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Active tectonics and active faults: Why these terms still lack consensus on definitions

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Abstract: The terms*: Active tectonics* and *active faults* have emerged as some of the most frequently used terms in geological literature, and traditionally, the main purpose of these definitions has historically remained devoted to either geological or engineering uses. However, most of the existing literature on the definitions has been gathered since >230 years that were spent on the understanding of the science of earthquakes, but a clear-cut consensus lacks on how to define *active tectonics* and *active faults,* for various reasons that are discussed at length here. Therefore, this paper presents a brief overview of the terms with a motivation to rekindle the discussion on what is considered active in tectonics. It also explores whether the traditional definitions are valid or not, and should we look for other alternatives. We present a brief historical background knowledge and understanding on the active faults, and particularly in some of the tectonically stable and presumably inactive portions of the Earth's crust. The two major strike-slip faulting events (Mw 8.6 and Mw = 8.2) that have occurred in the Wharton Basin, Indian Ocean in 2012 are discussed in detail. The events are specially quoted to make a case for reactivation of old fracture systems as these earthquakes ruptured the ~30-90 Ma old Indian oceanic crust. This clearly demonstrates that much older geological structures could also be re-activated, thereby questioning the traditional definition of the typical time span that is used to define *active tectonics* and *active faults*.

Keywords: Active tectonics, active faults, earthquakes, Wharton Basin

INTRODUCTION

Active tectonics is perhaps one of the most discussed subjects of Earth sciences in public domains as it is directly involved in the study of earthquakes and volcanoes, which have historically interacted with human societies and have caused considerable damage and destruction of life and property (e.g. Taylor & Yin, 2009; Marano *et al*., 2010; Malik *et al.*, 2007). Therefore, these hazards have a special place in the known written accounts of human history, mythology, and other similar tales**.** The continuous interference relationships of these hazards have forced humans to carve deeper in the scientific domains to master the processes that cause the formation of the faults with an underlying motivation to understand science and to secure life. The progression of scientific wisdom perhaps started much earlier, but the All Saints Day earthquake that considerably damaged Lisbon, Portugal on the 1st November 1775 is regarded to have laid the foundation of modern Seismology. However, after spending more than 230 years in the understanding of the science of earthquakes we are yet to reach a global consensus on how to define *active tectonics* and *active faults*. This is challenging because when educators and researchers teach students or the public about the science of active tectonics they are often overly involved in an examination of a plethora of definitions, and importantly none has attained the status of a formal definition that could be universally accepted. Therefore, we intend to rejuvenate this important discussion to brush our scientific curiosity to know more about the active tectonics, and whether we should work on a formal definition or not. The motivation is to present a concise scientific understanding of the topic by having deliberations on the nitty-gritty of the terms.

A BRIEF HISTORICAL JOURNEY OF EARTHQUAKE SCIENCES AND THE EMERGENCE OF *ACTIVE TECTONICS*

The deadliest earthquake ever recorded in the human historical past is the M8 1556 Huaxian earthquake that occurred in Shaanxi Province, China, and caused an estimated loss of 830,000 people (Kuo, 1957). This could mean that the scientific wisdom on the occurrences of earthquakes would have started much earlier, and perhaps immediately after this quake but the Lisbon earthquake of November 1, 1775, is considered to have stirred the developments of the modern seismology (e.g. Shah *et al*., 2019). The earthquake struck on All Saint's Day and caused death that varies from 12,000 to 90,000, but ~12,000 is considered a reliable estimation (Chester & Chester, 2010). It was Robert Mallet, an Irish engineer who studied earthquakes, and worked on the 1857 Neapolitan earthquakes, and later laid the foundations of modern observational seismology. The scientific understanding of the cause of earthquakes led him to suggest in 1862 that earthquakes are results of "the breaking up and grinding over each other of rock beds".

