The subduction initiation stage of the Wilson cycle

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Abstract: In the Wilson cycle, there is a change from an opening to a closing ocean when subduction begins. Subduction initiation is commonly identified as a major problem in plate tectonics and is said to be nowhere observable, yet there are many young subduction zones at the west Pacific margins and in eastern Indonesia. Few studies have considered these examples. Banda subduction developed by the eastwards propagation of the Java trench into an oceanic embayment by tearing along a former ocean–continent boundary. The earlier subducted slab provided the driving force to drag down unsubducted oceanic lithosphere. Although this process may be common, it does not account for young subduction zones near Sulawesi at different stages of development. Subduction began there at the edges of ocean basins, not at former spreading centres or transforms. It initiated at a point where there were major differences in elevation between the ocean floor and the adjacent hot, weak and thickened arc/continental crust. The age of the ocean crust appears to be unimportant. A close relationship with extension is marked by the dramatic elevation of land, the exhumation of deep crust and the spectacular subsidence of basins, raising questions about the time required to move from no subduction to active subduction, and how initiation can be identified in the geological record.

A crucial stage in the Wilson cycle is the change from opening to closing of an ocean basin and the development of subduction. There are many publications on the initiation of subduction and it is not the intention of this paper to review previous work. Producing new trenches is considered difficult, and subduction initiation is commonly identified as a major problem in plate tectonics (e.g. McKenzie 1977), ‘not easily answered by direct observation’. Gerya (2010) identified at least 14 hypothetical explanations and commented that the ‘major obstacle to investigate subduction initiation by observation is the absence of definite knowledge about localities where subduction possibly starts’. It has become widely accepted that the initiation of subduction cannot be observed and the majority of publications on the topic have advanced possible models or, in recent years, have described numerical or analogue modelling studies believed to offer explanations.

Among the many models and possible settings for the initiation of subduction, most of which have been reviewed by Stern (2004), two in particular receive much attention and are commonly linked to the west Pacific and ophiolite formation and/or emplacement. One early proposal was the initiation of subduction at a transform in a major ocean basin (e.g. Uyeda & Ben-Avraham 1972; Casey & Dewey 1984; Stern & Bloomer 1992) with a type area in the Izu–Bonin–Marianas arc. This model has linked forearcs, supra-subduction zone ophiolites, the unusual geochemistry of volcanic rocks such as boninites, and the growth of arc and continental crust. However, we now know that the West Philippine basin must have opened in a former Cretaceous arc setting (e.g. Ozima et al. 1977; Shiki et al. 1977; Mizuno et al. 1979; Tokuyama 1985; Tokuyama et al. 1986; Hall et al. 1995b; Deschamps & Lallmand 2002; Arculus et al. 2015), palaeomagnetic work has cast doubt on the reconstructions on which the original tectonic models were based (e.g. Haston & Fuller 1991; Ali & Hall 1995; Hall et al. 1995a, c; Queano et al. 2007) and the postulated age difference across the transforms are much larger than those observed anywhere in the current global ridge system (e.g. Norton 2000; Müller et al. 2008). Other models have suggested the initiation of subduction at an oceanic spreading centre based on studies of the Oman ophiolite (e.g. Coleman 1981; Boudier et al. 1988; Hacker 1991), but these too are controversial (e.g. Searle & Cox 1999; Warren et al. 2005, 2007; Boudier & Nicolas 2007). What is certainly true is that in neither case can the process of the initiation of subduction, which occurred 50 (Izu–Bonin–Marianas) or 90 myr ago (Oman), be observed. Testing the models is therefore difficult.

In contrast, there are many young subduction zones at the western Pacific margins and in eastern Indonesia. Almost all of these have formed since the Early Miocene, i.e. in the last c. 20 myr, but they generally receive little or no attention.
Regional background

The size of the Indonesian region is often overlooked, but it is similar to that of western Europe between Ireland and Turkey or to the coterminous USA (Hall 2017). Describing its geological history is therefore a challenge. Interested readers may begin with the references cited here as an introduction to this fascinating and geologically important region. I contend here that different stages in the development of subduction, from the earliest stages of the downward flexure of oceanic crust to the formation of a well-defined Benioff zone, can be observed in the eastern Indonesia and southern Philippines region. This paper does not offer a detailed physical or mechanical model, but summarizes observations identifying features that may be essential for the initiation of subduction and that could be incorporated in future modelling studies. Here I focus on two ways and areas in which subduction initiated.

(1) The Banda region provides an example of subduction that propagated from an existing subduction zone. This is one relatively easy way in which new subduction zones may develop. However, this mechanism does not account for the many young subduction zones nearby, which are not fully connected together.

(2) There are several subduction zones in the region around Sulawesi, each of which developed independently from a point. The Sula deep, Tolo trough, Cotobato trench and North Sulawesi trench (Fig. 1) are proposed as successive stages of development and to have initiated in an extensional setting. The Philippine trench shares many of the features of these young subduction zones and also developed from a point, but was more likely initiated by contraction.

(1982) provided one of the few accounts that discussed the initiation of subduction in some of them. None of the subduction zones initiated at active spreading centres or at transforms. All formed at the margins of ocean basins. Figure 1 shows those between the northern Philippines and western New Guinea. I contend here that different stages in the development of subduction, from the earliest stages of the downward flexure of oceanic crust to the formation of a well-defined Benioff zone, can be observed in the eastern Indonesia and southern Philippines region. This paper does not offer a detailed physical or mechanical model, but summarizes observations identifying features that may be essential for the initiation of subduction and that could be incorporated in future modelling studies. Here I focus on two ways and areas in which subduction initiated.

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During the Paleogene there was a long north-dipping subduction zone, traceable along the south Eurasian margin southeastwards from Sumatra and south of Java to Sumba (Fig. 2a). This was offset to the NE (Fig. 2a) along a transform segment to join a subduction zone beneath the North Sulawesi volcanic arc on the south side of the Celebes Sea, and from there into the west Pacific along the southern boundary of the Philippine Sea plate.

The form of the NW Australian margin was important for the Cenozoic history of eastern Indonesia. Jurassic rifting had formed an oceanic embayment, the Banda embayment, within the NW Australian margin, which contained oceanic crust of Late Jurassic age, a small part of which is preserved today in the Argo abyssal plain. The rifting left an elongate promontory of Australian continental crust, the Sula Spur (Klömpé 1954), which extended west from New Guinea on the north side of the Banda embayment (Fig. 2a).

