement Complex**

This consists of metamorphic, sedimentary, and ultramafic rocks and is found in two separate blocks in the Bantimala and Barru areas (Fig. 1.4) (Hamilton, 1979; Sukamto, 1982; van Leeuwen, 1981). Metamorphic rocks include high-pressure types, namely glaucophane schist (Parkinson, 1998), albite-actinolite-chlorite schist, chlorite-mica schists, garnet-glaucophane rock, garnet-glaucophane-quartz schist, garnet-chloritoid-glaucophane-quartz schist (Miyazaki et al., 1996), quartzites, graphite phyllites (Berry & Grady, 1987; Sukamto, 1982) and blocks of eclogite included in blueschist (Maulana et al., 2008; Miyazaki et al., 1996). The ages from K/Ar dating on muscovite-garnet and quartz-muscovite schists from the Bantimala basement complex are 111 Ma (Hamilton, 1979). In addition, Wakita et al. (1994) reported respectively ages of 132 - 114 Ma and 106 Ma from the Bantimala schist and from the Barru schist using K/Ar analyses on muscovite. The sedimentary rocks are comprised of melange, turbidite and shallow-marine clastic rocks (Wakita et al., 1996). Mélange occurs as tectonic blocks, and includes clasts of rock types such as sandstone, shale, siliceous shale, chert, basalt, schist, and felsic igneous rocks within a sheared matrix (Wakita et al., 1996). The middle Cretaceous (late Albian – early Cenomanian, i.e. about 105 - 95 Ma) chert unconformably overlies the high-pressure metamorphic rocks (Wakita et al., 1996). The ultramafic rock is dominated by serpentinised peridotite, which contains chromite lenses in some areas and is locally intruded by dacite and andesite (van Leeuwen, 1981).
2. **Upper Cretaceous Sedimentation**

It consists of three formations, namely the Balangbaru Formation, which is found in the western part of the region (Sukamto, 1982), the Marada Formation (van Leeuwen, 1981) confined to the Biru region, and the Latimojong Formation in the northern part of the region. The Balangbaru Formation unconformably overlies the basement complex, and is composed of interbedded sandstones and silty shales, with less important conglomerates, pebbly sandstones and conglomeratic breccias (Sukamto, 1982). The Marada Formation consists of a succession of alternating impure sandstones, siltstones and shales (van Leeuwen, 1981). The sandstones are mostly feldspathic greywacke which are locally calcareous, composed of subangular to angular grains of quartz, plagioclase and orthoclase with subordinate biotite, muscovite and angular lithic fragments embedded in a matrix of clay minerals, chlorite and sericite (van Leeuwen, 1981). Sedimentary structures in coarser units of this formation are typical of turbidites. The lithologies and fauna of the Balangbaru and contemporaneous Marada Formation to the east (van Leeuwen, 1981; Sukamto, 1982) are typical of an open marine, deep neritic to bathyal environment (Sukamto & Supriatna, 1982; van Leeuwen, 1981). The ages of these formations were inferred from their microfauna as Upper Cretaceous (van Leeuwen, 1981). The tectonic setting of the Balangbaru Formation is interpreted to be a small fore-arc basin on the trench slope. However, Wakita et al. (1996) regarded the Balangbaru Formation as part of the Bantimala tectonic complex. Pb and Nd isotopic signatures of shale from this formation are similar to those of graphite-rich shale from the Polewali area in the northern part of South Sulawesi (Elburg & Foden, 1999) and the Lasipu Formation in the Sumba region (Vroon et al., 1996; Wensink, 1997).

3. **Paleogene Volcanism**

Paleogene volcanism in the region is represented by the Kalamiseng, Langi and Bua Volcanics. The various names of the volcanic formation probably reflect its geographical distribution, since detailed studies on this formation do not exist. In the Bantimala region, these volcanics have been known as Bua Volcanics (Sukamto, 1982) whereas in the Biru area, they are called the Langi Volcanics (van Leeuwen, 1981). They unconformably overlie the Upper Cretaceous sediments, and in turn are unconformably overlain by Eocene sediments. The volcanics consist of lavas and pyroclastic deposits of andesitic to trachy-andesitic composition, with rare intercalations.
of limestone and shale towards the top of the sequence (van Leeuwen, 1981; Sukamto, 1982). They show a strongly fractured, poorly bedded texture. Fission track dating of zircon from tuff at the lower part of the volcanic sequence yielded an Early Paleocene age of 63 ± 2.2 Ma (van Leeuwen, 1981), whereas K-Ar dating from biotite monzonite in the Langi Intrusion suggests an age of 52.3 ± 0.5 Ma (Elburg et al., 2002). Hence, volcanic activity in this region started in the Paleocene and may have continued to the early Eocene (van Leeuwen, 1981). It was later suggested that the volcanics were generated above a west-dipping subduction zone beneath the South Sulawesi. (van Leeuwen, 1981).