This legacy was later renewed by Suess (1875), who was the first to suggest that "Earthquakes occur along lines of tectonic movement in a mountain system". Subsequently, in the 1880s, an American geologist, G. K. Gilbert studied the 1872 Owens Valley earthquake and argued that "when an earthquake occurs, a part of the foot slope goes up with the mountain and another part goes down relatively with the valley. It is thus divided and a little cliff marks the line of division. This little cliff is in geologic parlance, a fault scarp". The Mino-Owari earthquake of 1891 in Japan and the 1906 San Francisco earthquake of the United States are perhaps the important events which were studied in detail to record and understand the ground truth. However, the 1906 event was studied in greater detail by prominent scientist H. F. Reid, a professor of Geology at Johns Hopkins University at that time. It was this event that laid the foundations of the Elastic Rebound Theory (Reid, 1910), which is the popular explanation on the cause of earthquakes. The occurrence of earthquakes is therefore related to the accumulation of elastic strain, which is released when rocks slip along a fault during an earthquake (co-seismic event), and it accumulates when rocks are stuck during the inter-seismic periods: the process known as "stick-slip mechanism". Such a process occurs and recurs during a typical lifecycle of a fault, and active tectonics constitutes a branch of earth sciences that studies the details of the seismic cycle (e.g., McCalpin, 2009; Burbank & Anderson, 2011; Ren *et al*., 2018).

DEFINITIONS OF ACTIVE TECTONICS AND ACTIVE FAULTS

The available published literature on the terms *active tectonics* and *active faults* broadly suggest that the major purpose of these definitions has historically remained devoted to either geological or engineering uses (Wood, 1916; Willis, 1923; Sowers *et al*., 1998). And before 1950 only three definitions of active tectonics were known to exist, but that dramatically changed over the years with one account arguing for more than 30 known definitions (National Research Council and Geophysics Study Committee, 1986). The requirement of having a formal definition is usually encouraged as it becomes an easy tool to communicate the importance of a new term or phrase, and for *active tectonics*, the demand was more so because earthquakes directly impact life. And it is an important step towards our understanding on earthquake forecasting and eventual prediction, which in turn are directly linked to urban, rural, social, economic and other similar developments (e.g. Wu & Hu, 2019). Currently, there are many more known definitions on *active tectonics* and *active faults* that are adapted by various agencies throughout the world (e.g. Slemmons & McKinney, 1977; Keller & Pinter, 1996; Wu & Hu, 2019) but none has yet been universally accepted. A detailed look at these definitions reveals a major problem about time: for example, a number of public agencies have created active fault databases and have defined *active faults* with displacements in 10k, 35k, 150k, and twice in 500k yrs (e.g. Wu & Hu, 2019). Recently, Boschi *et al*. (1996) have proposed a "Consensus Statement" where *"An active fault of interest for Seismic Hazard Assessment is a structure that has an established record of activity in the Late Pleistocene (i.e. in the past 125 ka) and a demonstrable or inferable capability of generating major earthquakes."* Researchers in New Zealand have followed this definition and accordingly an active fault is *"defined as a fault that shows evidence of surface rupture or ground deformation within the last 125,000 years"* (Langridge *et al.*, 2016).

Perhaps the two most popular definitions in geological literature are: (a) *Active tectonics is the ongoing deformation of the earth's surface* (Schumm *et al*., 2002), and (b) *Active tectonics is defined as "those tectonic processes that produce deformation of the earth's crust on a time scale of significance to human society* (Keller & Pinter, 1996). Therefore, a detailed review of these two definitions is presented below to reflect on the current usage and understanding with a motivation to bring new and updated information on the topic. The first definition (a) says it is the *"ongoing deformation"* but what is ongoing has not been specified, and that is one of the major concerns that has always remained an unresolved problem, and for reasons that are discussed below. So the definition lacks a clear-cut time frame. Further, it says *"of the earth's surface"*, which again is difficult to comprehend as the involvement of only the earth's surface during various faulting events is not true and totally questionable. It is a well-established scientific fact that a typical brittle fault may reach more than 12 km of crustal depths, and earthquakes can originate at various crustal levels, and hence the dimensions of fault ruptures also vary vertically, laterally, and horizontally. Some quakes can even penetrate upper mantle depths as well. A look onto the global earthquake data illuminates these veracities of faulting (Figure 1a), and questions any such definition that uses earth's surface as a criterion for active faulting. The moment magnitude (MW) 7.0 and above earthquakes are plotted on the satellite image to show the global distribution of major earthquakes events and the associated depth of fault rupture. These data suggest that major earthquakes have dominantly ruptured plate margins but are also located in the interior regions (Figure 1b). The distribution clearly shows that faults are randomly rupturing, and past earthquakes have ruptured regions that were considered inactive (Figure 1b).