In the Early Miocene, at c. 23 Ma, the Sula Spur began to collide with the North Sulawesi volcanic arc and was the first part of the Australian continent to make contact with the SE Asian margin. Ophiolites in East Sulawesi (Kündig 1956; Silver et al. 1983), derived from the ocean north of the Sula Spur, were thrust southwards onto the continental crust of the Sula Spur in East Sulawesi beneath the North Sulawesi forearc. After this collision, continued northwards movement of Australia was absorbed in several ways, including the subduction of oceanic crust at the Java trench, the broad non-rigid counter-clockwise rotation of SE Asia (Borneo, West Sulawesi, Java) and contraction and uplift in East and SE Sulawesi.

As Australia moved north, subduction at the Java trench became aligned with the northern margin of the Banda embayment. At c. 17 Ma, from the east end of the Java trench, a tear propagated eastwards along the continent–ocean boundary from the western end of the Sula Spur. As the tear moved east, the oceanic embayment began to sink rapidly and the subduction hinge began to roll back into the Banda embayment (Fig. 2b). The consequences of rollback have been discussed by Spakman & Hall (2010), Pownall et al. (2014, 2016) and Hall & Spakman (2015). The subducted slab now has the form of a fold that plunges west, resembling the prow of a boat moving east (Pownall et al. 2013). There is a...
Fig. 1. (a) Modern subduction zones and postulated incipient subduction zones in eastern Indonesia and the adjacent west Pacific. The zones discussed in this paper are shown in red. SD, Sula deep; TT, Tolo trough. (b) Principal features of the same region on a digital elevation model from satellite gravity-derived bathymetry combined with Shuttle Radar Topographic Mission topography (Sandwell & Smith 2009)
prominent tear on the north side of the slab that narrows eastwards beneath Buru and terminates near west Seram.

Banda rollback led to major extension (Fig. 2c) above the subducted Banda slab, in a region which included parts of the pre-collision SE Asian margin in West Sulawesi and the collided Australian crust of the Sula Spur. There was extension-related volcanic activity in West Sulawesi (Polvé et al. 1997; Hennig et al. 2016), core complex formation in North Sulawesi (van Leeuwen et al. 2007, 2016; Hennig et al. 2016; Advokaat 2016), Banda arc volcanism started, and there was subsidence in the Banda forearc near Sumba (Fortuin et al. 1997; Rigg & Hall 2012).

New oceanic crust formed (Fig. 2c). The earliest phase led to the formation of the North Banda Sea between 12.5 and 7 Ma (Hinschberger et al. 2000). The Sula Spur was stretched and continental crust in East and SE Sulawesi was separated from fragments that remain in the Banda Ridges (Silver et al. 1985). A volcanic arc, from east of Wetar to Seram, was active for a short period (c. 8–5 Ma) before a second major phase of extension led to the formation of the South Banda Sea (Hinschberger et al. 2001). During the opening of the South Banda Sea, the arc and continental crust were further extended and some fragments formed the basement of the Banda forearc (Fig. 2d). Some of the Sula Spur continental crust is now found in Timor and several of the small outer arc islands from Leti to Babar (e.g. Bowin et al. 1980). The most recent extension (Fig. 2e) formed the Weber Deep (Pownall et al. 2016).

Initiation of subduction: Banda

The Banda subduction zone illustrates one method by which subduction may initiate, one which has probably been common in the past: the propagation of an existing subduction zone into a new region. The Java trench provided the site from which a tear propagated eastwards along the former continent–ocean boundary at the northern edge of the Banda embayment (Fig. 2f). This development is illustrated by seismic tomography, which reveals a major contrast between the shape of the slab subducted beneath western and eastern Indonesia. In the west, from Sumatra to Sumba, the slab subducted at the Java trench becomes almost vertical in the upper mantle at depths below c. 300 km and can be traced into a high-velocity anomaly in the lower mantle to depths of c. 1000 km (Fig. 3). In contrast, in the Banda region, east of c. 118° E, the deep high-velocity
anomaly is absent and seismicity defines the well-known Benioff zone that curves through 180° (e.g. Hamilton 1974, 1979; Cardwell & Isacks 1978; Bowin et al. 1980; McCaffrey 1989). Tomographic images of the subducted Banda slab (Widiyantoro & van der Hilst 1997; Richards et al. 2007; Spakman & Hall 2010; Hall & Spakman 2015) show that it is entirely confined to the upper mantle and there is a wide flat-lying part at the bottom of the upper mantle (Fig. 3).

The contrast in mantle structure from west to east records the different histories of subduction in the Java and Banda regions. This contrast is explained by the much longer period of subduction at the Java trench, which began in the Eocene. Subduction began in the Banda region only in the Neogene, with rollback into the oceanic Banda embayment within the Australian continental margin (Spakman & Hall 2010), which led to the characteristic rollback signature of the flat segment at the base of the upper mantle and the folded subducted slab in the upper mantle.

Subduction initiation: Sulawesi–Philippines

The Banda region illustrates probably the easiest and most common way by which subduction initiates: the growth of an existing subduction zone into a new region. However, there are numerous subduction zones in eastern Indonesia and many parts of the west Pacific margins that are not joined to other subduction zones and which must therefore have developed independently by other mechanisms. There are a number of deep bathymetric features in the eastern Indonesian region, which I suggest are subduction zones at different stages of development: the Sula deep, the Tolo trough, the Cotobato trench, the North Sulawesi trench and the Philippine trench (Fig. 1). There is no disagreement about the last three of these, which have long been recognized as subduction zones (e.g. Hamilton 1979; Cardwell et al. 1980). The Tolo trough has been recognized as a thrust (Silver 1981; Silver et al. 1983; Hinschberger et al. 2000, 2003), but not identified as an incipient subduction zone. The Sula deep has not been discussed before.

Recent work in the region means that we now have a significantly improved knowledge of the geology and tectonics of the region from the North Sulawesi trench to the North Banda Sea. The Sula deep, Tolo trough and Cotobato trench illustrate the steps inferred to have occurred during the earliest stages of subduction development and later stages can be interpreted from North Sulawesi on land and offshore. The deeps, troughs and trenches share a number of features. Each dies out at one or both ends and is not connected to another subduction zone. Two of them (the Tolo trough and the North Sulawesi trench) link at one end to active strike-slip faults. The subducted slabs reach shallow depths only (maximum depth <300 km). In the case of the Sula deep and Tolo trough, no slab can yet be identified from seismicity. The fact that the subduction zones die out means that the length of the subducted slab reduces to zero at their ends. They formed at the edges of ocean basins of different ages (Eocene to Miocene). They formed at positions where there are major changes in crustal thickness, mainly at the edges of former volcanic arcs.