The Kalamiseng Formation outcrops to the east of the Walanae Depression or Graben and consists of volcanic breccias and pillow basalts, as well as some rhyolitic flows. These are interbedded with tuffs, sandstones and marls (Sukamto, 1982; Sukamto & Supriatna, 1982). The lavas are spilitic basalts and diabases which have been metamorphosed to the greenschist facies. The K-Ar analyses from rhyolitic lava suggest an age of 21.72 ± 1.09 Ma (Early Miocene) (Polvé et al., 1997).

4. Eocene to Miocene Sedimentation

Eocene to Miocene sediments can be found in the western part of the Walanae Graben as the Mallawa Formation, and in the northern part near Latimojong Mountain as the Toraja Formation. They are composed of arkosic sandstones, siltstones, claystone, marls and conglomerates, intercalated with layers or lenses of coal and limestone. The Mallawa formation unconformably overlies the Balangbaru Formation and locally the Langi Volcanics, whereas the Toraja Formation overlies the Latimojong Formation. A Paleogene age for the Mallawa Formation is inferred from palynomorphs (Khan & Tschudy, in Sukamto, 1982) whilst ostracods suggest an Eocene age (Hazel, in Sukamto, 1982). The Mallawa Formation is inferred to have been deposited in a terrestrial/marginal marine environment passing transgressively upwards into a shallow marine environment (Wilson & Bosence, 1996).

The Tonasa Formation conformably overlies the Mallawa Formation or the Langi Volcanics. This formation has been described in detail by van Leeuwen (1981) and Wilson & Bosence (1996). It consists carbonate facies rock which can be classified into four members labelled A, B, C and D from the bottom to top (Wilson & Bosence, 1996). The age of the Tonasa Formation is inferred as Eocene to middle Miocene (van
Leeuwen, 1981; Sukamto, 1982) or Late Eocene to Middle Miocene (Wilson & Bosence, 1996). The formation is widely distributed in the western part of the Walanae Graben and is locally found in the southwest part of the South Arm peninsula. An equivalent formation known as the Makale Formation is found in the northern part of the region.

The Salo Kalupang is present in the Bone area, in the eastern part of South Sulawesi. This formation was deposited in deepwater depositional environment (Maryanto et al., 2004) and characterized by sandstone, shales and claystone interbedded with volcanic conglomerates, breccias, tuffs, lavas, limestones and marls (Sukamto, 1982). Based on foraminiferal content, the age of the Salo Kalupang Formation is interpreted to range from the Middle Eocene to Middle Miocene (Maryanto et al., 2004) or Early Eocene to Late Oligocene (Kadar, in Sukamto, 1982 and Sukamto & Supriatna, 1982).

The Lower Camba Formation consists of tuffaceous sandstones, interbedded with tuffs, sandstones claystones, volcanic conglomerates and breccia, marls, limestone and coals (Sukamto, 1982; Sukamto & Supriatna, 1982).

5. Miocene to Recent Volcanism and Sedimentation

Miocene to Recent volcanism and sedimentation in this region consists of various formations, including, in order of decreasing age, the Upper Camba Formation, Baturape–Cindako Volcanics, Soppeng Volcanics, Pare-pare Volcanics, Lemo Volcanics, and the Lompobattang Volcanics.

The Upper Camba Formation is made up of a volcanic series (the Camba Volcanics) interbedded with marine sediments and is located in the Western Divide Range (Sukamto, 1982; Sukamto & Supriatna, 1982). Foraminiferal dating from this member suggests a middle to late Miocene age (Sukamto, 1982). However, Yuwono et al. (1988) reported that the Camba Formation age ranges from Lower Miocene to Upper Miocene.

The Baturape and Cindako Volcanics occur in the western part of Makassar near Takalar regency. These two volcanic groups have the same characteristic alkali potassic extrusive and intrusive lithologies. However, K/Ar analyses of a basaltic flow from Baturape yields $12.81 \pm 0.64$ Ma and $12.38 \pm 0.62$ Ma (Middle Miocene) (Polve et al.,
The Soppeng Volcanics are found in the central part of the region and are mainly of basaltic composition. The K-Ar results from a basaltic flow and a trachyandesitic neck give dates of 9.27 ± 0.46 and 9.32 ± 0.37, respectively, i.e. Late Miocene age (Polve et al., 1997). However, Sukamto (1982) interpreted these volcanics as early Miocene in age since they are conformably overlain by rocks of the Camba Formation.

The Parepare Volcanics are alternating lava flows and pyroclastic breccias which are confined to Pare-pare region in the western part of the arm. K/Ar analyses obtained from a rhyolite block and a dacite imply late Miocene to Pliocene age (Polve et al., 1997).

The Lemo Volcanics unconformably overlie the upper Walanae Formation in the Biru area (van Leeuwen, 1981). It consists of volcanic breccia, tuffs, lava and dykes with the thickness of more than 350 m (Elburg et al., 2002). K/Ar dating for the Lemo Volcanics yielded an age of 4.47 ± 0.22 Ma (Pliocene) (Polve, et al., 1997) and 6.3-7.0 Ma (Elburg et al., 2002).