The second definition (b) makes it exclusively centered to Human society, which again is problematic as it will not be used in places where human settlements are missing, for example, Mars, Mercury etc. And the phrase *"significance to human society"* is ambiguous as it does not specify the time limit for human society that could be used for active tectonic research. A typical time constraint on the evolutionary journey of humans from hunter-gatherers to attaining social tendencies, culture, and finally human civilization is a controversial topic (Guo *et al*., 2020) and

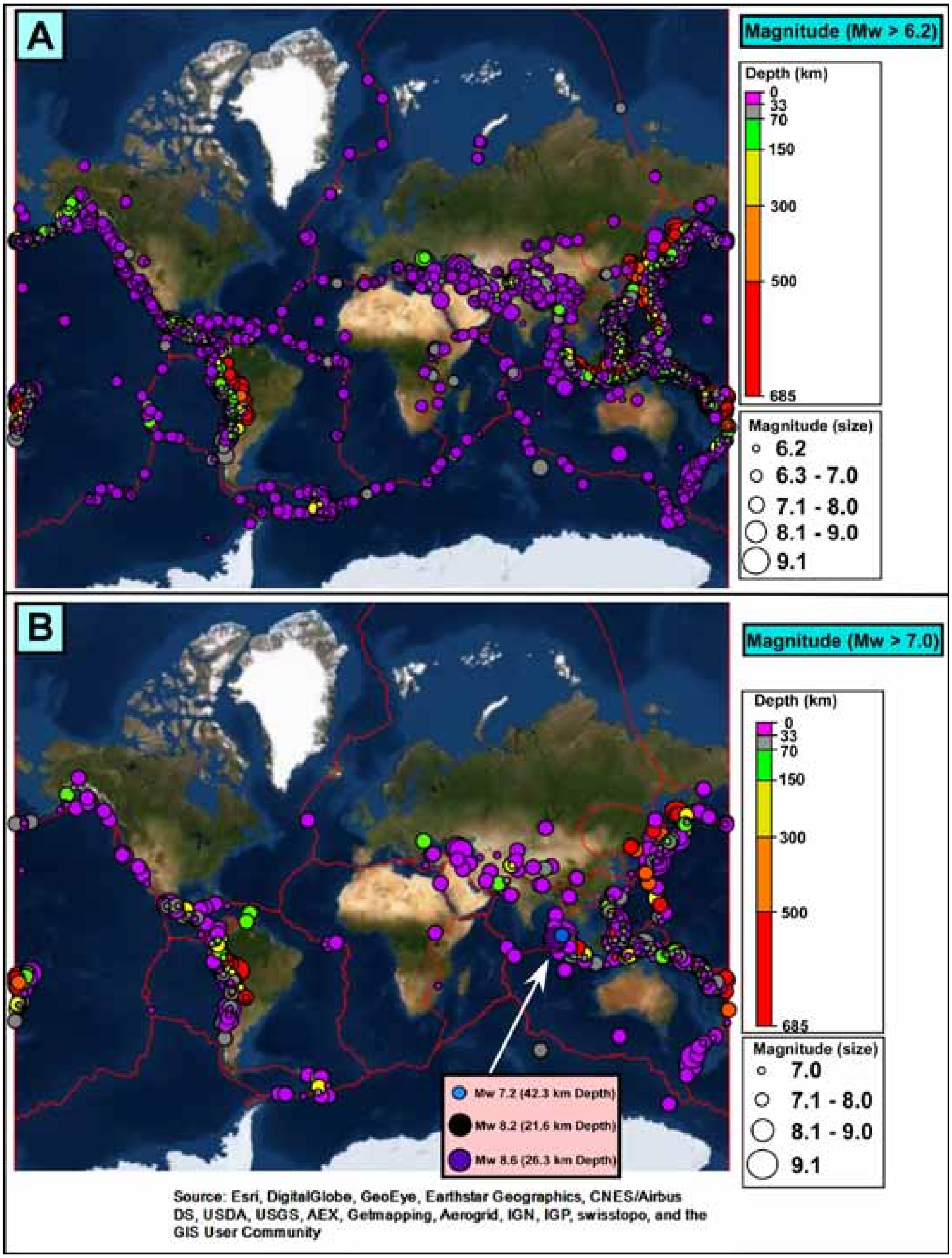

Figure 1: It shows the global satellite image in the background onto which are plotted tectonic plate boundaries (red lines), global seismicity (colour-filled circles) with moment magnitude Mw 6. 2 and above (A), and Mw > 7.0 (B). The three significant earthquakes that have occurred in the Wharton basin are especially highlighted to show the reactivation potential of older oceanic lithospheric faults and fractures, and the need to relook at the problems related to the timing in the definition of *active faults*. The source of the background satellite image, earthquakes, and plate boundaries is shown in the figure.

therefore existing wisdom on this clearly shows that such a topic is not yet properly understood. However, the existing knowledge on the chronology of human history on the planet makes it obvious that civilization is a young process and the traces of early human evolution date back to about 2 to 2.5 million years ago. It took roughly 200,000 years to spread across the globe and by 40,000 years the Homo sapiens attained the status of an intelligent species on earth. The civilization process that perhaps started earlier was not known until about 8,000 years ago when humans grasped the tools and techniques of social and agricultural practices etc. It means it will not be an exaggeration to use 10,000 years to represent human society on our planet.

LITHOLOGY IS NOT ALWAYS A GOOD TOOL TO DIFFERENTIATE ACTIVE FROM INACTIVE FAULTS