The Philippine trench shares some features with the other trenches, but has some differences which may indicate another path to subduction. Like the other young subduction zones, the trench dies out at each end and the subducted slab reaches only shallow depths. Volcanoes are broadly parallel to the trench, but almost all are situated close to a major strike-slip fault, the Philippine fault, also sub-parallel to the trench. It is not clear whether the volcanoes are products of subduction, in which case they may have influenced the position of the Philippine fault, or if the position of volcanic activity is controlled by the fault. This example is described briefly at the end of this paper.

A model for the initiation of subduction is first summarized based on observations of these deep bathymetric features and this summary is followed by a more detailed discussion of each of the examples.

Model for the stages in the initiation of subduction

The sequence of steps proposed for the initiation of subduction relevant to many marginal basins of the west Pacific margins is shown in Figure 4 and is based on observations from the North Banda Sea, the Cotobato region and the North Sulawesi region.

Crust is thickened by recent collision and/or arc activity (Fig. 4a). It is topographically high with elevations above sea-level. This crust is most likely a former arc, but may be underlain by an older continental fragment on which the arc has been built, or which has been thickened by underthrusting of continental crust during collision. There has been recent magmatism. The crust is hot. The lower crust is very weak. This is here termed continental crust and will form the upper plate in the new subduction setting.

The oceanic basin is deep; significantly deeper than predicted by the standard age–depth relations for the oceanic crust of large basins. This is the case for many west Pacific marginal basins, such as those of the Philippine Sea and Celebes Sea, and those of the Banda Sea are even deeper (e.g. Sclater et al. 1976; Park et al. 1990; Hinschberger et al.
The cause of the greater depth of these basins is not yet understood.

The continental margin is likely to be narrow and steep. In the North Banda Sea margins the average dip of the margin at the points where subduction is initiated is c. 9° and the width is of the order of 40 km. Subduction initiates at a corner point in the ocean basin adjacent to the thickened and elevated continental crust. The Sula deep is interpreted as representing the earliest observed stage in the initiation of subduction.

The continental crust collapses on the adjacent oceanic crust (Fig. 4b). Some of this may occur by localized slumping and the displacement of mass transport complexes, as observed near the Sula deep. At a later stage, thicker slices of the upper crust move downslope on extensional detachments. Based on interpretations of seismic lines from the Tolo trough and Cotobato trench, these thrust slices are likely to be 2–3 km thick and 30–50 km wide across-strike. Thrusting can be traced along-strike for the order of 200 km along the Tolo trough and 400 km along the Cotobato trench, but it is unlikely that the thrusting forms a single sheet. The North Sulawesi trench has a length of >500 km, but multi-beam bathymetric images show that the forearc structure changes along-strike. The troughs and trenches are all inferred to have grown in length over time and therefore there must be multiple thrust sheets.

The result of loading is depression of the oceanic floor. This causes the oceanic crust to dip towards the continent and will encourage further loading by mass transport complexes and thrust sheets. The sedimentary cover of the oceanic crust will also be deformed during the thrusting. The effect at the surface will be identical to structures seen at any subduction margin: thrusting towards the ocean and folding close to the developing trench. After the oceanic crust has been...
sufficiently depressed (Fig. 4c), deeper lower continental crust will extend over the oceanic crust. This further loads the oceanic crust, which continues to subside.

Extension of the upper plate continental crust may lead to magmatism, further weakening it. This will be enhanced by heating caused by the rise of the underlying mantle as the crust thins. The result is that the upper plate extends over the oceanic crust and loading continues to depress the oceanic lithosphere. The oceanic crust is eventually sufficiently depressed to transform to eclogite. The speed of this transformation is not known. However, the result is that the deeper oceanic crust now exerts an additional pull force on the subducting slab, initiating slab-pull and leading to true rollback (Fig. 4d). Once rollback begins, the subduction zone becomes self-sustaining. For North Sulawesi this stage is inferred to have begun 4–5 myr ago.

Interpretation of the development of the North Sulawesi region indicates that the initiation of subduction and rollback is accompanied by significant extension of the upper plate, which leads to exhumation of the core complexes (Fig 4c, d). The low-angle detachments that unroof the core complexes result in thinning of the upper plate, causing subsidence and basin deepening, which is contemporaneous with the uplift of the core complexes.

After rollback starts, the trench can grow in both directions and will be deeper in its central part and become shallower towards each end (Fig. 4d). This is the situation for the Cotobato and Philippine trenches. For the North Sulawesi trench, the trench appears to have grown in length westwards, but in a discontinuous manner, connected to different NW–SE- to NNW–SSE-trending strike-slip faults, active at different stages, on which there were significant vertical displacements.

**Examples of the stages in the initiation of subduction**

The model of the initiation of subduction presented here is based on field observations and new dating on land in eastern Indonesia, and on two-dimensional seismic and multibeam data acquired offshore during exploration for hydrocarbons and reported in the cited studies. In particular, high-resolution images of the land and seafloor have been most important. Fieldwork on land in Indonesia has been made much more effective in recent years with the aid of Shuttle Radar Topographic Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery, which can reveal the surface topography, despite vegetation cover, which is invaluable for structural and tectonic interpretations (e.g. Spencer 2010). Offshore, multibeam mapping can measure the depth to the seafloor to within a few centimetres using a high-resolution echo-sounder (Orange et al. 2010) and has provided images of the seafloor in eastern Indonesia with similar resolution and quality to that of the SRTM and ASTER. The bathymetric images provide details of the submarine geomorphology and structures and hence insights into tectonic processes, in this case interpretations of the stages in the development of subduction.

**North Banda Sea subduction: Sula deep**

The North Banda Sea has an average depth of c. 4800 m, which is much deeper than the depth predicted by age–depth curves for its 12–7 Ma age (Hinschberger et al. 2000, 2003), and is c. 600 m deeper than the depth predicted by the Philippine Sea–Celebes Sea age–depth relationship (Park et al. 1990). Figure 5 shows the main features of the North Banda Sea based on marine geophysical surveys and new multibeam bathymetry. West of the West Buru Fracture Zone, magnetic anomalies were mapped by Hinschberger et al. (2000) and indicated oceanic crust with an age between 12.5 and 7.15 Ma. The multibeam images cover areas further east that had not previously been mapped and oceanic crust is interpreted in the NE corner of the North Banda Sea, surrounded by the islands of Taliabu, Mangole and Sanana, and east of Sanana in the Buru basin (Patria & Hall 2017) at depths >4000 m.

