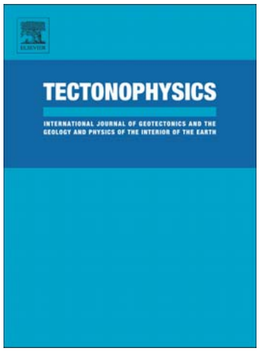

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Present-Day Stress Field of Southeast Asia

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Abstract

It is now well established that ridge push forces provide a major control on the plate-scale stress field in most of the Earth's tectonic plates. However, the Sunda plate that comprises much of Southeast Asia is one of only two plates not bounded by a major spreading centre and thus provides an opportunity to evaluate other forces that control the intraplate stress field. The Cenozoic tectonic evolution of the Sunda plate is usually considered to be controlled by escape tectonics associated with India-Eurasia collision. However, the Sunda plate is bounded by a poorly understood and complex range of convergent and strike-slip zones and little is known about the effect of these other plate boundaries on the intraplate stress field in the region. We compile the first extensive stress dataset for Southeast Asia, containing 275 A-D quality (177 A-C) horizontal stress orientations, consisting of 72 stress indicators from earthquakes (located mostly on the periphery of the plate), 202 stress indicators from breakouts and drilling-induced fractures and one hydraulic fracture test within 14 provinces in the plate interior. This data reveals that a variable stress pattern exists throughout Southeast Asia that is largely inconsistent with the Sunda plate's approximately ESE absolute motion direction. The present-day maximum horizontal stress in Thailand, Vietnam and the Malay Basin is predominately north-south, consistent with the radiating stress patterns arising from the eastern Himalayan syntaxis. However, the present-day maximum horizontal stress is primarily oriented NW-SE in Borneo, a direction that may reflect plate-boundary forces or topographic stresses exerted by the central Borneo highlands. Furthermore, the South and Central Sumatra Basins exhibit a NE-SW maximum horizontal stress direction that is perpendicular to the Indo-Australian subduction front. Hence, the plate-scale stress field in Southeast Asia appears to be controlled by a combination of Himalayan orogeny-related deformation, forces related to subduction (primarily trench suction and collision) and intraplate sources of stress such as topography and basin geometry.

Keywords: Intraplate Stresses; Present-day stress, Southeast Asia; Sunda plate

1. Introduction

Mapping of the plate-scale present-day stress field can reveal key insights into the forces controlling intraplate deformation (Müller et al., 1992; Richardson, 1992; Zoback, 1992; Hillis and Reynolds, 2000). Early phases of the World Stress Map (WSM) and Australian Stress Map projects demonstrated that the first-order intraplate stress field is primarily the result of forces generated at plate boundaries, most importantly mid-ocean ridge ‘push’, subducting slab ‘pull’, trench ‘suction’ and resistance due to continental collision (Forsyth and Uyeda, 1975; Zoback, 1992; Reynolds et al., 2002). However, the Sunda plate, that encompasses much of Southeast Asia, is almost entirely surrounded by collisional and subduction zones and only has a very short and poorly developed spreading centre in the Andaman Sea (Figure 1; Bird, 2003). The lack of any major spreading centre bounding the Sunda plate provides an opportunity to investigate the present-day stress field in a plate that is absent of the ridge push forces that dominate the stress field in all other major plates (Richardson 1992; Zoback 1992). However, little was known about the in situ stress field in Southeast Asia from early phases of the WSM project (Zoback, 1992; Mount and Suppe, 1992). The 2003 WSM database contained very few stress indicators from Southeast Asia, and the majority of these were derived from earthquakes that occurred close to the plate boundaries. Indeed, the 2003 WSM database contained only 37 A-C quality and 61 A-D quality data records from the interior of the Sunda plate (Reinecker et al., 2003).

The Sunda plate currently displays a remarkable contrast between its tectonically active margins, which exhibit intense seismicity and volcanism, and the stability of its interior. Indeed, the continental interior of the Sunda plate is often viewed as a region of stability both in the present-day and throughout the Cenozoic, even to the extent of being referred to as the ‘Sunda craton’ or ‘shield’ (Ben-Avraham and Emery 1973; Gobbett and Hutchinson 1973; Tjia and Liew 1996). However, irrespective of its apparent stability, the continental interior of the Sunda plate displays substantial evidence for widespread and intense Cenozoic tectonic activity characterized by high heat flow, intraplate volcanism, deep and rapidly formed basins and widespread uplift (Hall, 1996; Hall and Morley 2004; Morley 2002). Despite these extensive and varied deformational events, the Cenozoic tectonic evolution of Southeast Asia is often explained primarily as the result of deformation caused by collision of the Indian sub-continent with Eurasia (e.g. Molnar and Tapponnier, 1975; Tapponnier et al. 1982; England and Houseman, 1989; Kong and Bird 1997). However, several authors demonstrate the importance of also considering other factors, such as subduction related forces, Timor collision and Philippine plate rotation, in the tectonic evolution of Southeast Asia and have developed numerous detailed plate reconstructions of Southeast Asia throughout the Cenozoic (Hall 2002; Morley, 2002; Morley, 2007a; Hall et al., 2008).

This study compiles data from borehole breakouts, drilling-induced fractures and focal mechanism solutions to make the first description of the present-day intraplate stress field in the Sunda plate, Southeast Asia. We then demonstrate that the Sunda stress field, though variable across the plate and not aligned to absolute plate motion, is statistically consistent in 14 basin-scale provinces. Finally, we examine the stress field at smaller scales within a number of stress provinces and suggest that the stress field in Sunda is influenced by a combination of plate boundary forces, particularly resulting from the extrusion of the eastern Tibetan plateau, slab rollback, subduction and continental collision, as well as intraplate forces such as topography, basin geometry and local structures.

2. The Sunda Plate

Early models of global lithospheric plates considered Southeast Asia to be a part of the Eurasian plate. However, recent studies and particularly GPS analysis have revealed that Southeast Asia (the Sunda block) is moving separately from Eurasia and should be considered as a distinct plate (Michel et al., 2000; Bird, 2003; Simons et al., 2007). Yet, although Sunda is now widely regarded as a separate plate, the boundaries of the plate remain poorly defined and a subject of wide speculation (for example, Bird, 2003; Hall and Morley, 2004; Simons et al., 2007; Figure 1). Indeed, no parts of the Sunda plate boundary are typically agreed upon aside from a section immediately south of Java (Figure 1).

The purpose of this paper is to discuss the intraplate stress field of Sunda and not to debate the relative merits of the many different Sunda plate boundary models. Moreover, the lack of consensus regarding the boundaries of the Sunda plate significantly affects analysis of the intraplate stress field. Firstly, earthquake focal mechanism solutions located near plate boundaries are often considered unreliable as stress indicators and typically should not be included in plate-scale stress analysis (Townend, 2006; Barth et al., 2008). Secondly, the variety of Sunda plate models makes it difficult to separate stress data in the Sunda plate from data that may be located in adjacent plates. Herein, we have taken a conservative approach to only include stress data that we are confident is located in the interior of the Sunda plate and therefore have only considered stress data that is within the innermost zone of the range of published plate boundaries (Figure 1).

3. Present-day Stress Data

This study has compiled a database of 275 contemporary maximum horizontal stress orientations from throughout the interior of the Sunda plate using the same data types and quality-ranking scheme as the 2008 release of the World Stress Map project (Heidbach et al., 2008). The WSM project collects contemporary stress orientation data from a number of sources in the upper 40 km of the crust, namely: earthquake focal mechanisms, borehole breakouts, drilling-induced fractures, hydraulic fracturing, overcoring and recent geological structures (fault slips and volcanic vent alignments; Zoback et al., 1992; Heidbach et al., 2007). However, only data from earthquake focal mechanisms (72 indicators), borehole breakouts (189 indicators), drilling-induced fractures (13 indicators) and hydraulic fracture tests (1 indicator) were available for Southeast Asia and could be quality-ranked according to WSM standards (Figure 2; Table 1).

Quality Ranking

All stress indicators in the WSM database are quality-ranked for reliability and to better facilitate the comparison of data from different sources and depths (Sperner et al., 2003). The WSM ranking scheme ranges from A quality (highest, denoting that a large number of stress measurements in a significant volume of rock yield stress orientations reliable to ±15º) down to D quality (small number of samples and/or standard deviation of orientations of ±25-40º) and E quality (no reliable stress orientation data; see Heidbach et al., 2008 for full details on WSM quality ranking scheme). A-C quality data is typically considered the most reliable and used in most plate-scale stress studies (Zoback et al., 1992; Hillis and Reynolds, 2000). However, D-quality stress measurements from breakouts and drilling-induced fractures have also been used in this study as it is considered herein that multiple consistent D-quality stress indicators that are in close geographical proximity may also provide a reliable indication of the regional present-day stress orientation. Indeed, earlier versions of the WSM quality ranking system allowed data from multiple wells to be combined to yield A-C quality orientations and D-quality data has previously been included in the description of regional stress fields (Müller et al., 1992; Zoback, 1992; Hillis and Reynolds, 2000).

Focal Mechanism Solutions

Earthquakes can yield focal mechanism solutions, from which the principal stress orientations can be inferred (McKenzie, 1969; Michael, 1987; Barth et al., 2008). Indeed, focal mechanism solutions are highly valuable as they offer the only method for obtaining reliable stress information at depths greater than are commonly penetrated by drilling (>5km depth; Figure 2). There are a wide variety of methods for calculating focal mechanism solutions; though all but one of the 72 stress orientations compiled for the Sunda plate have been inferred from centroid moment tensor (CMT) solutions of single earthquake events compiled by the Global CMT project (Dziewonski et al., 1981; Zoback, 1992). Centroid Moment Tensor solutions use the radiation pattern of body and/or surface waves that are inverted to fit seismic waveforms calculated for a reference earth model (Dziewonski et al., 1981). In addition, focal mechanism solutions from a number of earthquakes offshore of south-eastern Sumatra have been combined to develop a single formal stress inversion solution (Harjono et al., 1991).

Well constrained single earthquake CMT solutions from the Global CMT project database are arbitrarily given a C-quality under the WSM project ranking scheme (Zoback, 1992; Sperner et al., 2003). This accounts for the large number C-quality stress indicators in the Sunda stress database, though the solitary formal stress inversion solution has an A-quality (Figure 2; Table 1). However, it is important to note that the majority of stress indicators derived from earthquakes are located near the edges of the Sunda plate (Figure 3). Stress information inferred from focal mechanism solutions near plate boundaries are believed to be particularly susceptible to errors as the presumably weak faults near plate boundaries may be more easily reactivated by non-optimally oriented stresses (Townend, 2006; Heidbach et al., *this issue*). Hence, to avoid this issue, earthquake derived stress data have not been included in the Sunda stress map database that is located within 100 km of a plate boundary (Townend, 2006).