The youngest volcanic products in this area are the Lompobattang Volcanics, which form a broad stratovolcano located in the southeast of south Sulawesi (Leterrier et al., 1990) and the Barupu Volcanics in the northern part of the region (Sukamto, 1975). The first were interpreted as a “post-collisional group” ranging from basaltic andesite to dacite and andesitic composition (Elburg and Foden, 1999). K/Ar dating of Lompobattang samples yields ages between 1.6 and 1.9 Ma (Polve et al., 1997; Elburg & Foden, 1999).
Fig. 1.5. Generalised geological map of south Sulawesi (modified after van Leuween, 1981; Sukamto, 1982; Sukamto & Supriatna, 1982; Wilson & Bosence, 1996).
CHAPTER 1
TECTONIC SETTING OF INDONESIA AND REGIONAL GEOLOGY OF SULAWESI

It has long been recognized that the Indonesian archipelago is one of the most enigmatic areas in Southeast Asia in terms of its geological and tectonic evolution (Hall, 1996, 2002; Hall & Wilson, 2000; Hamilton, 1979; Harris, 2003; Hinschberger et al., 2005; Katili, 1971; van Bammelen, 1949). It is a place where evidence of complex collision processes between tectonic elements can be observed. Understanding the geology of this area is, therefore, vital for reconstructing the overall geological history of the region.

Geological investigations on this archipelago have been conducted since the start of the 20th century by numerous workers from European countries, and have continued until the present by local and international workers. The first comprehensive investigation of Indonesian geology was the book “The Geology of Indonesia” (van Bammelen, 1949). This was the first comprehensive report on the regional geology, but described the geological evolution of the archipelago in terms of the pre-plate tectonic theory; known as “Undation theory”. Later studies by Katili (1971) and Hamilton (1979) interpreted the evolution of Indonesia in terms of plate tectonics.

1.1 TECTONIC SETTING OF THE INDONESIAN ARCHIPELAGO

The Indonesian archipelago was formed by interaction of at least three major plates, namely the Indian-Australian, the Pacific and the Eurasian (Daly et al., 1991; Hall, 1996; Hamilton, 1979), and many smaller plates (Charlton, 2000; Hamilton, 1988). The region is bounded to the northwest by the Eurasian Plate, to the west and south by the Indian-Australian Plate which is moving northward, and to the east by the Pacific and Phillipine Sea Plates, which are moving west–northwestward (Fig.1.1). The most up to date tectonic model of the Indonesia region is that published by Hall & Wilson (2000) and Hall (2002), based on computer simulations from various reported data.
The archipelago can be simply divided into two major tectonic settings: western and eastern Indonesia, separated by the Makassar Strait (Katili, 1971; Tjia, 1981). Katili (1971) noted that these two major regions had experienced different tectonic histories.

The western region, also known as the Sunda shelf or “Sundaland”, occupies the partially submerged southeastern part of the Eurasian continental mass, the large islands Sumatera, Java and Kalimantan which share its continental shelf, the Java Sea and the southern part of the South China Sea. The detailed tectonic setting has been reviewed by Katili (1971), Hamilton (1979) and Hall (1996). This region shows tectonic features including extinct and active subduction zones, volcanic arcs and volcanic plateaus, and foreland basins, all surrounding the continental mass. The major active volcanic arc now runs along the length of Sumatera and Java but continues eastward beyond west Indonesia, into Bali, Lombok, Sumbawa, Flores and small islands in the Banda Sea. Some back-arc basin extension due to subduction rollback has occurred in Sumatera, Java, South China and Kalimantan (Daly et al., 1991).

The eastern region, also called the Sahul shelf, extends from Sulawesi through the east part of the archipelago including the Indian-Australian continental shelf, extends from Papua through the Arafura Sea and the southern part of Timor Sea. The tectonic setting of the region has been discussed by many workers (Charlton, 2000; Hinschberger et al., 2005; Katili, 1971; Nishimura & Suparka, 1986; Nishimura & Suparka, 1990). It is more complex than the western region (Charlton, 2000; Harris, 2003). There are no very large continental masses in this area, the crust being of mainly oceanic affinity. However, it is characterised by the occurrence of several microcontinental fragments which detached from their Australian source during the Mesozoic (Pigram & Panggabean, 1984), and complex interactions between these microcontinents, volcanic arcs and back-arc basins, and trapped remnants of older Pacific and Indian ocean floor. Much of eastern Indonesia constitutes the “Eastern Indonesia Collision Complex” of Charlton (2000), a collection of structures resulting from multiplate collision since the Oligocene. Wakita (2000) identifies an older set of “Central Indonesia Cretaceous accretionary-collision Complexes” extending SW-NE across the archipelago from Java through Sulawesi. These approximately mark the divide between west Indonesia and the younger, less consolidated structures to the East. There is geographical overlap between the Mesozoic and Tertiary collision zones, the older structures being partially disrupted and otherwise overprinted by the younger.
Sulawesi, the island hosting the basement complexes of this study, did not exist as a single entity before the Eocene. The paleomagnetic investigations of Haile (1978) show large differences in paleolatitude between the eastern and western halves of the island in the Mesozoic. Charlton (2000) reported considerable differential rotation between southwest and northwest portions of the island since then. Tectonic reconstructions place south Sulawesi (including the field area of this study) against the southeast coast of Kalimantan prior to the opening of the Makassar Strait in the Eocene, while the eastern portions of the island formed hundreds of km to the south and east, on the Australian plate (Hall, 2002).