On the northern side of the North Banda Sea adjacent to Taliabu and Mangole, two-dimensional seismic lines show normal faults downthrown to the south with a narrow continent–ocean transition and a mean slope gradient up to 9°. Some of these normal faults are probably being reactivated as left-lateral strike-slip faults, as indicated by a few shallow earthquakes in the CMT catalogue of global seismic moment tensors (Ekström et al. 2012).

The NE corner has an elongate central area with depths below 5800 m (Fig. 6a), close to the ocean–continent boundary, named here the Sula deep (Fig. 6b). Locally, slope gradients between 1 and 5 km depth on the north and east sides of the Sula deep are up to 13° (Fig. 6b). The multibeam bathymetry shows extensional slump scars and slump fronts on the north and east sides of the Sula deep (Fig. 6c). The downslope movements of material on the steep continent–ocean margins are suggested to be responsible for loading and depression of the oceanic crust in this corner of the North Banda Sea to depths below 5800 m.

**North Banda Sea subduction: Tolo trough**

The Tolo trough is interpreted as the next stage in subduction development. This trough is an arcuate
feature at the western edge of the North Banda Sea (Fig. 7). The multibeam imagery does not provide complete coverage of the trough and Figure 7a shows the bathymetry from multibeam mapping merged with that from satellite gravity data (Sandwell & Smith 2009). The multibeam bathymetry shows that the deepest parts of trough are 6400 m at the south end and 5900 m at the north end.

The trough (Fig. 7b) was first named the Tolo thrust by Silver (1981). Hinschberger et al. (2000) named it the Tolo trough. Silver et al. (1983) suggested that the Tolo thrust was ESE-directed and linked to sinistral movement on the Matano fault; they also observed that the zone of deformation associated with the thrust is greater in its central part and dies out towards each end. The Matano fault is an active fault with sinistral displacement, is very young (Watkinson & Hall 2017), and has the geometry of a lateral ramp. There is significant seismicity along the Matano fault, but little seismicity associated with the thrust. There are a few thrust solutions for earthquakes at shallow (<30 km) depths close to the thrust in the CMT catalogue (Ekström et al. 2012), consistent with the shape of the thrust and the interpretation of Silver et al. (1983).

Rudyawan & Hall (2012) showed that the thrusting at the north end of the Tolo trough was at the eastern end of a detachment at 2 s two-way travel time (TWTT) below the seabed and associated with extensional faulting at the landward (western) end of the two-dimensional seismic lines (Fig. 8a), consistent with downslope movement of a major thrust sheet to the ESE (Fig. 7b). The geology of the SE Arm indicates that this detachment is probably within a Mesozoic sequence. The extensional features in the western part of this thrust sheet are also observed on land. Their geometry suggests that extensional displacement is roughly balanced by down-dip contraction as the continental crust is displaced onto the North Banda Sea oceanic crust offshore, depressing the ocean crust (Fig. 8b). The mean gradient of slopes close to the deepest part of the Tolo trough is typically 7°–8° and locally up to 10° below 1 km water depth.

The observations of the Sula deep and Tolo trough in the North Banda Sea and the evidence for extension on land in the SE Arm are suggested to record the earliest stages in the development of new subduction zones. Ocean crust is being depressed in corners of the North Banda Sea from an average depth of 4800 m to depths below 5800 m in the NE and 6400 m in the SW, close to the ocean–continent boundary, by the downslope movement of material. The continental margin of the basin in these corners is narrow and steep, with mean slope gradients >7° and locally steeper slopes up to 13°. This has led to depression of the ocean crust in these corners by between 1 and 1.6 km below the average 4.8 km depth of the ocean floor in the basin, which was already c. 1.5 km deeper than predicted by the age–depth curve for oceanic crust of Late Miocene age in large ocean basins.

Celebes Sea subduction: Cotobato trench

The Cotobato trench in the NE corner of the Celebes Sea south of Mindanao (Fig. 9) is interpreted as the third stage in subduction development. Here,
Fig. 6. Sula deep. (a) Multibeam bathymetric image of the NE corner of the North Banda Sea bounded by the Sula Islands of Taliabu, Mangole and Sanana. (b) Bathymetric contours outlining the flat central part of the Sula deep. (c) Principal tectonic features.
a seismically defined slab can be recognized, associated with a sinuous trench that dies out at each end (Fig. 9a). The central and southern part of the trench was mapped in detail by the MODEC cruise in 1995 (Rangin et al. 1996). The trench is a 25 km wide flat-bottomed area with a maximum depth close to

**Fig. 7.** North Banda Sea. (a) Digital elevation model of the region from satellite gravity-derived bathymetry combined with Shuttle Radar Topographic Mission topography (Sandwell & Smith 2009) merged with multibeam bathymetry of the North Banda Sea. (b) Principal structural features of the same region. SD, the Sula deep. The Matano fault on land is linked to thrusting at the Tolo trough, as suggested by Silver et al. (1983). Grey shaded area represents extended continental crust. Pale blue area is oceanic crust of the North Banda Sea, now partly overthrust by continental crust west of the Tolo trough and east of the Sula deep. Red line marks the position of the seismic line shown in Figure 8.

**Fig. 8.** (a) Uninterpreted and (b) interpreted seismic line at position shown in Figure 7b crossing the Tolo trough on the west side of the North Banda Sea. A detachment fault is inferred linking extension at the landward western end of the section to thrusting over the North Banda ocean floor at the seaward end of the section. A slice of continental crust of c. 2 s TWTT thickness has been thrust onto the oceanic crust, depressing it.
The deepest part of the trench is 5800 m (Fig. 9b). The deepest part of the trench is c. 140 km long along-strike and the entire trench has a length of c. 350 km. The trench narrows and shallows to 5000 m and dies out to the west and SE c. 100 km from the deep central part, at a similar depth to an extensive area of oceanic crust of the Celebes Sea to the south (Fig. 9b). The southern end of trench does not link to the North Sulawesi trench. It is separated from it by a 250 km wide zone crossed by active or recently active NNE-trending volcanic lineaments, which are the products of arc volcanism related to the westwards subduction of the Molucca Sea plate. One volcano is in, or almost in, the trench (Fig. 9a, b). To the west of 124° E the trench appears to continue northwards along the east side of Moro Gulf, although north of 6° N bathymetric detail (Sandwell & Smith 2009) is significantly lower than in the area mapped by the MODEC cruise. Schlüter et al. (2001) followed Cardwell et al. (1980) and traced the trench into Moro Gulf from south of Mindanao based on a few two-dimensional seismic lines crossing the area (Fig. 9b).

