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Indentation of the Philippine Sea plate by the Eurasia plate in Taiwan: Details from recent marine seismological experiments

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ABSTRACT

We analyze in this study a new set of marine data including 3D local tomography, 1992–2008 relocated earthquakes and two recent multichannel seismic lines to characterize the deformation style in the collision area offshore east Taiwan. We have mapped in detail the Mohos of the converging plates as well as the subduction interface with a resolution never reached before. We show that the sharp continental subduction of the Eurasia plate, beneath the middle part of the Central Range, indents the Philippine Sea plate (PSP) as attested by intra-oceanic slicing and incipient subduction of the PSP beneath the east coast of Taiwan. The westernmost part of the PSP slab is probably experiencing a beginning of break-off as attested by NW-trending en-échelon shear zones beneath the southern slope of the southern Ryukyu arc (SRA). These en-échelon shear zones have a sinistral component favored by the "collision-free" subduction of the PSP north of 24°30′N. The down-faulting of the subduction interface forms ramps along which earthquakes clusterize. Three M7 subduction earthquakes occurred offshore Suao city along these ramps with a recurrence interval of about 40 years: 1920 M_w7.7, 1963 M_w7.2 and 2002 M_w7.1 events. The 1966 M_w6.0–7.5 earthquakes sequence likely outlines a WNW-ESE left-lateral intra-slab shear zone. The SRA upper plate accommodates the complex geometry and deformation of the subducting PSP through seismic deformation. Shallow high velocities fringing the Luzon volcanic arc (LVA) beneath the Longitudinal Valley and north of the southernmost Ryukyu forearc basins are interpreted as relics of the LVA forearc basement squeezed in the collision zone. Based on the accommodation of a large part of the convergence through shortening within the PSP and the subsequent segmentation of the shallow subduction interface, we consider that the nucleation of a $M_w \geq 8$ earthquake along the southernmost Ryukyu megathrust is unlikely.

1. Introduction

Taiwan represents one of the youngest and most-studied collisional belt in the world (Angelier et al., 1986, 1990; Biq, 1972; Chai, 1972; Chemenda et al., 1997; Ho, 1986; Huang et al., 2006; Lallemand et al., 2001; Lu and Hsu, 1992; Malavieille and Trullenque, 2009; Malavieille et al., 2002; Sibuet and Hsu, 2004; Suppe, 1981, 1984; Teng, 1990, 1996; Teng et al., 2000; Tsai, 1986; Wu, 1970, 1978; Wu et al., 1997). The orogen results from the oblique southeastward subduction of the South China Sea (SCS) rifted margin beneath the northern prolongation of the Luzon volcanic arc (LVA) carried by the Philippine Sea plate (PSP). This view reasonably accounts for the geological observations south of 23°N (i.e., southern third of the island), but north of 23°N, singular features add complexities to this simple setting. First of all, the eastward continental subduction of Eurasia plate (EP) beneath the PSP is orthogonal with the southern Ryukyu subduction system where the PSP subducts northward beneath the EP, both plates interacting at depth beneath the northeastern part of Taiwan island. Secondly, the southern Ryukyu arc (SRA) is presently rifting, resulting in a rapid southward migration of the arc–trench system with respect to the EP (Chinese platform). A large part of this collisional area north of 23°N is submerged

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below deep waters so that its investigation requires marine facilities. Tremendous work has been done since the eighties but the intensity of the deformation encountered east of Taiwan is so high that the geophysical images were unclear and left to contrasting interpretations (e.g., Font and Lallemand, 2009).

To better illuminate the structure and the microseismicity of this complex region, we have conducted a series of local seismological cruises in the frame of the "Ryukyu Arc Tectonics and Seismology" (RATS) Project[1] conducted in parallel with the regional TAIGER Project[2] (Wu et al., 2007b). Preliminary results were published by Klingelhoefer et al. (2012) and Theunissen et al. (2012a). The RATS data allowed us to relocate past seismic events in the region within a new 3D velocity model, giving way to a revised geodynamic interpretation of the region.

Based on the new 3D velocity model and earthquakes relocation, as well as two new multichannel seismic lines, the remaining questions that we address in this study are the following: how does the PSP accommodate the increasing shortening from south to north offshore Taiwan? How are the eastern part of Taiwan and the SRA affected by this deformation? and what is the potential for a great subduction earthquake along the southernmost Ryukyu subduction interface?