Most previous work has concentrated on reconstructing the Tertiary evolution of east Indonesia, since the record is more complete and the present-day structures are of interest for hydrocarbon exploration. However, the basement complexes of the current study are preserved remnants of the older, Cretaceous structures, and hence provide some insight into the processes and tectonic environments that prevailed at the margin of Sundaland in the late Mesozoic.

1.2 GEOLOGY OF SULAWESI

Sulawesi Island, formerly called Celebes, is located in the central part of the Indonesian archipelago (Fig.1.1). The geological complexity of Sulawesi has attracted many Earth scientists over the years. The distinctive multi-armed shape of the island suggests that it is a complex assemblage of tectonic terranes, the details of which are still not fully elucidated (Katili, 1975; Helmers et al., 1989; Hall & Wilson, 2000; van Leeuwen & Muhardjo, 2005).

Investigations on the geology of Sulawesi were conducted initially by Dutch scientists in the early 19th century. Since then, numerous investigations by local and international Earth scientists have accumulated much data on the geology of Sulawesi. Like other regions, Sulawesi has had its field geology interpreted in different ways over the years. A consequence of this is that a historical review of the geology of Sulawesi must be divided into two stages: work according to the pre-tectonic geosynclinal paradigm, and plate tectonic interpretations. Before 1960, investigations on this island were dominated by Dutch geologists (van Bammelen, 1949) working within the geosynclinal paradigm whereas after 1960, the description of the geology of the island is based mainly on the tectonic model.
Fig. 1.1. The tectonic setting of the Indonesian Archipelago. (after Katili, 1971; Hamilton, 1979; Hall & Wilson, 2000; Hall, 2002).

The boundary line between west and east Indonesia is derived from Katili (1971).
1.2.1. Geosynclinal model

In the geosynclinal approach, Sulawesi was divided into a series of troughs and highs (or rises) that migrated in time and space (van Bammelen, 1949) (Fig. 1.2). Van Bammelen (1949) introduced the orogeny concept to the geology of Sulawesi, and defined three major orogenies: the northern Sulawesi orogeny which extends between the Sulawesi Trough and the Banggai Archipelago, the central Sulawesi orogeny which includes the region from the Makassar Trough to the Gulf of Tolo, and the southern Sulawesi orogeny, which is composed of the south and southeast arms of the island.

Fig. 1.2. Geosynclinal elements of Sulawesi (Simplified after van Bemmelen, 1949)
However, the geosyncline model failed to explain the various disparate geological terranes which can be described in the tectonic model as corresponding to different tectonic environments such as mid oceanic ridge, passive continental margin, island arc and mélangé occurrence. Diverse examples of such tectonically distinct units are widely distributed in Sulawesi.

1.2.2. Plate-tectonic model

The first plate tectonic interpretations on Sulawesi date from the early 1960s, and placed Sulawesi in a typical west Pacific setting involving either a single subduction system or multiple arc/subduction systems (Audley-Charles et al., 1972; Elburg & Foden, 1999; Hamilton, 1979; Katili, 1978; Miyashiro, 1961; Sukamto, 1982).

Miyashiro (1961) applied his idea of paired metamorphic belts to Sulawesi. A Miyashiro pair is composed of outer arc and inner arc belts, with respectively low-temperature high-pressure and high-temperature low-pressure metamorphism. These are now interpreted in the tectonic model as respectively a subduction/accretion complex and the associated volcanic arc. According to Miyashiro, the east arm, the southeast arm, the central arm and eastern part of central Sulawesi represented the outer arc of Sulawesi, consisting of a high-pressure metamorphic belt which formed beneath a trench zone. The north arm, the western part of central Sulawesi and the south arm constitute the inner arc, comprises a low-pressure metamorphic belt formed beneath a volcanic chain in the adjacent island arc or continental margin. He inferred that these components of a paired metamorphic belt were present, but dismembered by a great fault. This model was based on the similarity of the metamorphic rock assemblages to some in the Japanese archipelago and in other localities of the circum-Pacific region.

Katili (1971, 1978) was the most influential early worker to apply the plate tectonic framework to the geology of the island. He described a comprehensive model for the tectonic evolution of Sulawesi, with a series of reconstructions. He concluded that Sulawesi resulted from the interaction and collision of Eurasian, Indian-Australian and Pacific Plates. This origin was supported by the complex physiographic as well as the structural and stratigraphic successions on the island, including features such as the deformed tectonic belt, an inverted island arc and the development of reversed polarity in a small subduction zone.
Sukamto (1975) conducted geological investigations in Sulawesi and described the major structural patterns as well as the stratigraphy of the island. He recognized that each arm of the island appears to be a different terrane with a different tectonic origin. He later introduced the concept of tectonic provinces to distinguish and classify the tectonic differences between the regions of the island.