Seismicity indicates that the slab has reached a depth of <100 km. Cardwell et al. (1980) showed an east-dipping slab, which reaches almost 100 km on a line crossing Moro Gulf. Newer data do not change this interpretation and P-wave seismic tomodic slices clearly show only the west-dipping Molucca Sea/Sangihe slab (see supplementary movie in Hall & Spakman 2015). There is extensive shallow seismicity beneath Mindanao, some associated with the Philippine fault.

Volcanic activity closest to the eastern end of the Cotobato trench (Fig. 9b) is the result of westwards subduction of the Molucca Sea plate beneath the Sangihe arc, where there is a well-defined slab traceable to 600 km beneath the Celebes Sea and Mindanao imaged by both seismicity (Cardwell et al. 1980; Engdahl et al. 1998) and P-wave tomography (Hall & Spakman 2015). Ranneft et al. (1960) mapped extensive areas of Quaternary volcanic rocks on Mindanao NE of the Cotobato trench and Sajona et al. (1997) reported volcanic rocks of mainly Miocene age overlain by modern volcanoes. There are many volcanic in western Mindanao (Siebert et al. 2010), but they are all far from both the Philippine and Cotobato trenches. None of the volcanic activity in Mindanao can be related to subduction at the Cotobato trench because the slab is not yet deep enough and the volcanic rocks are too old and/or too far from the trench. SRTM images (Fig. 9a) indicate young NE–SW extension in Mindanao, which could be implicated in the volcanic activity.

Schlüter et al. (2001) showed two seismic profiles across the Cotobato trench (Fig. 10). One
SW–NE line crosses the almost deepest part of the trench south of Mindanao (Fig. 10a) and the second WNW–ESE line crosses the trench west of Mindanao in Moro Gulf (Fig. 10b). Both show similar features – an outboard thrust zone and an inboard extensional faulted zone – which Schlüter et al. (2001) interpreted as block-faulted continental crust. They mapped the two zones around Mindanao for a length of 400 km (Fig. 9b). I suggest that these seismic lines record an early stage in the development of a subduction zone. The thrusting at the Cotobato trench is roughly balanced by the extension of continental crust further inboard and is due to a major deep detachment at c. 3 s TWTT below the seabed, which has displaced a major thrust sheet downslope. The displacement has depressed the oceanic crust in this corner of the Celebes Sea to c. 400 m below the depth of the crust further south in the basin, which was already c. 1 km deeper than predicted by the age–depth curve for oceanic crust of Eocene age in large ocean basins (Parsons & Sclater 1977; Park et al. 1990).

The Cotobato region shares other features with those inferred for the early stages of the development of subduction beneath North Sulawesi, such as widespread magmatism shortly preceding subduction, suggesting a hot weak crust, and extension on land in Mindanao roughly parallel to the offshore extension (Rannfelt et al. 1960; Sajona et al. 1997; Schlüter et al. 2001).

Celebes Sea subduction: North Sulawesi trench

There is a seismically well-defined slab dipping southwards from the North Sulawesi trench and this represents the final stage in the development of a subduction zone. The trench runs roughly east–west along the southern side of the Celebes Sea (Fig. 11a). It is commonly shown on maps as a feature that begins in the east, near the eastern end of the

Fig. 10. Interpreted seismic lines redrawn from Schlüter et al. (2001) at positions shown in Figure 9b. Note different scales of the two sections, although both have the same vertical exaggeration. A detachment fault is inferred on both sections linking extension at the landward end to thrusting over the Celebes Sea ocean floor at the seaward end of each section. In both cases a slice of continental/arc crust of c. 3 s TWTT thickness has been thrust onto the oceanic crust, depressing it.
North Arm of Sulawesi, and is traced westwards to where it joins the active north–south Palu-Koro fault zone. Unlike many trenches, it is not a linear feature significantly deeper than the ocean floor being subducted. The trench has a similar depth (c. 5400 m) to the Celebes Sea to the north (c. 5500 m) (Fig. 11b). It has a similar depth from its eastern end to 120.7° E, where it becomes shallower over a short distance until it joins the Palu-Koro fault at c. 5000 m. The depth of the Celebes Sea is greatest in a triangular area north of the trench and this triangle is widest at its centre, north of the point at which the subducted slab reaches its greatest depth. Like the West Philippine Sea, the Celebes Sea is c. 1000 m deeper than predicted by the age–depth curves for the major oceans.

The trench has been interpreted as the result of a clockwise block rotation of the North Arm about a pole at the east end of the trench (Hamilton 1979; Silver et al. 1983). The rotation of a rigid block has been supported by global positioning system observations, measurements of rates of movement on the Palu-Koro fault (e.g. Walpersdorf et al. 1998; Stevens et al. 1999; Bellier et al. 2001; Socquet et al. 2006) and by palaeomagnetic results showing young clockwise rotations of the North Arm (Surmont et al. 1994).

Recent observations and newer data complicate this apparently simple picture, however. If there had been a block rotation about a pole near the east end of the North Arm, then the length of the subducted slab should increase westwards and reach a maximum at the Palu-Koro fault. This is not observed. Seismicity shows that the maximum depth reached by the slab (c. 260 km) is in the centre of the subduction zone and the poorly defined slab at the western end has no significant seismicity deeper than c. 100 km (Fig. 11c). The palaeomagnetic results (Surmont et al. 1994) are also ambiguous. There is evidence for Miocene or younger clockwise rotations, but these are only recorded from a small area in the centre of the North Arm where rotations range from 8 to 21°. Other sites are poorly constrained for rotation age or have variable...
inclinations, suggesting displacements that are more complex than simple vertical axis rotations.