Borehole Breakouts, Drilling-Induced Fractures and Hydraulic Fractures

Borehole breakouts and drilling-induced fractures (DIFs) are the most common method for stress analysis in the upper 5km of the earth's crust, provide the majority of higher A and B quality data (in both the WSM database and herein) and allow higher resolution examination of the stress field than earthquake focal mechanism solutions (Figure 2; Table 1; Tingay et al., 2005a; Heidbach et al., 2007). Both borehole breakouts and drilling-induced fractures result from the stress concentration that occurs around wellbores (or any subsurface opening; Kirsch 1898). Borehole breakouts are stress-induced elongations of the wellbore and occur when the compressive stress concentration at the borehole wall exceeds that required to cause shear failure of intact rock (Bell and Gough, 1979). The elongation of the wellbore is the result of compressive shear failure on intersecting conjugate planes, which causes pieces of the borehole wall to spall off (Bell and Gough, 1979). The maximum stress around a vertical borehole occurs perpendicular to the maximum horizontal stress (Kirsch, 1898). Hence, borehole breakouts are elongated perpendicular to the present-day maximum horizontal stress direction (Bell and Gough, 1979).

Drilling-induced fractures are caused by tensile failure of the borehole wall and form when the wellbore stress concentration is less than the tensile strength of the rock (Aadnoy, 1990). The minimum stress around the borehole occurs in the direction of the maximum horizontal stress in vertical boreholes (Kirsch, 1898). Hence, DIFs are oriented in the maximum horizontal stress direction in vertical boreholes (Aadnoy and Bell, 1998).

Borehole breakouts were interpreted herein from oriented four- or six-arm caliper log data (e.g. the High-Resolution Dipmeter Tool) or from acoustic or resistivity image logs (e.g. Formation Micro Imager, Simultaneous Acoustic and Resistivity Imager). Four and six-arm dipmeter logging tools provide data on the borehole dimensions in two or three directions respectively, which can be used to estimate the shape of the borehole cross-section and distinguish borehole breakouts from non stress-induced wellbore elongations (Plumb and Hickman, 1985; Wagner et al., 2004). Image logs provide a more reliable and direct means of interpreting breakouts (Zoback, 2007). Breakouts appear on resistivity image logs as pairs of broad, poorly resolved, conductive zones that are parallel to the borehole axis and separated by approximately 180º. Breakouts appear on acoustic image logs (primarily travel time logs) as a pair of wellbore elongation zones parallel to the borehole axis and separated by approximately 180º. Drilling-induced fractures cannot be reliably interpreted from four- or six-arm caliper log data, but appear as pairs of narrow conductive features (on resistivity images) or low amplitude features (on acoustic images) that are generally parallel to the borehole axis and separated by approximately 180º.

The stress database for Sunda also contains one indicator measured from hydraulic fracture tests in Indonesia (Rummel, 1987). Hydraulic fractures are one of the oldest techniques for stress estimation and are, in essence, purposely created DIFs (Hubbert and Willis, 1957). Hydraulic fracturing is undertaken by isolating a section of a wellbore and increasing the fluid pressure within the section until tensile fractures are initiated (Enever, 1993). The orientation of the induced fracture (and thus maximum horizontal stress in vertical wells) can then be established by use of an impression packer or image log (Enever, 1993).

4. The Southeast Asia Stress Map Database

The stress orientation database for the interior of the Sunda plate has been increased from only 37 A-C quality and 61 A-D quality data records in 2003 to a current total of 177 A-C quality and 275 A-D quality data records (Table 1; Figures 2 and 3). The new stress data for Southeast Asia comes from a variety of sources. The number of stress indicators from focal mechanism solutions has increased to 72 (from 15 in 2003), due to the inclusion of additional publicly available CMT-derived stress orientations. The majority of the additional CMT data is located near the plate boundaries in Indonesia, the Philippines and Indochina. However, there are also several new stress indicators from earthquakes that have occurred in the intraplate regions, particularly in Borneo (Figure 3).

It is particularly important to note that the current Sunda plate stress database contains 202 A-D quality stress indicators from borehole breakouts or DIFs (compared to 45 in the 2003 WSM database) that are predominately located away from the plate boundaries (unlike the majority of focal mechanisms solution data; Figure 3). The increase in stress indicators from borehole breakouts and DIFs is the outcome of both the author’s own analysis, as well as from several published basin-scale stress studies in Malaysia, Indonesia and Vietnam (Figure 3).

The authors have conducted extensive stress analysis throughout Brunei, Malaysia and Thailand (Tingay et al., 2005b; Tingay et al., 2006; Morley et al., 2008; Tingay et al., 2009a; King et al., 2009; King et al., *in press*). Four-arm caliper and image logs from 73 wells have been examined in the onshore and offshore Baram Delta system of Brunei and Malaysia, providing the first insights into the present-day state of stress in Northwest Borneo. The stress analysis conducted in a number of studies has resulted in 40 A-D quality (14 A-C quality) stress indicators in onshore and offshore Brunei (Figure 4; Tingay et al., 2005b; Tingay et al., 2009a; King et al., 2009).

The 2003 WSM database contained only four A-D stress indicators from borehole breakouts in Thailand (from the Khorat Basin). However, the authors have undertaken an extensive analysis of present-day stress in Thailand and the Gulf of Thailand, examining four- and six-arm caliper and image logs from 100 wells to compile 76 A-D quality (60 A-C quality) stress indicators from the Chumphon, Khorat, Pattani, Phitsanulok and the Suphan Buri/Khampaeng San Basins (Figure 5).

The 2003 WSM database contained no borehole breakout or DIF stress indicators in Malaysia despite the publication of results from an extensive analysis of present-day stress orientations in several Malaysian basins (Tjia and Ismail, 1994). Unfortunately, none of the stress indicators in this study were quality ranked and the results are highly confusing, typically providing both primary and “secondary”, ”other” and/or ”younger” maximum horizontal stress directions for each well (Tjia and Ismail, 1994). Furthermore, the authors infer that the different stress orientations in individual wells reflect different palaeostresses, rather than purely the contemporary stress. Hence, the results of this study had previously not been considered sufficiently reliable to include in the WSM database. However, the authors have recently been able to examine four-arm caliper and image log data in both the Malaysian and Thai sectors of the Malay Basin and this has allowed independent verification of some of the results presented by Tjia and Ismail (1994). The combination of these studies has resulted in a total of 26 A-D quality (8 A-C quality) stress indicators in Malaysian Basins (plus 6 wells that showed no breakouts/DIFs; Figure 5).

The stress field in Indonesia is most typically inferred from earthquake focal mechanism solutions. However, borehole breakout analysis has previously been conducted in the South and Central Sumatra Basins and in the Kutei Basin of Southeast Borneo (Mount and

Suppe, 1992; Syarifuddin and Busono, 1999). Mount and Suppe (1992) conducted borehole breakout analysis from four-arm caliper logs in 40 wells in onshore and offshore Sumatra as part of the earliest phases of the WSM project. Indeed, these 40 A-D stress indicators from Sumatra formed approximately half of the entire 2003 WSM stress database for the Sunda plate. Syarifuddin and Busono (1999) examined four-arm caliper log data from 134 wells to provide an extensive study of present-day stress orientations in the Kutei Basin. The results of this study were binned into seven large geographical regions, each containing several hundred breakouts from numerous wells that displayed a widely consistent orientation (Syarifuddin and Busono, 1999). Unfortunately, no results were provided for individual wells, as is required under WSM guidelines and, hence, this data has not been included in the WSM database. However, for the purposes of the study of the Southeast Asian stress field herein, we have included the average stress orientations determined for each of the seven Kutei Basin stress provinces, and have arbitrarily assigned each of these stress indicators a C-quality (Figure 3).

The 2003 WSM database contained no stress data from basins in Vietnam. However, Binh et al. (2007) have recently conducted the first investigation into the present-day state of stress in the Nam Con Son and Cuu Long Basins offshore Vietnam. As a part of this study Binh et al. (2007) interpreted borehole breakouts and DIFs from image logs in 10 wells, all of which yielded A- or B-quality stress indicators (Figure 3).

5. Stress Provinces

Stress orientations are highly variable across Southeast Asia (Figure 3). However, within individual provinces, such as sedimentary basins, stress orientations are generally broadly consistent (Figure 6). Herein, we have clarified large-scale trends in stress orientation by defining 14 regional stress provinces using circular statistics in a method based on that applied in other studies of plate-scale stress fields (Figure 7; Table 2; Coblentz and Richardson, 1995; Hillis and Reynolds, 2000; Hillis and Reynolds, 2003).

A minimum of four A-D quality stress orientation indicators within a distinct geological region (predominately a sedimentary basin) is defined herein to constitute a stress province (Table 2; Figure 6). Individual stress orientation indicators were weighted according to quality for the circular statistical analysis, with D-quality data receiving a weighting of one, C-quality a weighting of two, up to A-quality receiving a weighting of four (Hillis and Reynolds, 2003). The Rayleigh Test was then applied to the individual stress orientation data within each stress province to investigate whether, and how strongly developed; any preferred stress orientation is within the province (Mardia, 1972; Hillis and Reynolds, 2000). The Rayleigh Test determines the confidence level at which we can reject the null hypothesis that stress orientations within a province are random (Mardia, 1972; Coblentz and Richardson, 1995). Herein, a type 1 stress province indicates that the null hypothesis can be rejected at the 99.9% confidence level, type 2 at the 99.0% confidence level, type 3 at the 97.5% confidence level and type 4 at the 95% confidence level (Hillis and Reynolds, 2003).

The categorization of stress provinces should not be confused with the WSM quality ranking scheme used for individual stress indicators. The individual stress orientation data within a type 4 stress province are no less reliable *per se* than those in a type 1 province, rather that data in type 4 provinces display more scattered stress orientations (Hillis and Reynolds, 2000). However, the stress province type may give an indication of the degree of horizontal anisotropy in a region, with far-field forces possibly controlling the stress field in type 1 provinces, whereas local sources of stress may be more dominant in type 4 provinces (Hillis and Reynolds, 2000).

6. Regional Stress Orientations in Southeast Asia

The extensive present-day maximum horizontal stress orientation dataset compiled herein allows the first ever analysis of the stress field in Southeast Asia and, in particular, within the interior of the Sunda plate. The stress orientation data and regional stress provinces reveal that a complex and unusual stress pattern exists in Southeast Asia (Figure 7). The maximum horizontal stress interpreted from breakouts and DIFs is oriented approximately N-S (or between NNE-SSW and NNW-SSE) throughout onshore and offshore Thailand, the Malay Basin and Cuu Long Basin (offshore Vietnam; Figure 7). However, the contemporary maximum horizontal stress is predominately oriented NW-SE in the Baram Delta and Kutei Basin and NE-SW in the Central and Southern Sumatra Basins (Figure 7). Furthermore, focal mechanism solutions indicate maximum horizontal stress orientations that are approximately NNE-SSW near Java (Figure 7). Hence, the plate-scale maximum horizontal stress pattern in Sunda can be characterized at a broad-scale as approximately:

- N-S in the northwestern part of the plate (onshore/offshore Indochina);
- NW-SE in Borneo, and;
- perpendicular to plate boundaries near major subduction zones in Indonesia.