The field of active tectonics has grown over the decades and this growth curve is very steep for a typical tectonic geomorphological work where the mapping of active tectonic landforms is routinely investigated using a number of active tectonic features, techniques etc. It includes mapping of displaced and/or ruptured fluvial/glacial terraces, topographic breaks, river channels and marine terraces etc. The relative age relationship between the faulted landforms and lithology is routinely used as a criterion to date the faulting events, which usually involves mapping and measurements of active deformation of Holocene sedimentary deposits (e.g. Jackson & McKenzie, 1984; Nakata, 1989; Sieh & Natawidjaja, 2000; Malik & Nakata, 2003; Shyu *et al*., 2005; Taylor & Yin, 2009; Shah, 2013; Malik *et al*., 2014; Wang *et al*., 2017; Shah & Malik, 2017). However, these relationships may not always work as many faults do not rupture the younger lithological units (Figure 2A). This is illustrated by two scenarios: the first scene shows a reverse fault cutting through a sequence of old and young geological units, which according to the established definitions of an *active fault* will be considered active. The second scenario shows a normal fault that pierces through an older lithology but not through the younger units, and accordingly, this will not be considered active as per the popular definitions (see above). However, both the faults are active as the earthquake could have ruptured both faults recently (say in 2010), and this is the major problem with using lithology as the criteria for active tectonics. The figure also shows the two major strike-slip faulting events (Mw 8.6 and Mw = 8.2) that occurred in the Wharton Basin, Indian Ocean in 2012 (see details below). These events typify how that an old fracture system has been reactivated in the Indian Ocean that has a typical crustal age of ~30-90 Ma (details in Figure 3 and 4). These events demonstrate that old geological structures can be reactivated if the conditions favor the fault reactivation processes, thereby questioning the traditional definition of a typical time span that is used to define active tectonics and active faults. This means that earthquake causing faults and the associated hazards have to be relooked, and older structures have to be particularly watched for reactivation or even birth of new fault zones in apparently tectonically quiescent regions.