There is now also evidence for other NNW–SSE-trending major faults in addition to the Palu-Koro fault (Fig. 11c). The Tambarana fault is a major fault zone sub-parallel to, and east of, the Palu-Koro fault on which there is several kilometres of vertical displacement (Fig. 11d), as well as significant inferred strike-slip displacement, probably of Plio-Pleistocene age. Still further east are zones of faulting crossing the North Arm west and east of the Malino metamorphic complex, which was exhumed in the Pliocene (Advokaat et al. 2017), named here the Malino fault and the Buol fault (Fig. 11c). The latter zone of faulting appears to pass through the Togian Islands and can be traced into the eastern end of the East Arm. All of these are actually fault zones up to 20 km wide with several strands.

The area of Gorontalo Bay, south of the North Arm, was almost unexplored until recently, when seismic and multibeam data were acquired. It is now known that there are three major depocentres, each containing several kilometres of Miocene to Recent sediments (Fig. 11d). In the northern part of western Gorontalo Bay is the Tomini basin, with >5 km of sediment. At the centre of the basin water depths reach 2 km and north of this there are arcuate pinnacle reef lineaments indicating rapid subsidence and a northwards back-stepping of the shelf edge (Fig. 11a), interpreted to have occurred in the last 2–3 myr (Pezzati et al. 2012; Pezzati et al. 2014; Pezzati 2017). The Lalanga Ridge (Pholbud et al. 2012) in the SW part of the bay has large reef complexes, now at depths between 1.5 and 0.5 km. South of this ridge is the Poso sub-basin with >3 km of Upper Miocene to Recent sediments and water depths of 1.8 km (Pezzati et al. 2014). In the eastern part of Gorontalo Bay, between the North Arm and the Togian Islands, is the Tilamuta basin (Fig. 11d), also with water depths >2 km and > km of sediment (Rudyawan 2016).

There was a significant phase of acid and intermediate magmatism in the North Arm that began at c. 9 Ma and continued into the Pliocene (Advokaat et al. 2014; Advokaat 2016; Rudyawan et al. 2014; Rudyawan 2016). This phase probably provided volcanogenic material that contributed mostly to the deep Tilamuta basin. There was further acid magmatism in the North Arm, Neck and Central Sulawesi SW of the Poso basin in the Late Miocene and Pliocene, recorded by widespread acid tuffs and granites. Rhyolitic tuffs were reworked in a marine setting at c. 4 Ma and dacites of c. 2 Ma age which intrude them are now exposed in the Togian Islands (Cottam et al. 2011). Similar igneous rocks are found to the west in the volcano of Una-Una, which last erupted explosively in 1983 (Katili & Sudradjat 1984). North of Gorontalo Bay in the North Arm, in the Neck to the west, and in Central Sulawesi to the south are metamorphic complexes exhumed rapidly since the Miocene. Lineations on the Tokorondo and Pompaneo core complexes indicate that exhumation occurred during extension parallel to the NNW–SSE-trending major faults (Spencer 2010, 2011; Fig. 11a, d). Granites and metamorphic rocks record Late Miocene and Pliocene magmatism and metamorphism (Hennig 2015; Hennig et al. 2017). Granites at elevations of >500 m in the Neck were exhumed rapidly from depths of at least 2 km between 3 and 2 Ma (Hennig et al. 2016) and are now overlain by Quaternary alluvial fan conglomerates containing granite boulders passing up into fluvial sediments, now dipping at up to 20°.

The pattern of faulting, the exhumation of metamorphic core complexes, magmatism, subsidence and sedimentation in Gorontalo Bay (Pholbud et al. 2012; Rudyawan et al. 2014; Advokaat 2016; Hennig et al. 2016, 2017; Pezzati 2017) indicate a link between extension and the subduction of the Celebes Sea at the North Sulawesi trench, as previously suggested. However, the connection is not simply a response to a rigid block rotation, as explained earlier, and magmatism was not arc magmatism related to subduction. Acid and intermediate magmatism in the North Arm occurred where, even today, the slab is only 60 and 80 km deep. Una-Una volcano and the young magmatic rocks in the Togian Islands are south of the subducted slab and cannot be related to subduction at the North Sulawesi trench (Cottam et al. 2011).

For North Sulawesi, subduction is interpreted to have initiated at a corner in the ocean basin inferred from the shape of the subducted slab (Fig. 12). This corner was south of the centre of the present trench. Restoring the subducted slab to the surface (Figs 11c & 12) indicates that subduction developed in a series of stages. Loading of the ocean crust in the corner depressed it and allowed the weak crust south of the Celebes Sea to flow into this corner, further depressing it. The western end of the trench moved west in a series of stages. At each stage the trench was linked to a strike-slip fault zone, which allowed the clockwise rotation of segments of the upper crust. These were the Buol fault zone, the Malino fault zone, the Tambarana fault zone and the Palu-Koro fault zone. The exact chronology of the development of subduction is slightly uncertain for reasons discussed later, but a weak hot crust with the potential addition of volcanic debris suggests that loading began after magmatism in the North Arm and is suggested to have started at c. 8 Ma. Very rapid extension, which caused major subsidence of Gorontalo Bay, the exhumation and uplift of core complexes, and contributed to the later phase of acid magmatism probably began after 5 Ma and this most likely
indicates that the slab was by then sufficiently deep and dense to drive subduction rollback.

**Philippine trench**

The Philippine trench is longest and most obvious trench of those discussed here. The trench is 1800 km long and follows the eastern coast of the Philippine Islands at the edge of the Philippine Sea plate (Fig. 1). As observed earlier, the Philippine Sea basins are several hundred metres deeper for their age than the major ocean basins. The trench is exceptionally deep and reaches depths in its central part, between 9 and 11° N and east of Mindanao, up to 10 000 m (Fig. 13). The trench between 7 and 12° N is deeper than 9000 m. To the north and south the trench depth decreases, so that close to where the trench disappears as an obvious linear feature the depth is c. 5500 m. The trench terminates at its southern end at c. 3° N (Nichols et al. 1990) and in the north at c. 15° N.