Plate-scale stress patterns are thought to be the result of first-order plate boundary forces, such as mid-ocean ridge push, and secondary intraplate forces such as topography (Zoback, 1992). However, localized sources of stress can have a significant impact on small-scale stress patterns (Tingay et al., 2005a; Heidbach et al., 2007). Detailed analysis of the forces controlling the plate-scale and small-scale stress fields can be successfully conducted by finite element modeling (for example, Coblentz and Sandiford, 1994; Coblentz and Richardson, 1996; Gölke and Coblentz, 1996; Reynolds et al., 2002). However, such detailed finite element modeling is outside the scope of this paper. Thus, herein we speculate on the origins of the main characteristics of the plate-scale stress field in Southeast Asia and discuss observations of local stress perturbations.

Northwestern Sunda

A predominantly N-S maximum horizontal stress orientation, with high regional consistency, is observed in seven stress provinces in onshore and offshore Indochina (Chumphon, Cuu Long, Khorat, Malay, Pattani, Phitsanulok and Suphan Buri Basins; Figure 7; Table 2). This regionally extensive N-S orientation is also consistent with the stress orientations derived from earthquake focal mechanism solutions in Northern Thailand, the Gulf of Thailand and offshore Vietnam (Figure 7). The many Cenozoic structures that have developed throughout this region have often been considered to result from largely southwards directed compressive forces generated at the eastern Himalayan syntaxis (Molnar and Tapponnier, 1975; Tapponnier et al. 1982; Kong and Bird, 1997). Hence, it is likely that the N-S present-day stress orientation is also partly the result of radial stresses caused by the eastern Himalayan syntaxis. However, recent detailed studies of sedimentary basin formation, regional uplift and structural development of major faults in Thailand indicates that this part of the Sunda plate has undergone complex deformation that cannot be explained purely by extrusion of the eastern Tibetan plateau (Morley, 2001; Hall and Morley, 2004; Morley et al., 2004; Morley, 2007a; Searle and Morley, *in press*). In particular, Morley (2001) suggested that slab rollback along the Sumatran-Andaman Sea subduction zone has had a significant influence on the tectonic evolution of the region, particularly in the development of the numerous N-S elongated rift basins onshore and offshore Thailand. Trench suction forces resulting from slab rollback in this subduction zone (and its northern extension towards Myanmar) can also generate a largely N-S maximum horizontal stress in the north-western parts of the Sunda plate (Morley et al., 2004). Furthermore, there is the potential for localized N-S stresses resulting from gravitational collapse of the thickened continental crust in Indochina (Hall and Morley, 2004). Hence, it is hypothesized herein that the predominant N-S present-day maximum horizontal stress orientation observed throughout the north-western sections of the Sunda plate originates from the combination of plate boundary forces generated by the eastern Himalayan syntaxis, roll back of the Sumatra-Andaman Sea subduction zone and, possibly, more localized stresses caused by gravitational collapse.

Borneo

Borehole breakouts and drilling-induced fractures from the Baram Delta system and Kutei Basin indicate a predominantly NW-SE far-field maximum horizontal stress direction in Borneo, though there is also a NE-SW stress orientation observed in the outer shelf parts of the Baram Delta and from three earthquake focal mechanism solutions in North-eastern Borneo (Figures 4 and 7). A NW-SE maximum horizontal stress orientation in Borneo has long been postulated due to the orientation of geologically recent lineaments and the NW-SE oriented inversion of many major structures (Hamilton, 1979; Hutchinson, 1989; Morley et al., 2003). However, the origin of this NW-SE orientation remains uncertain.

The NW-SE present-day stress direction is similar to the ESE absolute plate motion, and thus the stress orientation may result from a combination of multiple plate boundary forces (Tingay et al., 2005b). In particular, a present-day NW-SE maximum horizontal stress may be generated by forces resulting from the eastern Himalayan syntaxis as well as active subduction under Sulawesi and the Philippines (Figure 1; Tingay et al., 2005b). In addition, some authors have suggested that far-field NW-SE compression throughout

Borneo may result from continental collision of the Australian plate near Timor, with stresses transmitted to Sunda via the Timor, Banda and Molucca plates (Figure 1; Ingram et al., 2004).

The NW-SE maximum horizontal stress orientation may also be the result of relatively local sources of stress. Some authors suggest that there is still weakly active continental collision occurring across the Northwest Borneo margin, though this is primarily oriented E-W (Figure 4; Ingram et al., 2004; Simons et al., 2007). In addition, the Crocker-Rajang accretionary complex has undergone significant amounts of Cenozoic uplift, often at rates similar to those observed in the Himalayas (4-8 km since the Late Miocene; Hutchinson et al., 2000; Hall and Nichols, 2002; Hall and Morley, 2004; Morley and Back, 2008). Numerous mechanisms have been suggested for this uplift, including buoyant rebound of partially subducted continental crust (Hutchinson, 2004); partial delamination of a thickened mantle lithospheric keel (Hall and Morley, 2004), and; detachment of the lithospheric slab that was subducted underneath Northwest Borneo during the Oligocene and Early Miocene (Morley and Back, 2008). These different mechanisms could generate a variety of stress patterns in Borneo that may result in the dominant NW-SE oriented present-day stress. However, even the simple presence of the uplifted Crocker-Rajang can exert significant gravitational topographic forces oriented perpendicular to the mountain range and thus yield NW-SE stresses in the Baram Delta system and Kutei Basin (James, 1984). In summary, the origin of the NW-SE maximum horizontal stress field in Borneo remains uncertain. However, there exists a wide variety of both far-field and local forces that may generate the observed contemporary stress direction.

Sumatra and Java

Earthquake focal mechanism solutions indicate that the present-day maximum horizontal stress is oriented primarily NE-SW in Sumatra, and NNE-SSW in Java, with the NE-SW stress direction in Sumatra confirmed from borehole breakouts and hydraulic fracture tests (Figure 7; Mount and Suppe, 1992). The stress orientations observed in these regions are essentially perpendicular to the strike of the adjacent subduction zone, suggesting that the regional stress orientation is dominated by forces generated at this plate boundary. However, the arc-normal stresses observed near Sumatra and Java occur in the over-riding plate and thus are in stark contrast to the trench-parallel maximum horizontal stress that would be predicted in this region due to trench suction forces and the formation of associated back-arc basins such as the South and Central Sumatra Basins and East Java Basin (Forsyth and Uyeda, 1975; Zoback, 1992). Arc-normal maximum horizontal stresses can be generated in the over-riding plate in advancing subduction zones, where the velocity of convergence between the two plates is faster than the velocity of subduction (Engelder, 1993). Indeed, Mount and Suppe (1992) suggest that the NE-SW maximum horizontal stress observed in Sumatra is the result of such strong coupling between the subducting Indo-Australian plate and the over-riding Sunda plate. Furthermore, the stress orientations compiled for Sumatra and Java also occur near zones of arc-parallel topography that may generate arc-normal maximum horizontal stress orientations in adjacent regions. Therefore, the arc-normal maximum horizontal stress orientations observed in these regions are hypothesized herein to be the result of gravitational forces generated by the high topography, in addition to the possible subduction zone related forces.

Smaller Scale Stress Pattern Variations

The plate-scale stress field discussed previously is controlled by plate boundary forces and major intraplate sources of stress. However, the present-day stress data for Southeast Asia compiled herein also reveals a number of smaller localized stress orientation variations, ranging in scale from one to one hundred kilometres, which are superimposed upon the plate scale stress field. The most notable of these are the NE-SW maximum horizontal stress orientations observed in stress provinces in the Nam Con Son Basin and outer shelf of the Baram Delta system (Figures 3 and 7).

The Baram Delta system exhibits a striking variation in stress orientation from NW-SE in the inner shelf, to NE-SW in the outer shelf near the shelf edge, and then back to NW-SE in the deepwater region at the delta toe (Figure 4; King et al., 2009). As discussed above, the NW-SE maximum horizontal stress orientation in the Baram inner shelf and deepwater stress provinces is thought to primarily reflect far-field stresses. However, the outer shelf region of the Baram Delta system is an area of active margin-parallel extensional faulting that is generated by the shape of the deltaic wedge (Tingay et al., 2005b; Morley, 2007b). The NE-SW maximum horizontal stress in the outer shelf most likely reflects this active deltaic gravity spreading tectonics and is decoupled from the far-field NW-SE maximum horizontal stress by overpressured basal shales (Tingay et al., 2005b; Tingay et al., 2007; Tingay et al., 2009b). Furthermore, gravity spreading tectonics is typically linked to margin-perpendicular compression in the delta toe, and has been suggested to further contribute towards the NW-SE maximum horizontal stress orientation observed in the Baram Deepwater stress province (King et al., 2009).

Binh et al. (2007) present five stress orientations from within the Nam Con Son Basin, one N-S maximum horizontal stress orientation in the basin centre and four NE-SW maximum horizontal stress orientations in the northern parts of the basin. Unfortunately, the origin of the NE-SW maximum horizontal stresses in the northern parts of the Nam Con Son is unknown. These stress indicators are located near the edge of the continental shelf and thus may also be localised stress orientations related to the transition from thick continental to thin oceanic crust (Bell, 1996). Furthermore, the structural grain of this part of the Nam Con Son basin strikes NE-SW and the maximum horizontal stress is sub-parallel to the strike of most extensional faults in the region. Mechanical property contrasts associated with some geological structures are known to cause localized stress perturbations ranging in scale from meters to several kilometres (Bell, 1996; Yale, 2003; Tingay et al., 2006). In particular, present-day maximum horizontal stresses have been observed to be oriented sub-parallel to mechanically weak faults (Bell, 1996; Yale, 2003). Hence, we suggest that the NE-SW stress orientation in the northern Nam Con Son Basin reflects local stress perturbations either due to the continent-ocean transition or near mechanically weak faults.

The localized perturbation of stresses near faults is also hypothesized to occur in the Pattani Basin in the Gulf of Thailand (Figure 5). The average maximum horizontal stress orientation throughout the Pattani Basin (and most adjacent basins) is north-south (Figure 5). However, the stress orientations within individual wells are highly variable. In particular, maximum horizontal stress orientations along the Platong-Pladang trend range from NNW-SSE to NE-SW and appear to be locally deflected to remain sub-parallel to the strike of post-rift extensional faults (Figure 8).