Hamilton (1979) later described Sulawesi as an active plate boundary and initially proposed incipient segmentation of Sulawesi based on the diverging north, south, east and southeast arms of the island. The differences between the eastern and western parts of the island led him to divide the island into two arcs, western and eastern, similar to the division of Miyashiro (1973). The western arc consists of the north arm, south arm and western part of central Sulawesi. This was interpreted to be subduction complexes overlain by sediments deposited in an outer-arc basin. The eastern arc consisted of the east and southeast arms and the eastern part of central Sulawesi, comprised of fragments of ophiolites and younger subduction complexes.

After the 1970’s, numerous workers continued to conduct a series of studies on the arms of this island in isolation. Sukamto (1982) and Sukamto & Supriatna (1982) published the first systematic geological map of the southern part of the island. Davies (1990), Kadarusman et al. (2004) worked on its east arm whereas Priadi et al. (1994), Elburg et al. (1998) and van Leeuwen et al. (2007) worked on north arm of the island. Helmers et al. (1990), Parkinson (1998) and Villenueve et al. (2002) worked on the central part of the island while Wilson & Bosence (1996), Wakita et al. (1996), Bergman et al. (1996), Coffield et al. (1993), and Elburg et al. (1999a, 1999b, 2002) worked on the western arm of the island and Smith et al. (1991) worked on the southeast arm and Buton Island. The overall geological model of Sulawesi did not change significantly despite the various additional local data and reconstructions by those workers.

The Neogene orogeny in Sulawesi was discussed by Simandjuntak and Barber (1996). They concluded that the Neogene orogeny in this island was initiated by the collision of the eastern part of the island with two microcontinental blocks of Australian origin; Tukang Besi and Banggai-Sula. This collision was followed by a series of regional tectonic events including the obduction of the East Sulawesi Ophiolite, the formation of the Central Sulawesi Thrust Belt and development of the Palu–Koro sinistral transcurrent fault (Fig.1.3).
Paleomagnetic investigations carried out by Haile (1978), Sasajima et al. (1980), Otofuji et al. (1981), Surmont et al. (1994), Mubroto et al. (1994) and Wensink (1997) also contributed to our current understanding of the evolution of the island. Differences of paleoaltitude between western Sulawesi and the eastern arc suggest significant geographical separation before colliding in the Miocene.

Based on the overall geological framework that has emerged from these studies, lithotectonic Sulawesi can be divided into four (4) tectonic provinces, namely (1) the Western and North Sulawesi Pluto-Volcanic Arc, (2) the Central Sulawesi Metamorphic Belt, (3) the East Sulawesi Ophiolite Belt and (4) the Banggai-Sula and Tukang Besi continental fragments (Fig. 1.4). The detailed description is as follows:

1. **West and North Sulawesi Pluto-Volcanic Arc**

   This province can be subdivided into two segments:

   (i) the West region, which consists of a continental margin segment with metamorphic basement rocks of pre-Tertiary Sundaland origin (including Bantimala and Barru Complex) (Wakita et al., 1996; Parkinson et al., 1998) and overlain by Upper Cretaceous and Cenozoic volcanic-sedimentary sequences. This region, including part of the south arm, was part of east Sundaland during the Mesozoic (Elburg et al., 2002; Hamilton, 1979) prior to the opening of the Makassar Strait in the Eocene (Guntoro, 1999; Hall, 2002). Paleomagnetic studies show that it rotated through 35-50° as a rigid block with Malaya and west Kalimantan between the Cretaceous and then (Haile, 1978). After separation from Kalimantan, the north part of this province has undergone a clockwise rotation of approximately 20-25° since the Miocene (Surmont et al., 1994).

   (ii) the North region, which consists of a Late Miocene to Recent subduction-related volcanic arc (Elburg & Foden, 1998), resulting from the west-dipping subduction of the
Molucca Sea Plate (Jezek et al., 1981). This region is built on an oceanic substrate in most of the north (Kavalieris et al., 1992; van Leeuwen et al., 2007), and a Paleozoic microcontinental block, the Malino Metamorphic Complex which was derived from the New-Guinea-Australian margin of Gondwanaland (van Leeuwen et al., 2007).

2. **Central Sulawesi Metamorphic Belt**

   This belt is confined to the centre and part of the eastern arm of the island, and is assumed to have resulted from collision between fragments of Gondwana and the active Asiatic margin in the late Oligocene or early Miocene (Villeneuve et al., 2002). It consists of sheared metamorphic rocks including the Pompangeo schist complex and a mélange complex (Parkinson et al., 1998), as well as a Miocene Ophiolite (Lamasi Complex) (Bergman et al., 1996). This region has been assumed to be an accretionary complex formed during Cretaceous and Paleogene time (Hamilton, 1979), or a suture between western and eastern part of Sulawesi (Villeneuve et al., 2002); the two are not exclusive. The major structures are a westward directed fold and thrust belt with a thrust front in the Makassar Strait (Coffield et al., 1993), and the sinistral strike-slip Central Sulawesi Fault System, which consists of the Palu-Koro Fault to the NNW and the Matano Fault to the SSE (Bellier et al., 1998). Radiometric dating suggested that this fold belt was developed about 13 – 5 Ma (Bellier et al., 2006).