Cardwell et al. (1980) showed only a 100 km Benioff zone contour for the subducted Philippine Sea plate, but commented on the steepness of the slab dip compared with other subduction zones. Lallemand et al. (1998) interpreted an additional 200 km contour through Mindanao, roughly along the trace of the Philippine fault. Neither more recent seismicity (Engdahl et al. 1998; USGS Earthquakes Hazard Program 2017) nor P-wave tomography (Hall & Spakman 2015) provide clearer images of the subducting slab. Most volcanoes in eastern Mindanao and the central Philippines are close to the Philippine fault, but deviate from it in the northern Philippines. It is not clear whether the volcanoes are the product of melting above the subducted slab or magmatism associated with the Philippine fault. If the 200 km Benioff zone contour is in the position drawn by Lallemand et al. (1998), then the source of the magmas is rather deep, but the steepness of the slab and the difficulty in accurately defining the top of the slab means that this is uncertain. There has also been abundant volcanic activity unrelated to subduction in Mindanao, far to the west of any influence from Philippine Sea plate subduction. Sajona et al. (2000) suggested that this may be related to older subduction and/or collision in Mindanao.

The length of the subducted slab, between 100 and 200 km, appears similar along most of the length of the Philippine trench (Fig. 13). Lallemand et al. (1998) suggested that subduction initiated between 7 and 10° N, where the trench is deepest, and the
trench grew northwards and southwards from there in the past 5 myr. The similar length of the subducted slab along the trench suggests that it grew rapidly to the north and south from the point of initiation which, assuming a simple linear propagation, corresponds to a rate of 180 km myr along-strike.

Discussion
There can be no doubt that new subduction zones have been created in many parts of the west Pacific margins and eastern Indonesia in the Neogene. It is also likely that they formed by different mechanisms. To understand the processes that have led to the present day tectonic situation, it is important to have an accurate identification of the plate boundaries that exist today. Unfortunately, this is often overlooked. Maps such as those of Bird (2003), largely derived from Rangin et al. (1999), based mainly on recent seismicity and global positioning system measurements, show a number of ‘microplates’ (Fig. 14a) with fully connected plate boundaries – but this is not the situation. Most ‘plate boundaries’ in the region are not connected (Fig. 14b). Subduction zones terminate. The wrongly interpreted complete connection of plate boundaries implies the rapid (almost instantaneous) creation of new plate boundaries, very small plates (some would be thicker than they are laterally extensive at the surface) and the propagation of trenches from another plate boundary, or a change of a boundary type as motion directions changed. This is not what is observed. Today, we observe a single frame in a kinematic sequence of tectonic change and this implies considerable ‘intra-plate’ deformation. The Neogene history of the Celebes Sea shows that new subduction zones start at points and grow laterally – even today, the North Sulawesi trench and the Cotobato trench are not connected (Fig. 1).

This raises the important issue of how the initiation of subduction can be recognized. The crucial stage is getting the slab to the depth where slab-pull forces can take over. How long does it take to depress the top of the oceanic crust from the seabed to depths of >50 km where, for example, the increased density due to phase changes could enhance slab-pull forces? Very few studies address this issue – most models of the initiation of subduction simply show a new subduction zone that has already reached a depth of 100 km.

What is used to recognize past subduction and identify a new subduction zone? Typically, this is a volcanic arc, but volcanism normally starts only when a slab reaches c. 100 km. For a subduction angle of 45° (140 km length subducted) and 7 cm a^{-1} (the present convergence rate at the Java trench) this would require 2 myr. An absolute minimum of 1 myr is required with an average dip to 100 km of 45° and a convergence rate of 14 cm a^{-1}. In most places around Indonesia, the slab dip to 100 km is much less than 45°. Slab dips typically increase below depths of 100 km. For North Sulawesi, the horizontal distance from the trench to a point vertically above the Benioff zone contour of 100 km is c. 170–200 km and the slab dip is close to 30°.
create this configuration at a convergence rate of 7 cm a\(^{-1}\) would require c. 3 myr.

However, even using the arc as a marker is problematic because subduction-related volcanic activity has not started above the slabs subducted at the North Sulawesi trench or the Cotobato trench, and possibly not at the Philippine trench. Most of the volcanic activity in the south and central Philippines west of the Philippine trench appears likely to be related to the Philippine fault (Fig. 13).

There are several important features that are crucial to the initiation of subduction in this region. All of the subduction zones formed at the edge of ocean basins. Many west Pacific marginal basins are deeper than predicted by age–depth relationships for major oceans (Parsons & Scater 1977). Scater et al. (1976) reported this for the Philippine Sea and Park et al. (1990) confirmed it. Hinschberger et al. (2003) showed the Banda Sea basins are c. 1000 m deeper for their age than the Philippine Sea basins. These are locations with large topographic contrasts (commonly a change in elevation of the order of 6 km) over distances of the order of 40 km, therefore with steep slopes that are likely to be unstable.

The trenches (North Sulawesi, Cotobato, Philippines) formed in areas where there has been recent magmatic activity and relatively young crustal thickening following collisions. The North Banda Sea is a young ocean basin (12–7 Ma), which means that the adjacent continental margins are hot. These observations suggest that hot crust/lithosphere may be a precondition for the initiation of subduction. Arc and young collision settings provide this.

Sulawesi has been part of the upper plate above the Banda subduction zone, which formed and began to roll back at c. 17 Ma. The entire upper plate was extended and weakened by magmatism, by the asthenospheric rise that accompanied crustal thinning, and later by the formation of new ocean basins. The initiation of subduction that began in an extensional setting is therefore likely for the North Sulawesi trench and plausible for the Cotobato trench and Tolo trough. Seismic lines record extension in all these areas.

In each case the subduction zone is observed (Cotobato trench, Tolo trough, Sula deep) or inferred (North Sulawesi) to have initiated at a corner in the ocean basin, where relatively local downslope failures can cause significant initial depression of the oceanic crust. The two-dimensional sections of analogue models by Lévy & Jaupart (2012) resemble what is observed – subduction begins during crustal extension at a continental margin.

The Cotobato trench is interesting because in purely mechanical terms it was not obviously needed. Plate convergence was already taken up by the subduction of the Philippine Sea plate at the Philippine trench and subduction of the Molucca Sea plate. This suggests that some subduction zones are initiated simply because conditions are right, such as the existence of a corner in an ocean basin, large topographic contrasts or weak adjacent crust. The Philippine trench more likely formed in a contractional setting associated with convergence of the Philippine Sea plate with Eurasia after regional plate reorganization at c. 5 Ma (Hall et al. 1995b; Hall 1996, 2002; Lallemand et al. 1998). The trench is 1800 km long and, despite subduction of only c. 200 km, the slab rapidly becomes steep and the trench is very deep (10 km) in its central part. Lallemand et al. (1998) suggested that subduction initiated at this location and grew from the centre to the south and north. In both directions the trench shallows to c. 5500 m and dies out. Like the subduction zones around Sulawesi, the subduction initiated at a point, at the edge of an ocean basin where there was a large difference in elevation, in an area of hot crust, and grew along-strike. In all cases subduction initiated at the former continent–ocean boundary where there were pre-existing faults.