7. Present-Day Stress Orientations and GPS-Derived Motions

Comparison between Stress Orientations and Absolute Plate Motions

Early studies of plate-scale stress patterns revealed that the maximum horizontal stress orientation in Western Europe, South America and North America is largely sub-parallel to absolute plate motion (Richardson, 1992). Indeed, the correlation between plate-scale stress orientation and absolute plate motion resulted in one of the key findings of the World Stress Map project – that plate boundary forces exert a first-order control on lithospheric stress patterns (Zoback, 1992). However, it is immediately apparent that the varied stress orientations observed in Southeast Asia are not predominantly aligned with the largely ESE absolute motion of the Sunda plate (based on the NUVEL-1 absolute plate motions of DeMets et al. (1990) used in the Richardson (1992) analysis). Indeed, calculation of the misfit between maximum horizontal stress orientation and absolute plate motion for all 275 A-D stress indicators suggests that there is no correlation between present-day stress orientation and plate motion (Figure 9).

A complex stress pattern and lack of correlation between absolute plate motion and present-day stress orientations have also been observed in the Indo-Australian plate (Richardson, 1992; Hillis and Reynolds, 2000). However, finite element modeling has revealed that even the complicated stress pattern observed in Australia can be accurately reproduced from plate boundary forces and intraplate sources of stress (Coblentz et al., 1998; Reynolds et al., 2002). Hence, it is likely that the complicated stress pattern observed in Southeast Asia may be accurately modelled in future studies.

Comparison between Stress Orientations and Intraplate Motions

Although there is a lack of correlation between absolute plate motions and the present-day stress field in Southeast Asia, there does appear to be some degree of correlation between stress orientations and intraplate motions in some regions. Recent studies of GPS data from Southeast Asia have provided new insights into the dynamics of the Sunda plate (Michel et al., 2000; Simons et al., 2007). In particular, Simons et al. (2007) highlighted regions of intraplate deformation by subtracting absolute Sunda plate motion from the motion vector at each GPS station in order to yield residual velocities (i.e. intraplate motions relative to a hypothetical ‘stationary’ or ‘stable’ Sunda plate). The analysis of Simons et al. (2007)

reveals a complex pattern of motions relative to a ‘stationary’ Sunda plate, suggesting that there is ongoing intraplate deformation occurring in regions such as Borneo, Northern Sumatra, Southern Thailand (near Malaysia), Java and Northern Thailand (near Myanmar). In this section we compare the relative intraplate motions in Northwest Borneo, Sumatra and Southern Thailand with the available stress data compiled for these regions.

Northwest Borneo appears to be moving at approximately four to six millimetres per year westwards relative to a ‘stationary’ Sunda plate, and exhibits the greatest amount of relative motion observed within the Sunda plate (Figure 4; Simons et al., 2007). This westward relative intraplate motion is somewhat inconsistent with the approximately NW-SE far-field maximum horizontal stress orientations observed in the Baram Delta stress provinces (Figure 4; Table 2). However, both the present-day stress orientations and the GPS-derived relative intraplate motions suggest that there may still be ongoing collisional deformation occurring across the NW Borneo margin despite the overall absence of seismicity.

GPS data from Indonesia indicates that Sumatra (on the Sunda side of the Great Sumatran Fault) is moving approximately 6 millimetres per year north-eastwards relative to ‘stable’ Sunda, consistent with the NE-SW maximum horizontal stress orientations observed from focal mechanism solutions and borehole breakouts (Figures 5 and 7; Mount and Suppe, 1992; Simons et al., 2007). However, it is interesting to note that the northeast relative intraplate motion and NE-SW present-day stress are highly oblique (70-80º) to the major strike-slip Great Sumatran Fault, an observation that is similar to the high obliquity of present-day stress orientations to the San Andreas Fault (Zoback et al., 1987; Mount and Suppe, 1992). Hence, as discussed above, it appears that relative intraplate motions and present-day stresses in Sumatra reflect collisional forces generated by subduction of the Indo-Australian plate, possibly combined with stresses generated by topography, rather than forces related to trench suction, back-arc extension or motion of the Great Sumatran Fault.

The majority of onshore Peninsular Malaysia and Southern Thailand exhibit very little motion relative to a ‘stationary’ Sunda (less than 1 millimetre per year in a variety of directions; Figure 5). However, three GPS stations in Southern Thailand, between the Ranong and Khlong Mauri Fault Zones, show two to four millimetres per year NNE relative intraplate motions and indicate some active motion along these faults (Figure 5; Simons et al., 2007). Indeed, the M_b 5.6 earthquake that occurred in September 1978 confirms that the Ranong Fault Zone is currently seismically active (Shrestha, 1990). The NNE relative intraplate motion of this fault-bound block is not aligned with the NNW-SSE maximum horizontal stress orientation observed in the Chumphon Basin immediately adjacent to the Khlong Mauri Fault Zone and the N-S stress orientation predominantly observed in the Pattani Basin (Figure 5; Table 2). However, the NNW-SSE Chumphon Basin maximum horizontal stress is suitably oriented to yield the brittle, late sinistral motion suggested to occur on the seismically-active Ranong Fault Zone (Garson et al., 1975; Watkinson et al., 2008; Morley et al., *in press*).

8. Summary and Conclusions

The Sunda plate that encompasses most of Southeast Asia is almost entirely surrounded by collisional zones and is one of only two plates that are not partially bounded by a mid-oceanic ridge. Despite this unique tectonic configuration, the Sunda plate has undergone extensive Cenozoic deformation that has typically been thought to be driven by deformation associated with India-Eurasia collision (e.g. escape tectonics). This study aimed to determine the present-day stress orientation throughout the Sunda plate and to examine the forces likely to be controlling the stress field. A quality-ranked stress database was compiled, according to World Stress Map project standards, containing 275 A-D quality stress orientation indicators, a significant increase on the 61 stress indicators available in the WSM project database in 2003. The stress database for the Sunda plate includes 72 stress orientations from earthquake focal mechanism solutions that are primarily located near the peripheries of the plate. In addition, stress orientations have been derived from borehole breakouts and drilling-induced fractures in approximately 200 wells in 14 sedimentary basins, allowing the first insights into the stress pattern within the interior of the Sunda plate.

The contemporary plate-scale stress field in Southeast Asia is variable and not sub-parallel to absolute plate motion, as is observed in most other plates. The stress field ranges from approximately north-south in onshore and offshore Indochina (Thailand, Malaysia, Vietnam), to largely NW-SE in Borneo (both the Baram Delta system and Kutei Basin) and is roughly perpendicular to the plate boundary in Sumatra (NE-SW) and Java (NNE-SSW). The plate scale stress field suggests that multiple plate boundary and intraplate sources of stress are acting in Southeast Asia. Hence, although we suggest that forces arising from the eastern Himalayan syntaxis play a significant role, the plate-scale stress field in Southeast Asia is also interpreted to be driven by forces related to subduction and topography.

The extensive compilation of borehole breakout and drilling-induced fracture data also reveals a number of localised stress variations in the Baram Delta system, Nam Con Son Basin and Pattani Basin that are superimposed onto the plate-scale stress field. Maximum horizontal stress orientations in the Baram Delta system vary from NW-SE in the inner shelf, to NE-SW in the outer shelf (in the region of active extension near the shelf edge), and then back to NW-SE in the deepwater region at the delta toe. This is interpreted to result from a margin-parallel (NE-SW) deltaic stress orientation, generated by the shape of the deltaic wedge, which is superimposed on the far-field NW-SE maximum horizontal stress. Unusual stress orientations are also observed in the Nam Con Son and Pattani Basins. The maximum horizontal stress is typically oriented sub-parallel to the strike of major extensional faults in both these provinces and we suggest that stresses may be locally deflected by the mechanical contrasts associated with these structures.

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Figure captions

Figure 1: Examples of recently published geometries for the Sunda plate highlighting the wide range of proposed Sunda plate boundaries. Large arrows indicate absolute plate motions, white areas indicate oceanic crust and light grey shaded regions indicate continental crust. (a) Sunda plate and neighbouring plate boundaries hypothesized by Bird (2003). (b) Sunda plate geometry after Hall and Morley (2004) (c) Sunda plate geometry after Simons et al. (2007). (d) Range of boundaries suggested for the Sunda plate and the intraplate study area used herein.

Figure 2: Summary of stress data in the Sunda plate database. (a) Distribution of stress data by types for A-C and A-D quality indicators. (b) Distribution of stress data types with depth. (c) Distribution of stress data types by quality. Note that caliper and image logs from an additional 57 wells were analyzed in high deviation wells or wells that did not contain any borehole breakouts (BO) or drilling-induced fractures (DIF) and have thus received an E-quality. FMS: stress indicator derived from earthquake focal mechanism solution, HF: stress orientation determined from hydraulic fracturing.

Figure 3: Southeast Asia maximum horizontal stress map for A-D quality data. Absolute plate motion directions, major plate boundaries and faults are also presented (modified from Hall and Morley, 2004). Grey shaded background indicates continental crust, white denotes oceanic crust. NF: normal faulting stress regime; SS: strike-slip faulting stress regime; TF: thrust faulting stress regime; U: stress regime undefined.

Figure 4: Present-day maximum horizontal stress orientations determined from borehole breakout and drilling-induced (DI) fractures in the Baram Delta system, Northwest Borneo. Stresses in the Baram Delta system vary from NW-SE (margin-normal) in the inverted inner shelf; to NE-SW (margin-parallel) in the region of active extensional faulting at the shelf edge (white dashed box), and; back to NW-SE in the deepwater fold-thrust belt in the delta toe (adapted from Tingay et al., 2005b and King et al., 2009). We interpret the NE-SW outer shelf maximum horizontal stress direction to be a localized zone of deltaic stresses generated by the shape of the clastic wedge that is superimposed onto the NW-SE far-field maximum horizontal stress orientation. Furthermore, it is interesting to note that the present-day NW-SE maximum horizontal stress orientation is somewhat inconsistent with the westwards motion of Northwest Borneo relative to a ‘stable’ Sunda (grey arrows).

Figure 5: Present-day maximum horizontal stress orientations, major structures and GPS-derived motions (relative to a stable Sunda plate) in onshore and offshore Thailand, Vietnam and peninsular Malaysia. Stress orientations have been compiled from Binh et al. (2007), Tjia and Ismail (1994) and the authors’ own analysis. There is significant scatter in stress directions between individual wells. However, the present-day maximum horizontal stress is typically oriented north-south at a basin-scale, aside from the largely NE-SW maximum horizontal stress orientation observed in the Nam Con Son Basin

Figure 6: Stress provinces based on the Southeast Asia stress map database.