DISCUSSION

Why no definition will work for active tectonics and active faults

Active tectonics is a combination of two words: *active*, which means ongoing, and *tectonics* has been derived from the Greek word texts, which means builder. Therefore, active tectonics refers to an ongoing process that builds something at microscopic to megascopic scales. However, the geological significance of *ongoing* is controversial because how do we know where to start. This requires precise information on, for example, paleo-tectonics, strain accumulation/release, rupture dynamics, and other related details, which until now remain largely unresolved. Importantly, it is hard to put a time constraint on faults and classify them as active or inactive because there is increasing evidence to prove that previously inactive faults have also hosted earthquakes, and with the above definitions such faults would have to be considered completely dead. For example, one of the best and recent examples to represent the reactivation of older structures is the occurrence of two major strike-slip faulting events (Mw = 8.6 and Mw = 8.2) in the Wharton Basin (Couturier-Curveur *et al*., 2020), Indian Ocean, SE Asia (Figure 1b). These faults are active and were actively slipping since at least 10 Ma (Stevens *et al*., 2020), and remarkably, earlier studies have shown evidence of fault reactivation in the region to as early as ~14-15.5 Ma with the relatively active occurrence at ~7-8, 4-5 and 0.8 Ma (Krishna *et al*., 2009). There are even suggestions that active faulting could be much earlier (Geersen *et al*., 2015) at ~20 Ma with evidence of reactivated fractures since 40 Ma. The earthquake structural data on these events (Figure 3b) suggest that the faults have occurred along the ~N-S trending fracture zones, which cut through the Indian Oceanic crust of ~30-90Ma old (Figure 4). These fractures are reactivated as strike-slip faults with the angle of fault dip varying from 75° to 80° and the rake angle ranges from 5° to -10° (Figure 3A and 3B). The fracture reactivation mechanism could be related to the variation in the rates of lithospheric plate convergence at the subduction zone where the Indo-Oceanic plate subducts beneath the Sunda plate (Figure 3). These rates have to be higher along the Sunda megathrust (mainly south and southeast portions), and lower at the north and northwest (towards Indian continent). This will reactivate the left-lateral strike-slip system, and if it was otherwise then the right-lateral strike-slip faults will form. The continent-continent collision of India and Eurasia in the north provides a perfect scenario because collision would initiate jamming, and therefore slow convergence rates, as compared to a typical subduction system where plate subduction facilitates easy plate movements.

The active faulting in the Indian Ocean suggests that the traditional scientific wisdom on the definition of *active tectonics* and *active faulting* is problematic, and therefore such a definition may not be an easy scientific task to comprehend. This is visible from the global distribution of earthquakes hypocenters that show faults are actively slipping even in the interior of tectonic plates, which were previously considered stable. Borneo Island is perhaps one of the least tectonically active portions in SE Asia and yet it ruptured a significant portion of a normal fault in Sabah in 2015 that is related to a more than 200 km long active fault system (Wang *et al*., 2017; Shah *et al*., 2018) onto which the historic seismicity records are not well documented, and no paleoseismological records exist. Therefore, a significant variation in recurrence and reactivation of faults is a major hindrance to define *active tectonics* and *active faults*, which are dominantly related to lack of knowledge on a number of unknown parameters that control the fault initiation, growth, and development. For example, lack of knowledge on unknown faults, rupture history, strain partitioning, and precise information on the size of previous earthquake events etc. These are some of