2. Geodynamic context and previous work

2.1. Kinematics

The Taiwan mountain belt build up over the «quasi-stationary» (with respect to hotspots) subducting continental lithosphere of the EP. The buttress, against which the orogen grows by addition of crustal units in the foreland, consists of the deformed volcanic edge of the overriding PSP. Near 23°N, two-third of the 8 cm/year of shortening mainly localizes along the thrust deformation front near the western coast of the island and the steeply dipping thrust of the Longitudinal Valley that separates the indenting northern LVA from the growing orogen (Yu et al., 1997) (Fig. 1). The rest of the shortening must be accommodated offshore (Huang et al., 2010; Malavieille et al., 2002; Simoes and Avouac, 2006). Near 24°N, one-third or less of the convergence between the EP and the PSP is accommodated on the island mainly in the Longitudinal Valley. North of 24°N, GPS measurements indicate block rotations and south-eastward extrusion (Hou et al., 2009; Hsu et al., 2009; Lin et al., 2010; Rau et al., 2008; Yu et al., 1997) that necessitates to account for more than 8 cm/year of convergence offshore. The most prominent offshore expression of convergence north of 24°N is undoubtely the WNW-ESE trending southern Ryukyu accretionary wedge, which strikes almost parallel to the direction of EP-PSP convergence (N307°, Seno et al., 1993), and thus cannot be the expression of NW-SE compression. Recent GPS measurements indicate a southward drift of the SRA Japanese islands reaching up to 7 cm/year in Yonaguni (Nakamura, 2004; Nishimura et al., 2004) which makes the convergence in the Ryukyu trench much less oblique and implies a rapid southward trench roll back (Fig. 1). Such motions are very recent since the amount of N-S extension in the southern Okinawa Trough (SOT) has been estimated to 80 km in the last 2 Myr, i.e., about 4 cm/year in average (Kimura, 1985; Letouzey and Kimura, 1986; Sibuet et al., 1998). One would expect N-S transform zones cutting through the arc to accommodate its soutward drift, especially near Taiwan as searched by Lallemand and Liu (1998) or later by Lallemand et al. (1999) but most marine investigations in this sense were unsuccessfull except some indications in the Hoping Basin (Font et al., 2001). Kinematic studies have also shown that the motion of the PSP was more northward or even northeastward before 5 or 8 Ma ago (Faccenna et al., 2009; Hall et al., 1995; Seno and Maruyama, 1984). Lallemand et al. (2001) have proposed that this motion change contributed in the westward migration of the Ryukyu trench across a propagating tear within the EP. The corollary of this is that the present SRA constituted the northern passive margin of the (now subducted) SCS prior to the westward migration of the Ryukyu trench (Fig. 2). The former northward motion of the PSP along its western convergent boundary is probably responsible for the steepness of the subducting SCS as seen on global tomographic sections (Lallemand et al., 2001) despite the rapid rollback that the Manila trench encounters since the change of plate motion. Indeed, highly oblique subduction zones such as Andaman, West Aleutian or South-Mariana are all associated with steep slabs.

The revised subduction obliquity along the southern Ryukyu trench, that accounts for the southward drift of the SRA, is still of the order of 50° with respect to trench normal west of 122°40′E. The revised subduction rate in the direction of convergence presently reaches 14 cm/year with a trench-normal component of 9.3 cm/year and a trench-parallel component of 10.5 cm/year. Previous studies have shown that the high subduction obliquity was responsible for trench-parallel stretching within the forearc basins and strain partitioning at the scale of the accretionary wedge (Lallemand et al., 1999). No strain partitioning at the scale of the SRA basement was evidenced yet as previously suggested by Kao et al. (1998). Instead of that, WNW-ESE sinistral transcurrent faulting was evidenced during the 1966 seismic crisis that included one M_w7.5 earthquake and three $6.0 \leq M_w \leq 6.2$ aftershocks occurring below the south-facing Ryukyu arc slope southwest of Yonaguni island (Wu, 1978) whereas dextral strike-slip faulting is expected in case of strain partitioning compatible with the present subduction obliquity. All four events aligned along the NW-SE left-lateral nodal plane (see Fig. 1).

2.2. Seismicity

The seismicity rate is extremely high on, or east and south of, Taiwan even if no historical M_w8 earthquake was recorded by the local seismic network (Theunissen et al., 2010). In 1998, Kao, based on a study of historical earthquakes, said that it was inconclusive whether a $M > 8$ event may occur or not in and around Taiwan. In terms of distribution, both Benioff zones are clearly visible east of 121°30′E for the PSP slab and south of 23°N for the SCS slab. Many authors consider that the SCS slab, despite the absence of Benioff zones north of 23°N, still extends until at least 24°N (Fig. 2) or even more northward, based on global or local tomography (Lallemand et al., 2001; Ustaszewski et al., 2012; Wang et al., 2006; Wu et al., 1997). Seismicity concentrates in some very active areas such as the Foothills in the western part of the orogen (e.g., 1999 M_w7.6 Chichi Earthquake), the Coastal Range which is an extinct segment of the LVA colliding with the orogen (e.g., 1951 M_w7 earthquakes triplet), the coastal region north of the Coastal Range is also extremely seismic as well as the E-W-trending South Okinawa rift valley near 24°45′N. One puzzling feature is the clustering of earthquakes in the SRA forearc. Instead of showing a classical pattern of seismogenic zone extending from ≈10–20 km to ≈50–60 km in depths (e.g., Heuret et al., 2011; Peacock and Hyndman, 1999), we observe a concentration of earthquakes at shallow depths below the forearc basins. Font and Lallemand (2009) have studied in detail this region by relocating events taking advantage of a new code and 3D velocity model (MAXI; Font et al., 2004) and the joint use of Taiwanese and Japanese land stations. They succeeded to better locate the epicenters of the events but were unsuccessfull in determining accurate depths using only land stations far from the sources. The largest magnitude earthquake never recorded in Taiwan (M_w7.7) occurred within this cluster (Theunissen et al., 2010) that comprises mostly shallow northward dipping thrust faults (Kao et al., 1998). The stress pattern, inversed from focal mechanisms of crustal earthquakes in the region northeast of Taiwan, is complex (Huang et al., 2012; Wu et al., 2010a,b). E-W intra-PSP compression is observed in many places offshore the northern Coastal Range (e.g., 1967 M_w6.8 or 1986 M_w7.3 events) as well as

[1] The RATS Project is part of the Active Tectonics and Seismic Hazard in Taiwan (ACTS) French ANR program.

[2] TAIGER: TAiwan Integrated GEodynamic Research project between US and Taiwanese teams.