Figure 7: Mean maximum horizontal stress orientations within Southeast Asian stress provinces and isolated A-D quality data that do not lie within the defined stress provinces

(see Table 2 for further details). The plate-scale maximum horizontal stress field of Southeast Asia can be characterized as being largely north-south in the northwestern part of the plate (onshore and offshore Indochina); NW-SE in Borneo, and; largely perpendicular to the plate boundary inboard of subduction zones in Indonesia.

Figure 8: Maximum horizontal stress orientations in the Platong-Pladang trend in the Pattani Basin (Gulf of Thailand). Present-day maximum horizontal stress orientations appear to be rotated sub-parallel to neighbouring extensional faults and to jogs in the half-graben structure.

Figure 9: Distribution of misfit between maximum horizontal stress orientations and absolute plate motion in the Sunda plate (A-C quality in light grey, D-quality in dark grey; calculated by subtracting NUVEL-1 absolute plate motion direction from present-day maximum horizontal stress orientation). Stress orientations in the Sunda plate show no correlation with absolute plate motion, in stark contrast with the correlation observed by Richardson (1992) in most other tectonic plates.

Table 1. Quality and type of stress indicators in the Sunda plate database, Southeast Asia.

	A	B	C	D	E	Total
Breakout	12	34	52	91	52	241
Drill-Ind Fracture	1	3	2	7	0	13
Focal Mech Soln.	1	0	71	0	0	72
Hydrofrac	0	1	0	0	0	1
Total	14	38	125	98	52	327

Table 2. Stress provinces defined within the Sunda plate (see figure 6 for locations). BO: borehole breakout stress indicators, DIF: drilling-induced fracture stress indicators, S.D.: standard deviation of stress azimuths, R: length of the mean resultant vector of maximum horizontal stress orientations within a province (Mardia, 1972). If R exceeds a certain value dependent on the number of data, then the null hypothesis that stress orientations in the province are random can be rejected at the stated confidence level (Conf).

Province	**No.**	**Data Origin**		**Quality**				**Mean**		**Statistics**		
	A-D	**BO**	**DIF**	**A**	**B**	**C**	**D**	**(ºN)**	**S.D.**	**R**	**Conf.**	**Type**
Khorat Basin	11	10	1	3	1	4	3	173	23.7	0.71	99.0%	2
Phitsanulok Basin	13	12	1	1	1	5	6	012	23.2	0.72	99.9%	1
Suphan Buri Basin	5	5	0	0	0	2	3	000	15.8	0.86	97.5%	3
Chumphon Basin	7	6	1	0	1	3	3	159	16.5	0.847	99.0%	2
Pattani Basin	40	40	0	0	9	12	19	001	25.1	0.681	99.9%	1
Malay Basin (all)	26	25	1	0	1	7	18	168	24.4	0.696	99.9%	1
Central Sumatra	30	30	0	1	7	7	15	040	34.2	0.491	99.9%	1
South Sumatra	9	9	0	3	1	2	3	048	26.9	0.644	97.5%	3
Nam Con Son	5	4	1	0	5	0	0	043	19.6	0.791	95.0%	4
Cuu Long Basin	5	3	2	4	1	0	0	172	1.8	0.998	99.9%	1
Baram Shelf Edge	5	4	1	0	0	0	5	034	15.2	0.868	97.5%	2
Baram Inner Shelf	26	21	5	1	6	4	15	127	24.4	0.695	99.9%	1
Deepwater Baram	9	9	0	0	2	1	6	122	14.9	0.873	99.9%	1
Kutei Basin	7	7	0	0	0	7	0	137	7.1	0.97	99.9%	1

Figure 1

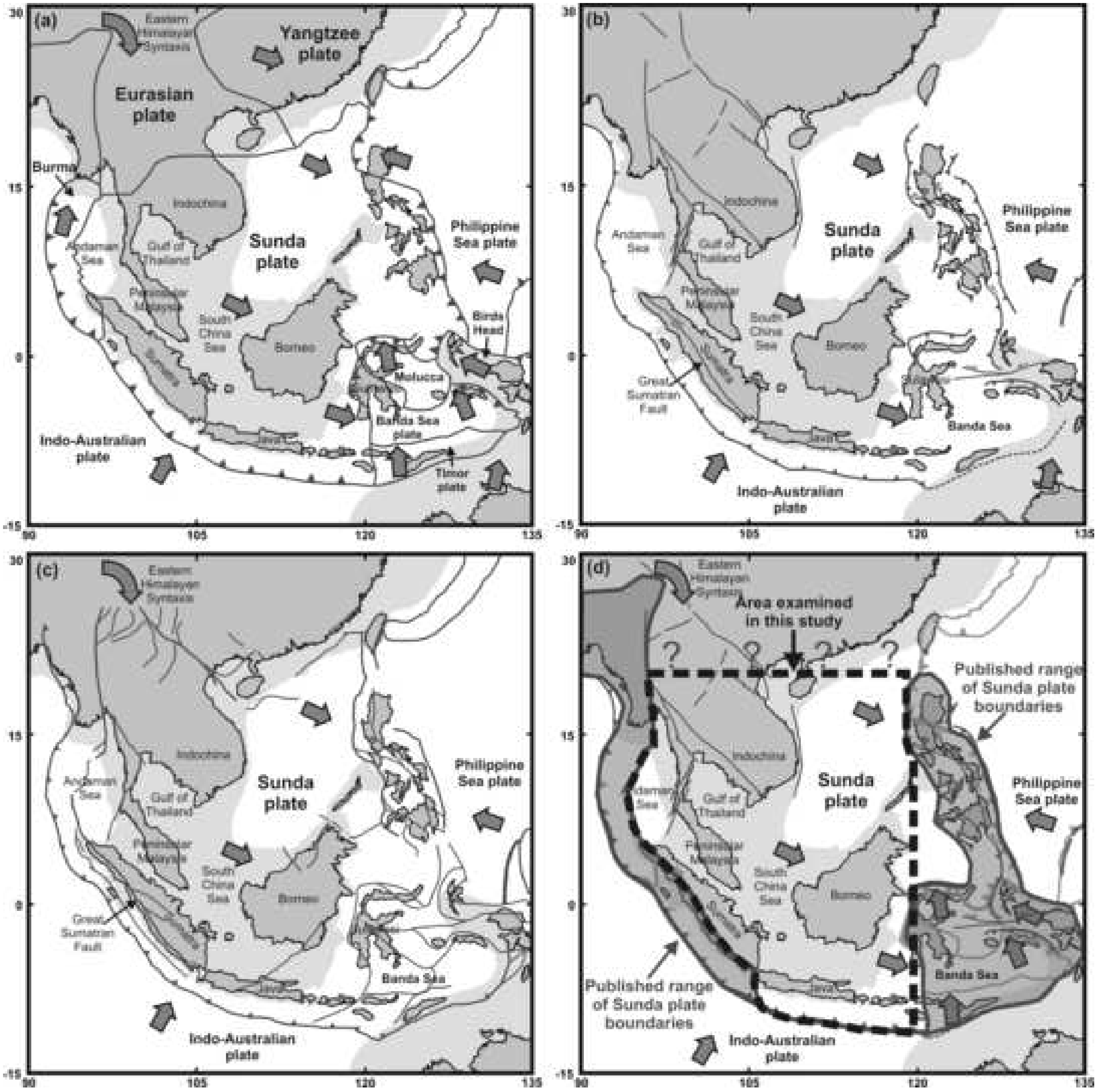

(a)
Eastern Himalayan Syntaxis
Yangtzee plate
Eurasian plate
Burma
Indochina
Andaman Sea
Gulf of Thailand
Sunda plate
Philippine Sea plate
Peninsular Malaysia
South China Sea
Borneo
Sumatra
Birds Head
Molucca
Banda Sea plate
Java
Timor plate
Indo-Australian plate
(b)
Indochina
Andaman Sea
Gulf of Thailand
Sunda plate
Philippine Sea plate
Peninsular Malaysia
South China Sea
Borneo
Great Sumatran Fault
Banda Sea
Java
Indo-Australian plate
(c)
Eastern Himalayan Syntaxis
Indochina
Andaman Sea
Gulf of Thailand
Sunda plate
Philippine Sea plate
Peninsular Malaysia
South China Sea
Borneo
Great Sumatran Fault
Banda Sea
Java
Indo-Australian plate
(d)
Eastern Himalayan Syntaxis
Area examined in this study
?
?
?
?
Published range of Sunda plate boundaries
Indochina
Andaman Sea
Gulf of Thailand
Sunda plate
Philippine Sea plate
Peninsular Malaysia
South China Sea
Borneo
Sumatra
Banda Sea
Java
Published range of Sunda plate boundaries
Indo-Australian plate
30
15
0
-15
90
105
120
135