3. **The Eastern Sulawesi Ophiolite Belt**

   This belt extends from the central Sulawesi trough across the east and southeast arms, including Buton and Muna Islands. It consists of tectonically dismembered and highly faulted ophiolite associated with Mesozoic metamorphic rocks and sediments. These form a basement for this region, which is overlain by Cenozoic sediments (Kadarusman et al., 2004; Mubroto et al., 1994; Simandjuntak & Barber, 1996). The ophiolite series comprises residual mantle peridotite, mafic-ultramafic cumulate and gabbro, sheeted dolerites and basaltic volcanic rocks. The oceanic plateau component of the ophiolite has been interpreted as a product of the southwest Pacific Superplume (Kadarusman et al., 2004). Gravity data suggest that the ophiolite thickens westward and dips beneath schist along a major fault (Silver et al., 1978). The belt is interpreted as a Neogene accretionary complex formed by westward dipping subduction and by partial underthrusting of the Sula and Tukang Besi platforms.
4. The Banggai-Sula and Tukang Besi continental fragments

These continental fragments are located in the eastern and southeastern parts of Sulawesi, respectively. The Bangai-Sula microcontinent is represented above sea level by a group of islands, including Peleng, Banggai, Taliabu and Mangole Islands (Garrard et al., 1988) whereas the Tukang Besi microcontinent is comprised of Buton, Muna and smaller surrounding islands.

Banggai–Sula has a metamorphic basement which was intruded by Late Paleozoic granitoids and overlain by Triassic felsic to intermediate volcanic products (Pigram & Panggabean, 1984). The region is interpreted to have originated from New Guinea in the late Cenozoic (Pigram et al., 1985) and to have transported by extension on the Sorong Fault during the Neogene (Audley-Charles et al., 1972). The Buton Islands consist of metamorphic rocks associated with ophiolite, Mesozoic – Paleogene deep water limestone with minor terrigenous clastic rock (Smith & Silver, 1991), ultramafic and mafic rock and Neogene and Quaternary sediments, which rifted from the Australian-New Guinea Gondwana margin during the Mesozoic and collided with Sulawesi in mid-to-late Tertiary times (Davidson, 1991; Hamilton, 1979). Most of the Tukang Besi Platform is submerged; the exposed part of the platform is occupied by Upper Neogene and Quaternary reef limestone. Like other microcontinents in the region, Buton and the rest of the Tukang Besi platform are interpreted as an Australian continental fragment (Hinschberger et al., 2005). However, Fortuin et al. (1990) suggested that Buton Island and the Tukang Besi Archipelago represent different continental fragments which were formerly separated from each other by oceanic crust.

1.3 GEOLOGICAL SETTING OF SOUTH SULAWESI

The south Sulawesi terrane lies in the south arm of Sulawesi (Fig.1.4) and is made up of sediment and volcanic arc products overlying a pre-Tertiary basement complex. The present day tectonic system is dominated by two major NNW-SSE trending strike-slip faults, namely the West Walanae Fault (WWF) and East Walanae Fault (EWF). Movement on these is mainly sinistral (Berry & Grady, 1987), but an extensional component has resulted in opening of the Plio-Pleistocene Walanae Graben (Fig. 1.5) between them (van Leeuwen, 1981).
Fig. 1.4. Tectonic Setting of Geology of Sulawesi (modified after Hamilton, 1979; Hall & Wilson, 2000).
Various parts of south Sulawesi appear to have undergone significant (up to 80º) rotation in either clockwise or anticlockwise directions, which may be rotation of local blocks associated with movement on this fault system (Charlton, 2000).

Sukamto (1975, 1982) mapped throughout the area, and the results were compiled by Sukamto (1982) and Sukamto & Supriatna (1982) in the form of 1:250,000 Geological Maps in several sheets (Ujung pandang, Benteng and Sinjai sheet and Pangkajene and Western part of Watampone sheet) and explanatory notes.

From previous investigations, the geology of south Sulawesi is depicted in Fig. 1.5 and described as follows:

1. **Pre-Tertiary Basement Complex**

This consists of metamorphic, sedimentary, and ultramafic rocks and is found in two separate blocks in the Bantimala and Barru areas (Fig. 1.4) (Hamilton, 1979; Sukamto, 1982; van Leeuwen, 1981). Metamorphic rocks include high-pressure types, namely glaucophane schist (Parkinson, 1998), albite-actinolite-chlorite schist, chlorite- mica schists, garnet-glaucophane rock, garnet-glaucophane-quartz schist, garnet- chloritoid-glaucophane-quartz schist (Miyazaki et al., 1996), quartzites, graphite phyllites (Berry & Grady, 1987; Sukamto, 1982) and blocks of eclogite included in blueschist (Maulana et al., 2008; Miyazaki et al., 1996). The ages from K/Ar dating on muscovite-garnet and quartz-muscovite schists from the Bantimala basement complex are 111 Ma (Hamilton, 1979). In addition, Wakita et al. (1994) reported respectively ages of 132 - 114 Ma and 106 Ma from the Bantimala schist and from the Barru schist using K/Ar analyses on muscovite. The sedimentary rocks are comprised of mélange, turbidite and shallow-marine clastic rocks (Wakita et al., 1996). Mélange occurs as tectonic blocks, and includes clasts of rock types such as sandstone, shale, siliceous shale, chert, basalt, schist, and felsic igneous rocks within a sheared matrix (Wakita et al., 1996). The middle Cretaceous (late Albian – early Cenomanian, i.e. about 105 - 95 Ma) chert unconformably overlies the high-pressure metamorphic rocks (Wakita et al., 1996). The ultramafic rock is dominated by serpentinitised peridotite, which contains chromite lenses in some areas and is locally intruded by dacite and andesite (van Leeuwen, 1981).
2. **Upper Cretaceous Sedimentation**

It consist of three formations, namely the Balangbaru Formation, which is found in the western part of the region (Sukamto, 1982), the Marada Formation (van Leeuwen, 1981) confined to the Biru region, and the Latimojong Formation in the northern part of the region. The Balangbaru Formation unconformably overlies the basement complex, and is composed of interbedded sandstones and silty shales, with less important conglomerates, pebbly sandstones and conglomeratic breccias (Sukamto, 1982). The Marada Formation consists of a succession of alternating impure sandstones, siltstones and shales (van Leeuwen, 1981). The sandstones are mostly feldspathic greywacke which are locally calcareous, composed of subangular to angular grains of quartz, plagioclase and orthoclase with subordinate biotite, muscovite and angular lithic fragments embedded in a matrix of clay minerals, chlorite and sericite (van Leeuwen, 1981). Sedimentary structures in coarser units of this formation are typical of turbidites. The lithologies and fauna of the Balangbaru and contemporaneous Marada Formation to the east (van Leeuwen, 1981; Sukamto, 1982) are typical of an open marine, deep neritic to bathyal environment (Sukamto & Supriatna, 1982; van Leeuwen, 1981). The ages of these formations were inferred from their microfauna as Upper Cretaceous (van Leeuwen, 1981). The tectonic setting of the Balangbaru Formation is interpreted to be a small fore-arc basin on the trench slope. However, Wakita et al. (1996) regarded the Balangbaru Formation as part of the Bantimala tectonic complex. Pb and Nd isotopic signatures of shale from this formation are similar to those of graphite-rich shale from the Polewali area in the northern part of South Sulawesi (Elburg & Foden, 1999) and the Lasipu Formation in the Sumba region (Vroon et al., 1996; Wensink, 1997).

3. **Paleogene Volcanism**

Paleogene volcanism in the region is represented by the Kalamiseng, Langi and Bua Volcanics. The various names of the volcanic formation probably reflect its geographical distribution, since detailed studies on this formation do not exist. In the Bantimala region, these volcanics have been known as Bua Volcanics (Sukamto, 1982) whereas in the Biru area, they are called the Langi Volcanics (van Leeuwen, 1981). They unconformably overlie the Upper Cretaceous sediments, and in turn are unconformably overlain by Eocene sediments. The volcanics consist of lavas and pyroclastic deposits of andesitic to trachy-andesitic composition, with rare intercalations
of limestone and shale towards the top of the sequence (van Leeuwen, 1981; Sukamto, 1982). They show a strongly fractured, poorly bedded texture. Fission track dating of zircon from tuff at the lower part of the volcanic sequence yielded an Early Paleocene age of 63 ± 2.2 Ma (van Leeuwen, 1981), whereas K-Ar dating from biotite monzonite in the Langi Intrusion suggests an age of 52.3 ± 0.5 Ma (Elburg et al., 2002). Hence, volcanic activity in this region started in the Paleocene and may have continued to the early Eocene (van Leeuwen, 1981). It was later suggested that the volcanics were generated above a west-dipping subduction zone beneath the South Sulawesi. (van Leeuwen, 1981).

The Kalamiseng Formation outcrops to the east of the Walanae Depression or Graben and consists of volcanic breccias and pillow basalts, as well as some rhyolitic flows. These are interbedded with tuffs, sandstones and marls (Sukamto, 1982; Sukamto & Supriatna, 1982). The lavas are spilitic basalts and diabases which have been metamorphosed to the greenschist facies. The K-Ar analyses from rhyolitic lava suggest an age of 21.72 ± 1.09 Ma (Early Miocene) (Polvé et al., 1997).

4. Eocene to Miocene Sedimentation

Eocene to Miocene sediments can be found in the western part of the Walanae Graben as the Mallawa Formation, and in the northern part near Latimojong Mountain as the Toraja Formation. They are composed of arkosic sandstones, siltstones, claystone, marls and conglomerates, intercalated with layers or lenses of coal and limestone. The Mallawa formation unconformably overlies the Balangbaru Formation and locally the Langi Volcanics, whereas the Toraja Formation overlies the Latimojong Formation. A Paleogene age for the Mallawa Formation is inferred from palynomorphs (Khan & Tschudy, in Sukamto, 1982) whilst ostracods suggest an Eocene age (Hazel, in Sukamto, 1982). The Mallawa Formation is inferred to have been deposited in a terrestrial/marginal marine environment passing transgressively upwards into a shallow marine environment (Wilson & Bosence, 1996).