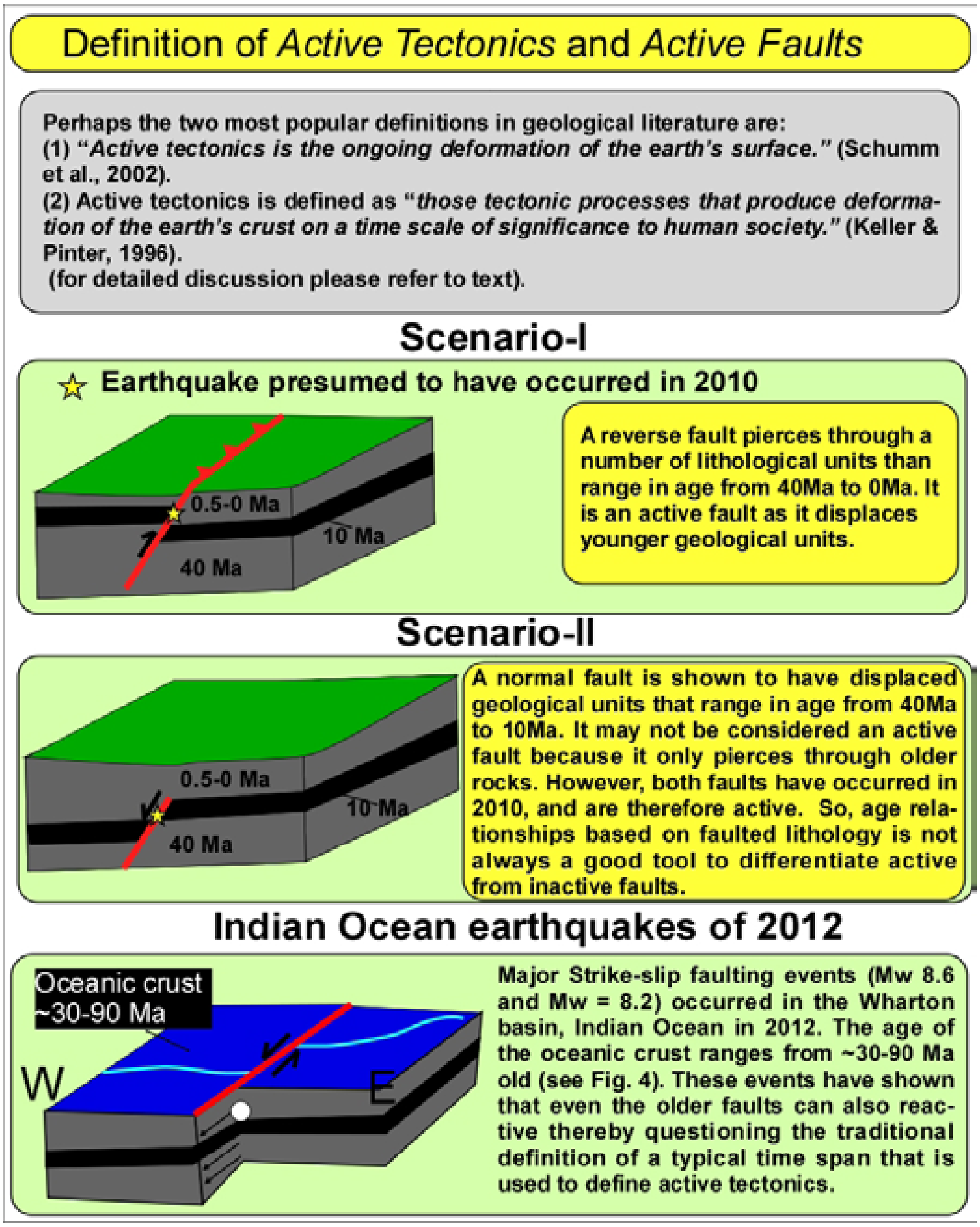

Figure 2: The cartoon shows typical definitions of *active tectonics* and *active faults* and the problems that complicate these definitions (details in text).

the important aspects (not a comprehensive list) that are needed to put tight time constraints on faulting (see Ren *et al*., 2018), which are hard to achieve, and therefore, the present scientific wisdom supports no formal definition for *active tectonics*, and *active faults*. This also reflects that science of earthquakes has to grow many folds before tight time constraints are possible on a particular fault system, and since faults work as a family unit, and are often connected and linked to each other and to tectonics therefore regional tectonics have to be understood in greater details to comprehend the genesis, anatomy, and expression of faults. This has serious implications for earthquakes hazards and existing structural models, and it suggests a thorough review of the existing active fault and earthquake hazard maps with a comprehensive database on faults and not just active faults. This is particularly significant in SE Asia where recent earthquake events in the Indian Ocean have questioned the existing models (Figure 3).

Proposed definitions of active faults

The data shown above suggest that although it is not scientifically valid to define active faults in the light of the problems that are discussed at length here, however the definitions of active faults are helpful for engineering and other similar purposes, therefore, the following classifications may be useful:

Very active faults: The ongoing processes that build structures at various scales (e.g. microscopic, macroscopic