Figure 2

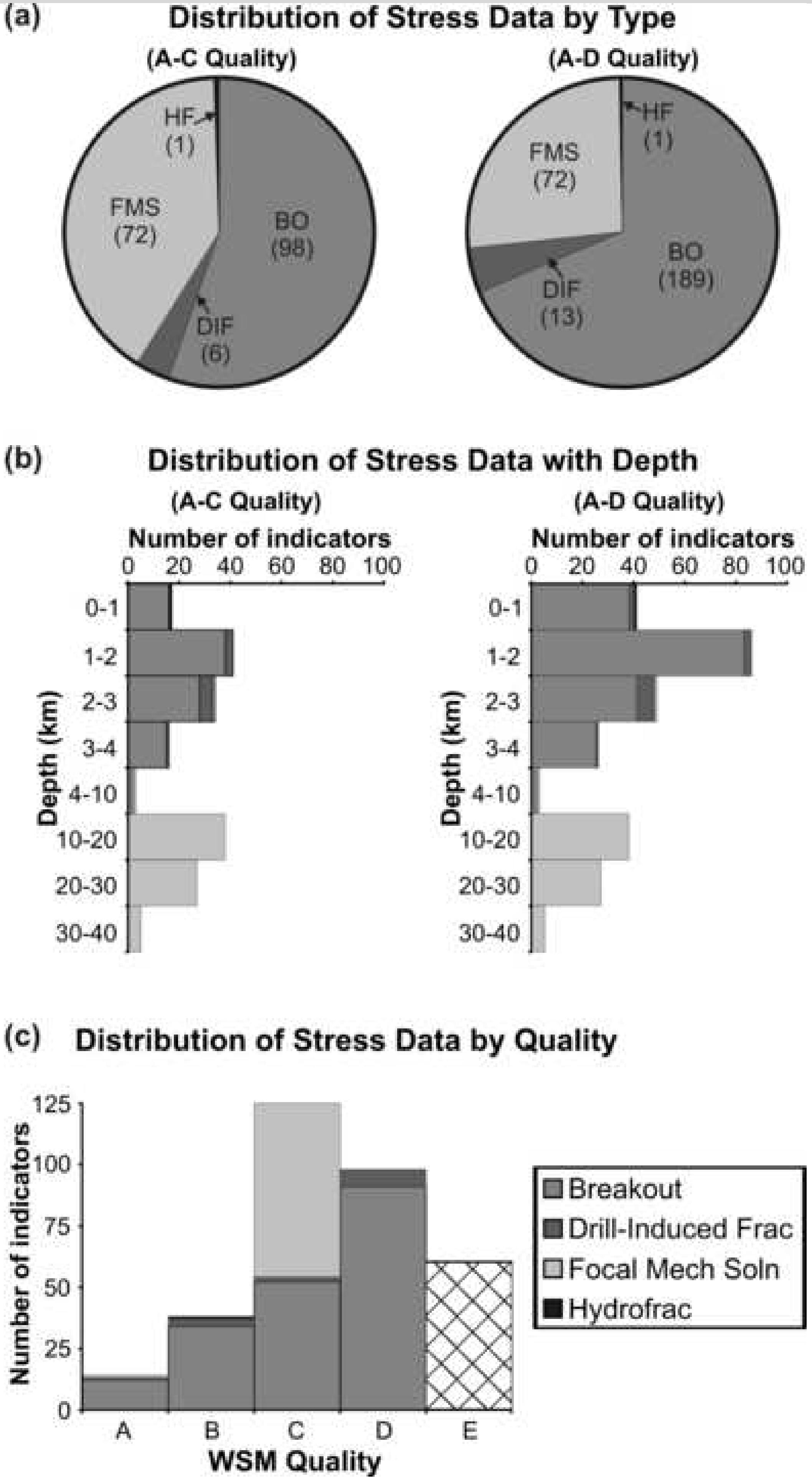

(a)
Distribution of Stress Data by Type
(A-C Quality)
HF (1)
FMS (72)
BO (98)
DIF (6)
(A-D Quality)
HF (1)
FMS (72)
BO (189)
DIF (13)
(b)
Distribution of Stress Data with Depth
(A-C Quality)
Number of indicators
0 20 40 60 80 100
Depth (km)
0-1
1-2
2-3
3-4
4-10
10-20
20-30
30-40
(A-D Quality)
Number of indicators
0 20 40 60 80 100
Depth (km)
0-1
1-2
2-3
3-4
4-10
10-20
20-30
30-40
(c)
Distribution of Stress Data by Quality
Number of indicators
0
25
50
75
100
125
A
B
C
D
E
WSM Quality
Breakout
Drill-Induced Frac
Focal Mech Soln
Hydrofrac

Figure 3

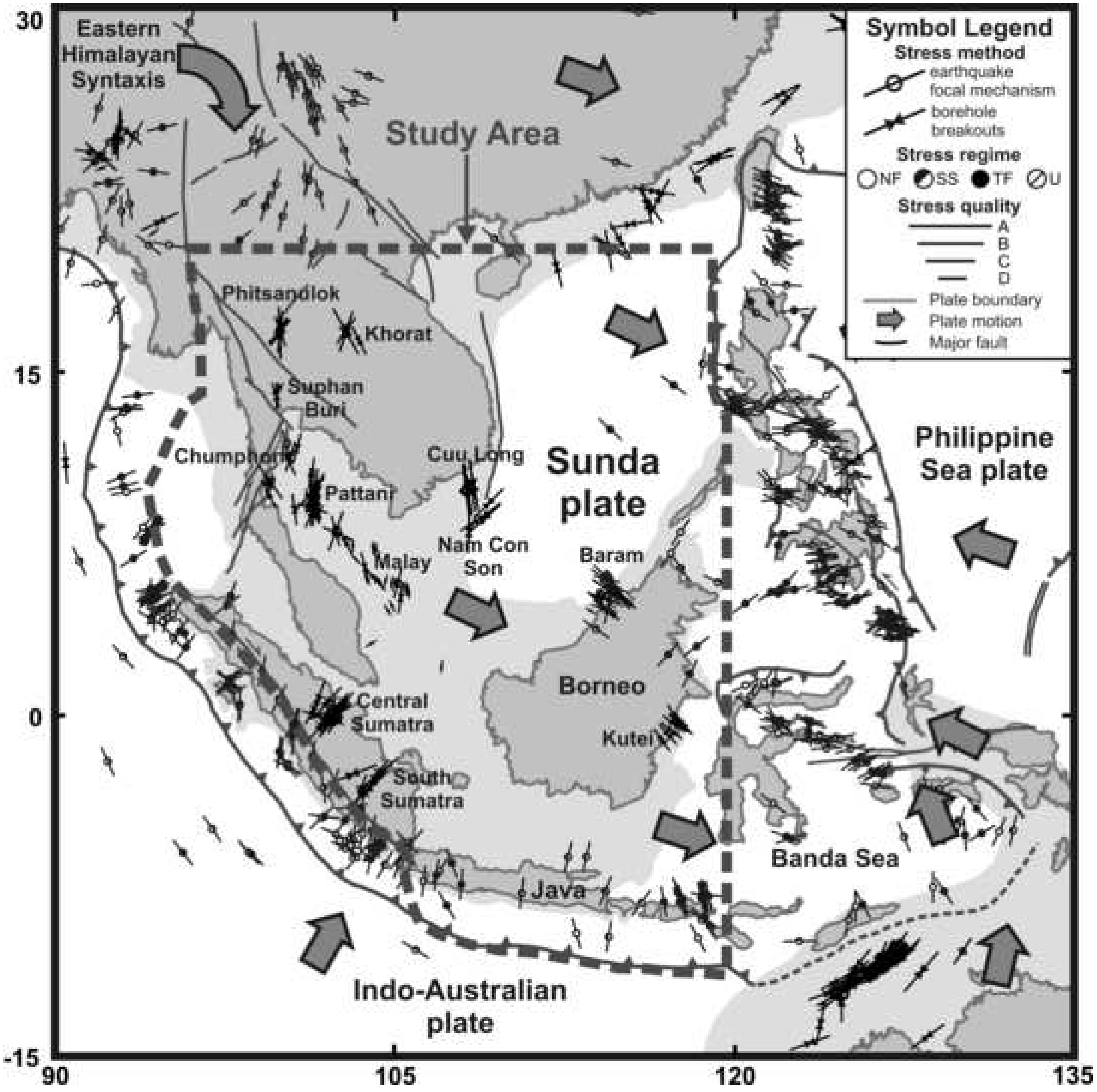

Eastern Himalayan Syntaxis
Study Area
Symbol Legend
Stress method
earthquake focal mechanism
borehole breakouts
Stress regime
NF
SS
TF
U
Stress quality
A
B
C
D
Plate boundary
Plate motion
Major fault
Phitsandlok
Khorat
Suphan Buri
Chumphon
Pattani
Cuu Long
Sunda plate
Nam Con Son
Baram
Malay
Philippine Sea plate
Borneo
Kutei
Central Sumatra
South Sumatra
Java
Banda Sea
Indo-Australian plate
30
15
0
-15
90
105
120
135

Figure 4

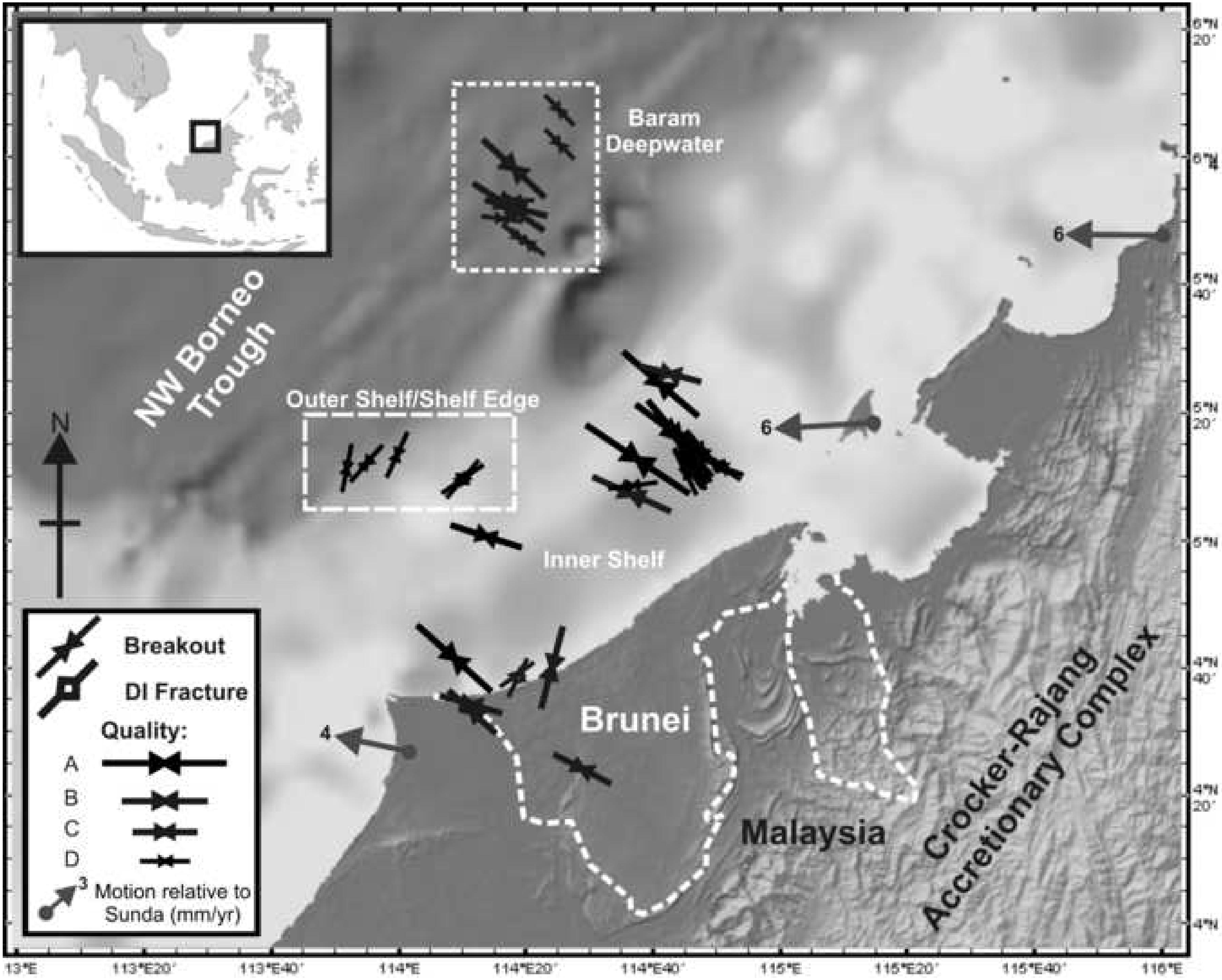

Baram
Deepwater
NW Borneo
Trough
Outer Shelf/Shelf Edge
N
Inner Shelf
Brunei
Malaysia
Crocker-Rajang
Accretionary Complex
6
6
4
Breakout
DI Fracture
Quality:
A
B
C
D
3
Motion relative to Sunda (mm/yr)
6°N 20'
6°N
5°N 40'
5°N 20'
5°N
4°N 40'
4°N 20'
4°N
13°E
113°E20'
113°E40'
114°E
114°E20'
114°E40'
115°E
115°E20'
115°E40'
116°E