The Tonasa Formation conformably overlies the Mallawa Formation or the Langi Volcanics. This formation has been described in detail by van Leeuwen (1981) and Wilson & Bosence (1996). It consists carbonate facies rock which can be classified into four members labelled A, B, C and D from the bottom to top (Wilson & Bosence, 1996). The age of the Tonasa Formation is inferred as Eocene to middle Miocene (van
Leeuwen, 1981; Sukamto, 1982) or Late Eocene to Middle Miocene (Wilson & Bosence, 1996). The formation is widely distributed in the western part of the Walanae Graben and is locally found in the southwest part of the South Arm peninsula. An equivalent formation known as the Makale Formation is found in the northern part of the region.

The Salo Kalupang is present in the Bone area, in the eastern part of South Sulawesi. This formation was deposited in deepwater depositional environment (Maryanto et al., 2004) and characterized by sandstone, shales and claystone interbedded with volcanic conglomerates, breccias, tuffs, lavas, limestones and marls (Sukamto, 1982). Based on foraminiferal content, the age of the Salo Kalupang Formation is interpreted to range from the Middle Eocene to Middle Miocene (Maryanto et al., 2004) or Early Eocene to Late Oligocene (Kadar, in Sukamto, 1982 and Sukamto & Supriatna, 1982).

The Lower Camba Formation consists of tuffaceous sandstones, interbedded with tuffs, sandstones claystones, volcanic conglomerates and breccia, marls, limestone and coals (Sukamto, 1982; Sukamto & Supriatna, 1982).

5. Miocene to Recent Volcanism and Sedimentation

Miocene to Recent volcanism and sedimentation in this region consists of various formations, including, in order of decreasing age, the Upper Camba Formation, Baturape–Cindako Volcanics, Soppeng Volcanics, Pare-pare Volcanics, Lemo Volcanics, and the Lompobattang Volcanics.

The Upper Camba Formation is made up of a volcanic series (the Camba Volcanics) interbedded with marine sediments and is located in the Western Divide Range (Sukamto, 1982; Sukamto & Supriatna, 1982). Foraminiferal dating from this member suggests a middle to late Miocene age (Sukamto, 1982). However, Yuwono et al. (1988) reported that the Camba Formation age ranges from Lower Miocene to Upper Miocene.

The Baturape and Cindako Volcanics occur in the western part of Makassar near Takalar regency. These two volcanic groups have the same characteristic alkali potassic extrusive and intrusive lithologies. However, K/Ar analyses of a basaltic flow from Baturape yields $12.81 \pm 0.64$ Ma and $12.38 \pm 0.62$ Ma (Middle Miocene) (Polve et al.,
1897); whereas K/Ar dating for the Cindako Volcanics yielded an age of $8.2 \pm 0.41$ Ma (Late Miocene) (Yuwono et al., 1988).

The Soppeng Volcanics are found in the central part of the region and are mainly of basaltic composition. The K-Ar results from a basaltic flow and a trachyandesitic neck give dates of $9.27 \pm 0.46$ and $9.32 \pm 0.37$, respectively, i.e. Late Miocene age (Polve et al., 1997). However, Sukamto (1982) interpreted these volcanics as early Miocene in age since they are conformably overlain by rocks of the Camba Formation.

The Parepare Volcanics are alternating lava flows and pyroclastic breccias which are confined to Pare-pare region in the western part of the arm. K/Ar analyses obtained from a rhyolite block and a dacite imply late Miocene to Pliocene age (Polve et al., 1997).

The Lemo Volcanics unconformably overlie the upper Walanae Formation in the Biru area (van Leeuwen, 1981). It consists of volcanic breccia, tuffs, lava and dykes with the thickness of more than 350 m (Elburg et al., 2002). K/Ar dating for the Lemo Volcanics yielded an age of $4.47 \pm 0.22$ Ma (Pliocene) (Polve, et al., 1997) and 6.3-7.0 Ma (Elburg et al., 2002).

The youngest volcanic products in this area are the Lompobattang Volcanics, which form a broad stratovolcano located in the southeast of south Sulawesi (Leterrier et al., 1990) and the Barupu Volcanics in the northern part of the region (Sukamto, 1975). The first were interpreted as a “post-collisional group” ranging from basaltic andesite to dacite and andesitic composition (Elburg and Foden, 1999). K/Ar dating of Lompobattang samples yields ages between 1.6 and 1.9 Ma (Polve et al., 1997; Elburg & Foden, 1999).
Fig. 1.5. Generalised geological map of south Sulawesi (modified after van Leuween, 1981; Sukamto, 1982; Sukamto & Supriatna, 1982; Wilson & Bosence, 1996).