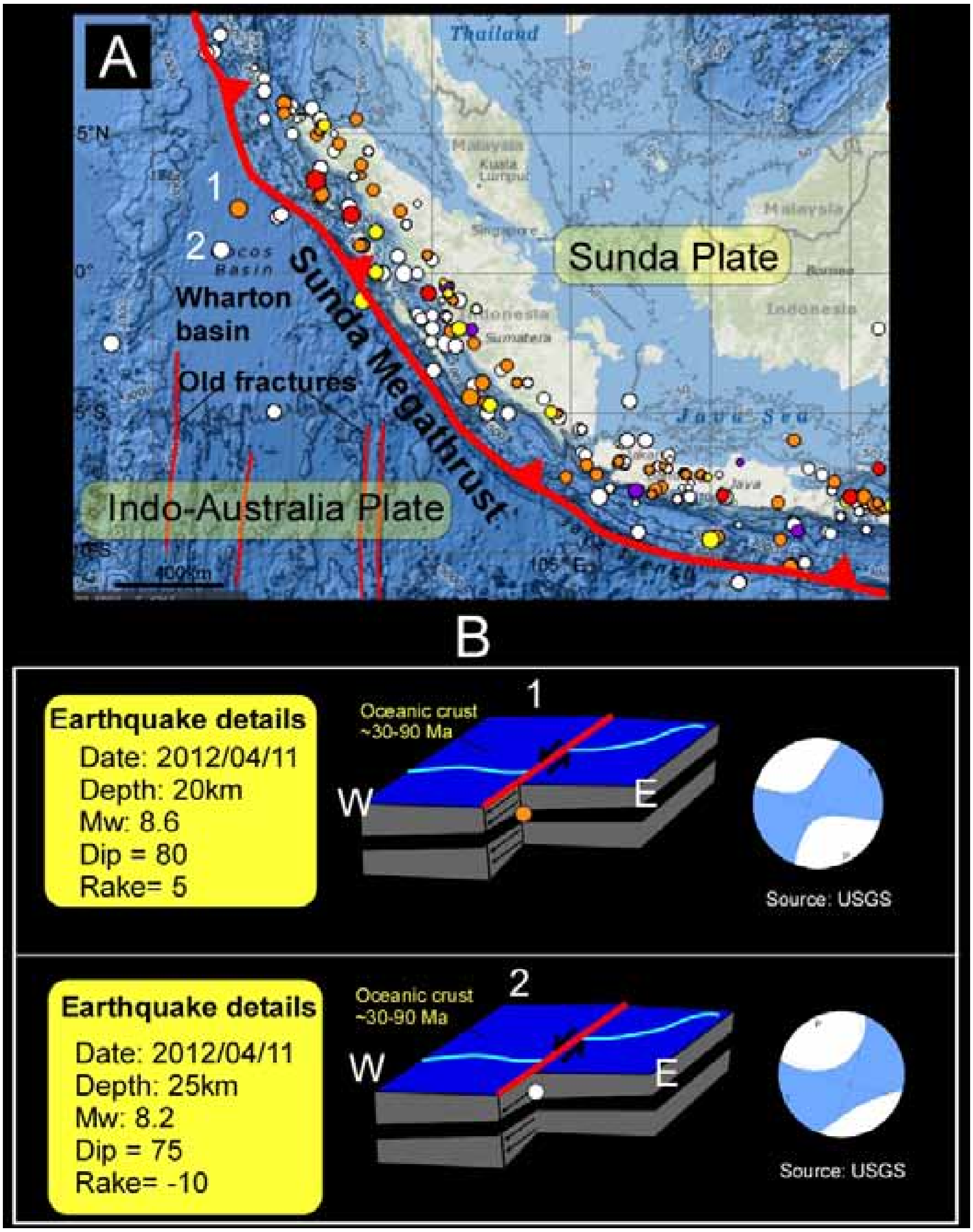

Figure 3: Shows the significant earthquake events and the associated casualties. Colour of the circle indicates the number of deaths (e.g. red indicates a high number of deaths), and the size of the circle indicates the earthquake magnitude. Events labelled as 1 and 2 are the major earthquakes that have occurred in 2012 (b). Figure 3A is prepared from the data obtained on 07 May 2020 from Natural Hazards Viewer of NOAA (2020) and Figure 3B is based on the data from the United States Geological Survey (USGS) web portal.

etc.) and have produced more than one seismic event during the human civilizations (~10,000 yrs).

Moderately active faults; The ongoing processes that build structures at various scales (e.g. microscopic, macroscopic etc.) and have produced at least one seismic event during the human civilizations (~10,000 yrs).

Potentially active faults: The ongoing processes that build structures at various scales (e.g. microscopic, macroscopic etc.) and have produced no seismic event during the human civilizations (~10,000 yrs) but have the potential to host one in future.