Figure 5

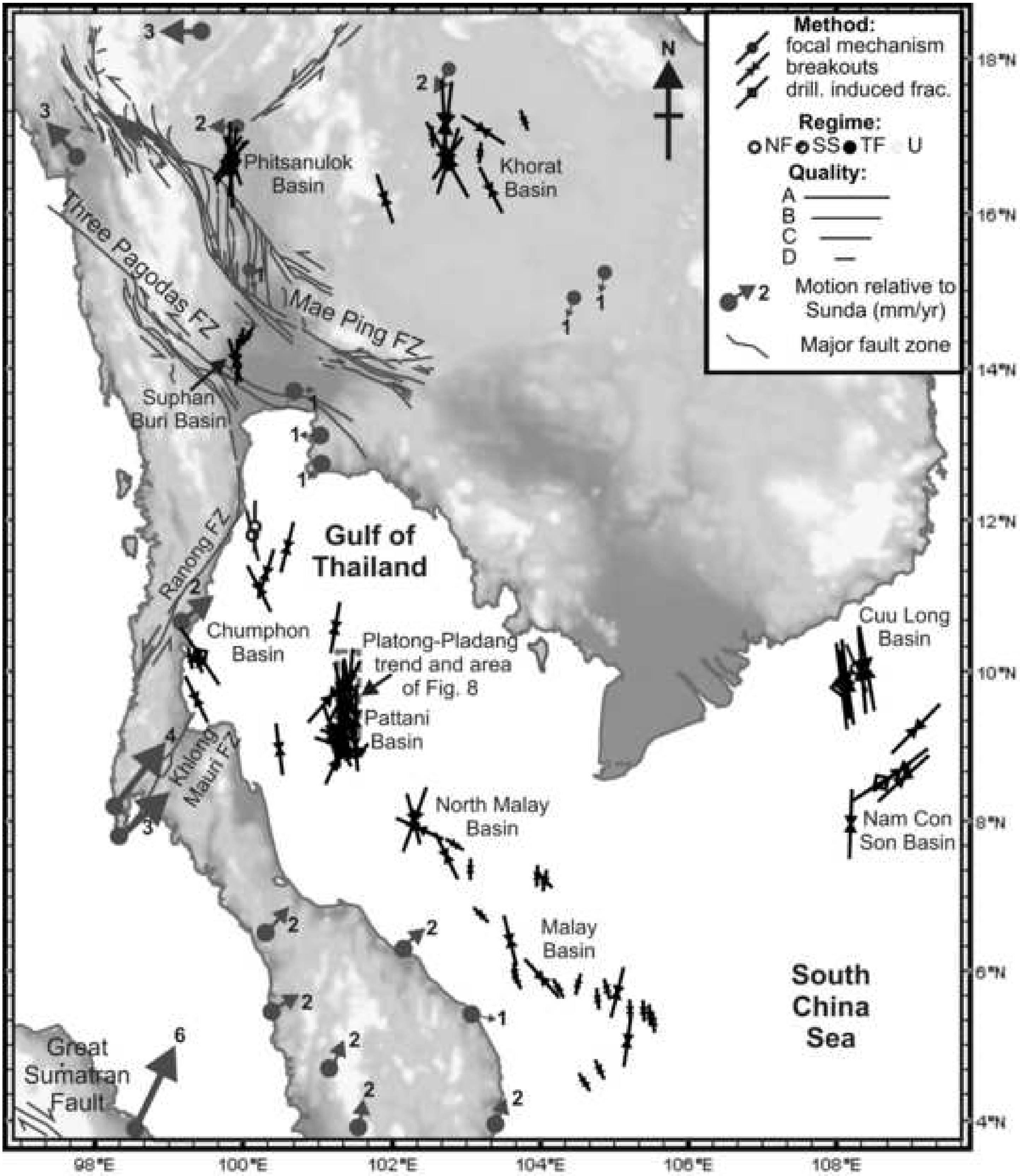

Method:
focal mechanism
breakouts
drill. induced frac.
Regime:
○ NF ● SS ● TF ● U
Quality:
A
B
C
D
Motion relative to Sunda (mm/yr)
Major fault zone
N
Phitsanulok Basin
Khorat Basin
Three Pagodas FZ
Mae Ping FZ
Suphan Buri Basin
Gulf of Thailand
Ranong FZ
Chumphon Basin
Platong-Pladang trend and area of Fig. 8
Pattani Basin
Khlong Marui FZ
North Malay Basin
Malay Basin
Cuu Long Basin
Nam Con Son Basin
South China Sea
Great Sumatran Fault
18°N
16°N
14°N
12°N
10°N
8°N
6°N
4°N
98°E
100°E
102°E
104°E
106°E
108°E

Figure 6

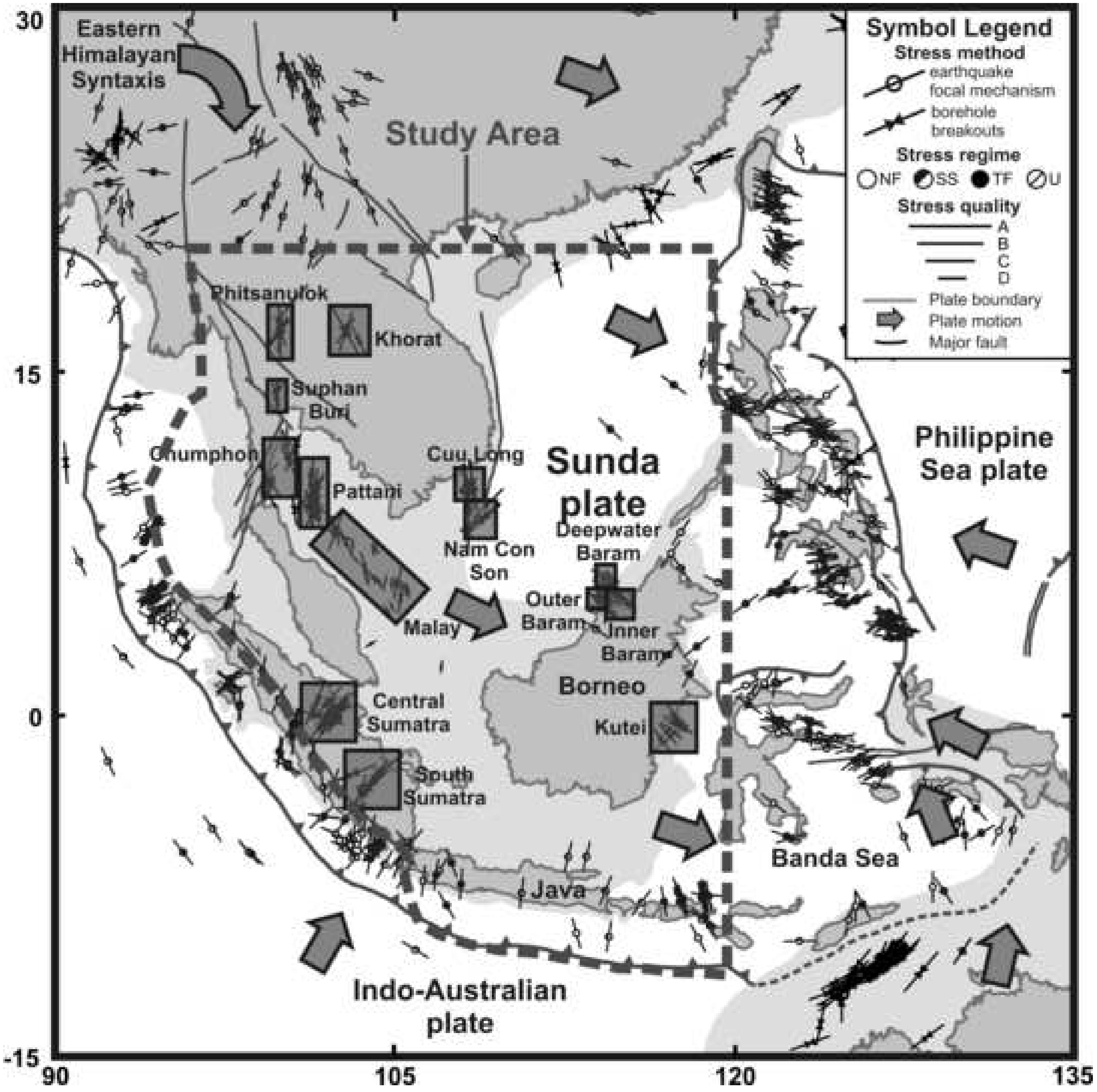

Eastern Himalayan Syntaxis
Study Area
Symbol Legend
Stress method
earthquake focal mechanism
borehole breakouts
Stress regime
NF
SS
TF
U
Stress quality
A
B
C
D
Plate boundary
Plate motion
Major fault
Phitsanulok
Khorat
Suphan Buri
Chumphon
Pattani
Cuu Long
Nam Con Son
Malay
Sunda plate
Deepwater Baram
Outer Baram
Inner Baram
Borneo
Kutei
Central Sumatra
South Sumatra
Java
Banda Sea
Philippine Sea plate
Indo-Australian plate
30
15
0
-15
90
105
120
135