The Philippine trench and fault have been interpreted as part of a strain partitioning system in which the trench takes up the orthogonal convergence of the Philippine Sea plate and the fault absorbs the lateral component (Fitch 1972). This explains well the parallelism of the trench and fault from Mindanao to Masbate (Fig. 13), but implies that the Philippine fault is very young. However, between Masbate and southern Luzon, the fault separates into several strands; the fault crosses from the east in southern Luzon to the west side of northern Luzon, where it horse-tails into several strands (Allen 1962). The simple strain partitioning model breaks down for this region. The path of the fault can be explained if it reactivates older faults in Luzon; this is consistent with suggestions of an older Miocene history of displacement on the Philippine fault in Luzon. In most cases it is impossible to determine the ages of the oldest movements on faults, but it is common to find indications of earlier movements on active faults which may have reactivated older structures. Thus another factor in the initiation and development of subduction is likely to be pre-existing faults.

Some trenches have been interpreted on the west side of the Philippines (close to Negros and north of the Sulu arc). The feature offshore of Negros is currently a thrust, not a trench. It is unlikely to develop into a trench because the Sulu Sea is not underlain by oceanic crust, but by highly extended arc crust (see discussion in Hall 2013). A subduction zone on the north side of the Sulu arc is sometimes shown on tectonic maps, which partly reflects the limited information from this region. Based on the continuation of the arc into Sabah, it is now clear that the arc was the product of north-directed, not south-directed,
subduction of the Celebes Sea, which ceased at the end of the Miocene (Hall 2013). Nonetheless, these and other thrust zones in eastern Indonesia often suggested to be incipient subduction zones (the Wetar thrust, Flores thrust and Manokwari trough) are all situated at the edge of oceanic basins.

Ophiolites are commonly linked to the initiation of subduction, such as the models proposed based on the Izu–Bonin–Marianas arc or the Oman ophiolite. These models have some unusual features. For example, the popular Stern & Bloomer (1992) model postulates the initiation of subduction at a transform fault, but with an age difference across the transform of 99 Ma, a situation observed nowhere on the present day Earth. Models based on the Oman ophiolite commonly predict the initiation of subduction at spreading centres. Both types of model could account for the unusual features of the Eocene western Pacific, such as boninites, or the Late Cretaceous Tethys where many ophiolites formed in a short interval of time and were emplaced along an along-strike distance of thousands of kilometres. But these are not models that are easy to test, certainly not by direct observation, and it is impossible to determine the progression of stages taking ocean crust to depths of 100 km.

These models do not apply to the many young subduction zones of the west Pacific margins and eastern Indonesia, which must have formed by other mechanisms. None of the subduction zones discussed in this paper are associated with young ophiolites. Ophiolites are found in many areas, including Sulawesi, Halmahera and the Philippines, but are typically the basement of arcs, are much older than the Neogene subduction zones and were mainly emplaced during collision. Some of the supposed ophiolites in this region previously considered to be young, such as rocks on Seram (e.g. Linthout & Helmers 1994; Linthout et al. 1997), are now known to be sub-continental mantle rapidly exhumed during rollback-driven extension (Pownall et al. 2013, 2014). Nor are the young subduction zones associated with unusual magmatic rocks such as boninites. Ophiolites are a red herring in understanding the initiation of young subduction zones in the west Pacific margins and east Indonesia.

Conclusions

The initiation of subduction is easy – in the right place. Marginal basins are the right place (as suggested by Cloetingh et al. 1984). Major ocean basins with passive margins are not the right place.

For an old passive margin, the migration of an existing plate boundary is probably the easiest way to initiate subduction. The Banda region illustrates such a development. Duarte et al. (2013) proposed a similar propagation of plate boundaries possibly initiating subduction at the Atlantic margin at the present day.

Elsewhere, young subduction zones in the eastern Indonesian region offer insights into the frequent and apparently easy initiation of subduction that, up to now, have been overlooked. In all cases subduction starts at a point at the edge of an ocean basin. This is very important and is not a scenario addressed by numerical or analogue modellers.

The age of the marginal basin seems to be unimportant. In most of the examples discussed here, major extension of topographically higher crust preceded true subduction as the continental crust spread over adjacent oceanic crust and depressed it. Trenches formed close to areas where there had been recent magmatic activity and/or relatively young crustal thickening following collisions.

Hot crust/lithosphere may be a pre-condition for the initiation of subduction. Arc and young collision settings provide this. Once the oceanic lithosphere reaches c. 50–80 km depth, eclogites can form and slab-pull takes over. The subduction zone then grows along-strike, typically in both directions, from the starting point. Subduction rollback then begins.

The Philippine trench is similar to the circum–Sulawesi examples, but may have initiated in a contractional setting. Nonetheless, it confirms some of the key features required for the initiation of subduction: there was a significant topographic difference between the continent and ocean, subduction started at a point, initiation was at the edge of an ocean basin and it was close to a region of young arc magmatism.

The initiation of subduction can be observed, but places where this is possible have been overlooked or ignored. This may, in part, be due to the apparent tectonic complexity of the eastern Indonesian region, but oversimplified plate models showing fully connected microplate boundaries are hindering our understanding, not aiding it. Modelling is currently not dealing adequately with the problem. Both analogue and numerical models try to deal with the instantaneous initiation of subduction across the entire width of a model, rather than at a point. Some analogue models (e.g. Mart et al. 2005) do resemble aspects of the examples described here; experiments by Lévy & Jaupart (2012) are closest to what is observed in eastern Indonesia, where subduction began during crustal extension at a continental margin.

The Wilson cycle postulates a change from a mature ocean to a declining ocean (Burke 2011) by the initiation of subduction. However, it is difficult to identify former passive margins of mature oceans that have, or are soon likely to, become active margins. It is also ironic that the Pacific is identified as an example of a declining ocean, yet has probably existed for much longer than mature oceans such
as the Atlantic. The many young subduction zones of the west Pacific margins and eastern Indonesia suggest that subduction of the mature oceans will begin by the propagation of subduction from marginal basins where subduction initiates easily. Places like the Caribbean, South Sandwich Islands or the Gibraltar Arc could be sites where this process will begin for the Atlantic.

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