CONCLUSIONS

The brief review on the frequently used terms, *active tectonics* and *active faults*, presented above is intended to help readers, and particularly young earthquake scientists to quickly grasp the nitty-gritty and veracity of science behind it. The progress in scientific wisdom together with the new earthquake data that has emerged over the past has helped us to relook at the traditional definitions of active tectonics and active faults, and offer new insights to understand more about these terms. The age of faulting is a concern that remains unresolved to put tight constraints on

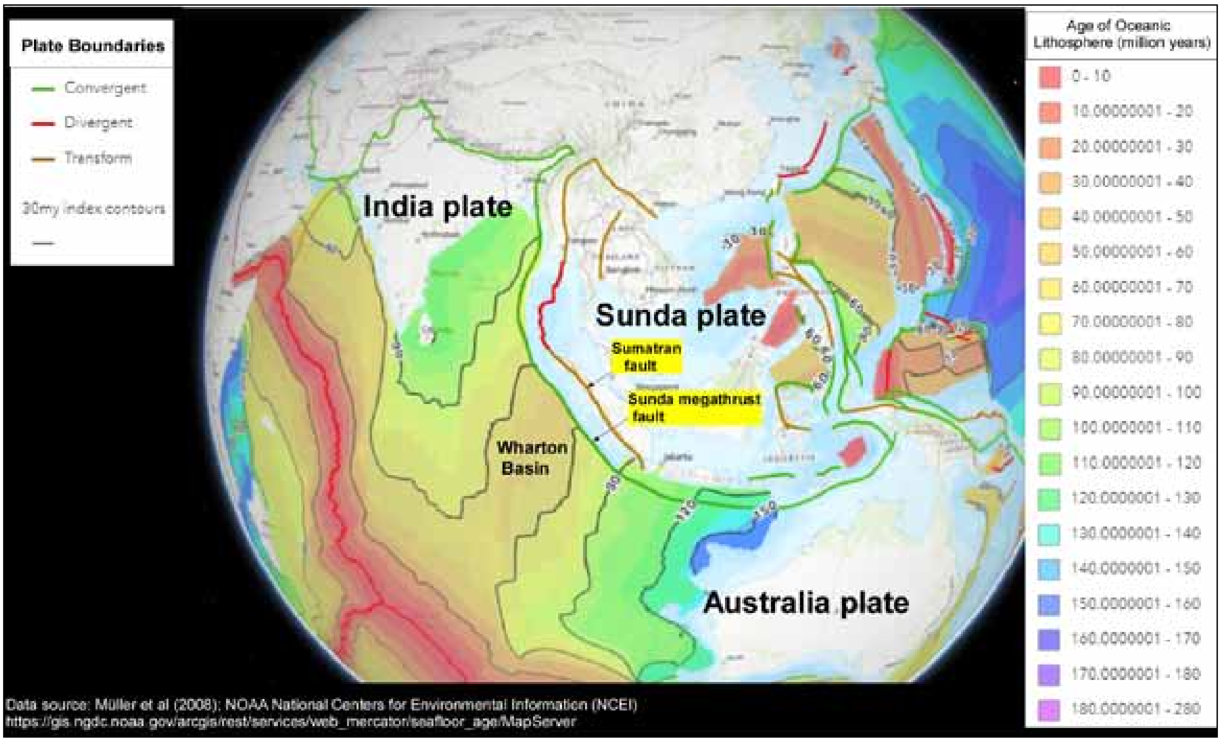

Figure 4: Shows the age of the oceanic crust in South and SE Asia. The two major strike-slip faulting events (Mw 8.6 and Mw = 8.2) that occurred in the Wharton Basin, Indian Ocean in 2012 have ruptured ~30-90 Ma old crust (see Figure 3 for the location of earthquakes).

the definitions, and therefore, the terms cannot be defined with certainty, unless, the aforementioned gaps in data are filled. We need to produce data on faults where all faults, and particularly the major fault systems in the world, are characterized with accuracy. The precise information on formation, evolutionary history and chronology should be added to the dataset to make the faulted Earth dataset a reality, and such a platform could be freely available to users. Once this is achieved it will help us to move forward and understand the behaviors of faults, and what to expect and why, which may open gates to precision, and eventually the earthquake prediction, that has remained unresolved, and challenging for us.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

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