Figure 7

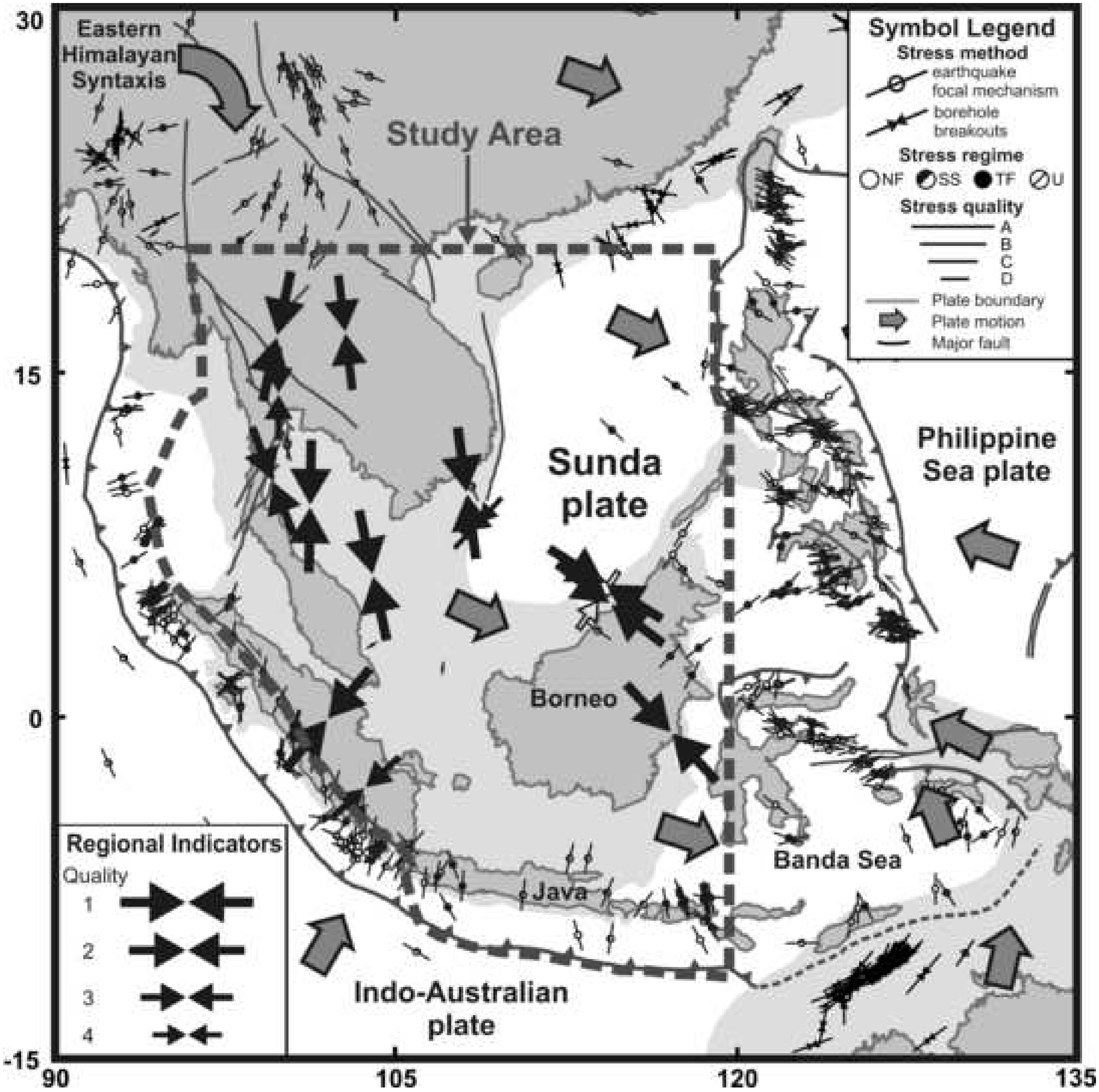

30
15
0
-15
90
105
120
135
Eastern Himalayan Syntaxis
Study Area
Sunda plate
Philippine Sea plate
Borneo
Java
Banda Sea
Indo-Australian plate
Symbol Legend
Stress method
earthquake focal mechanism
borehole breakouts
Stress regime
NF
SS
TF
U
Stress quality
A
B
C
D
Plate boundary
Plate motion
Major fault
Regional Indicators
Quality
1
2
3
4

Figure 8

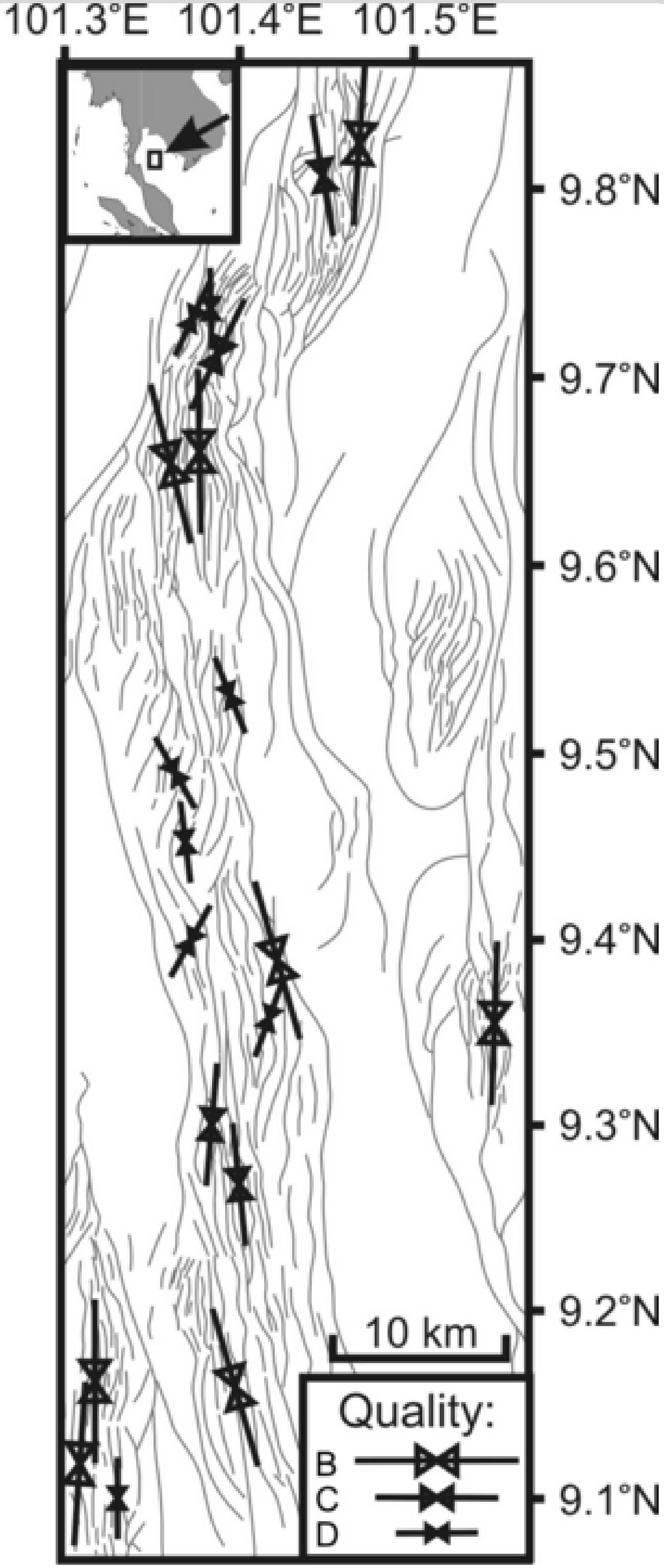
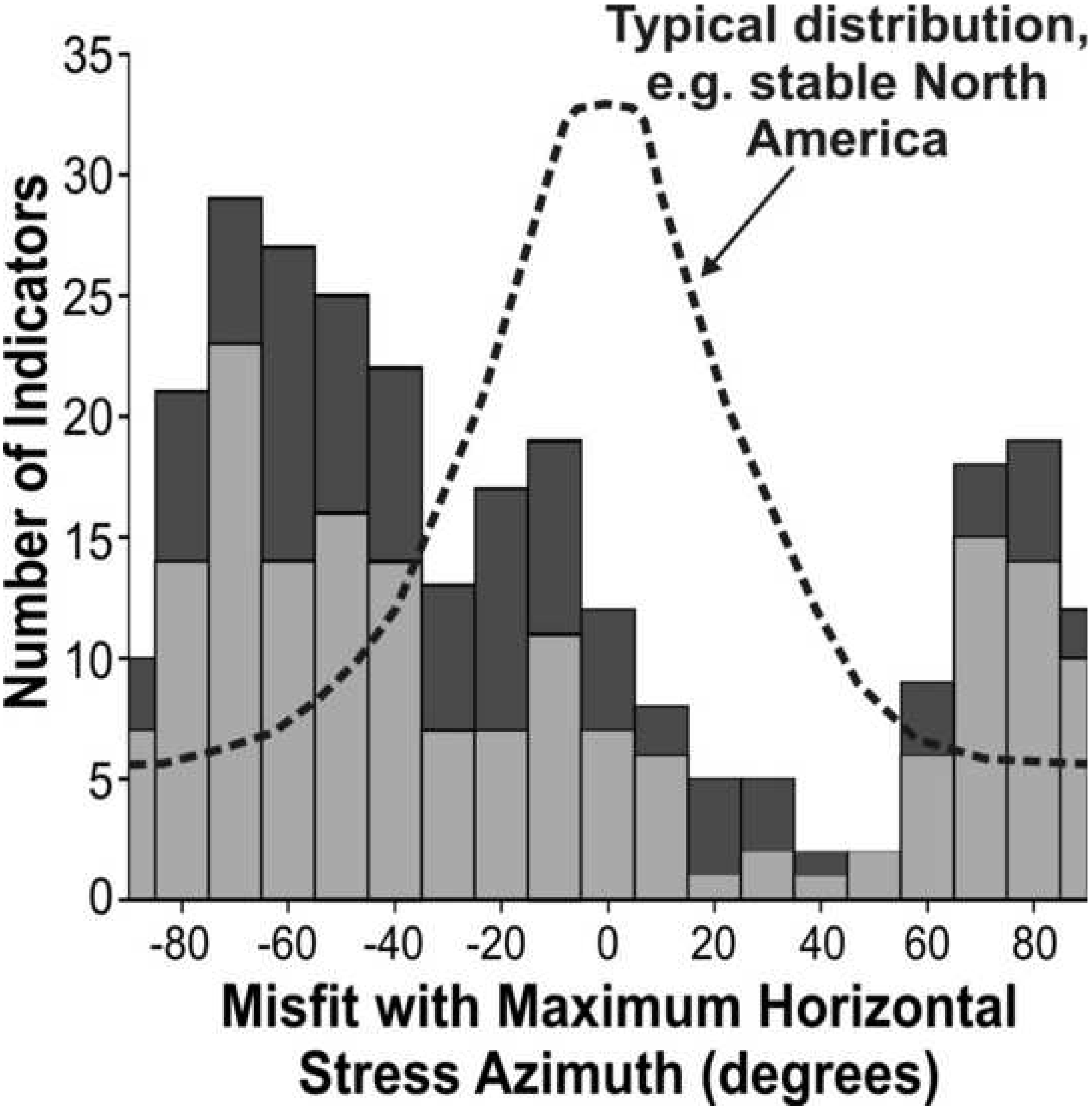

101.3°E
101.4°E
101.5°E
9.8°N
9.7°N
9.6°N
9.5°N
9.4°N
9.3°N
9.2°N
9.1°N
10 km
Quality:
B
C
D

Figure 9


Typical distribution,
e.g. stable North
America
Number of Indicators
35
30
25
20
15
10
5
0
-80
-60
-40
-20
0
20
40
60
80
Misfit with Maximum Horizontal
Stress Azimuth (degrees)