Authors' reply to RC #2

We would like to thank the reviewer for the insightful comments.

In this response, we address the main comments raised by Referee 2 (Dr. John Encarnacion).

Referee comments are in black and our responses are in blue.

Page 1 Line 13: Delete "uniquely" and just say "predominant."
We feel that it is indeed unique, especially the occurrence of high-silica boninite. This point is raised by Reagan et al., (2017) as well.

Page 2 Lines 2-4: The statement that Cenozoic subduction initiation (SI) requires pre-existing weak zones or lithospheric collapse is erroneous. All models of SI require a weak zone, even lithospheric collapse.
This statement is a general characterization to differentiate spontaneous and induced SI from plume-induced SI.

Page 2 Lines 9-10: I wouldn't say that the IBM is "the most appropriate locality" to test models of subduction initiation. It might be the most appropriate place to test the Stern and Bloomer-type model, but there are other models as well. Maybe say "one of the most appropriate…"
Sentence modified → "...one of the most appropriate…"

Page 2 Lines 24-25: Cite references for "spontaneous" (e.g., Leng and Gurnis) and "induced" (e.g., Hall et al.) SI that have been replicated by numerical modeling.
These references were cited in the following sentences (original MS page 2 lines 25-29.

Page 2 Line 28: delete semi-colon
Semi-colon deleted.

Page 2 Line 30: Maybe change "unequivocally be attributed" to "uniquely explain."
Sentence modified.

Page 3 Line 1: In discussing the basement complexes of the Philippines, Encarnacion (2004) might be an appropriate paper to cite. (Encarnacion, 2004, Multiple ophiolite generation preserved in the northern Philippines. Tectonophysics.)
Additional references added.

Page 3 Line 17: Change "structurally bound" to "fault-bound" (if that is what is meant by "structurally bound").
Changed to "fault-bound"

Page 3 Lines 21-22: In reference to "terrane docking," I presume the Zambales ophiolite is the terrane. But what is it docking with? (Indeed, what do you mean by "docking"?)
Here terrane docking is used in a way similar to Pubellier et al., (2004). We mean

that by the Pliocene its transport from equatorial positions to its present location probably have ceased. The identity of what Zambales ophiolite “docked with” is still unknown. It may be a composite of the following (1) an ocean basin that predates the South China Sea (pre-2016 there is consensus that this is proto-South China Sea), the vestiges of which are the Jurassic-Cretaceous cherts in the West Luzon Shear Zone of Karig, (1983) and complemented by recent radiolarian studies of Queaño et al., (2017a, 2017b) and (2) the northern extension of the Palawan microcontinental block (based on seismic data, Arfai et al., (2011) speculates that West Luzon Basin west of Zambales ophiolite is partly underlain by continental basement).

Page 3 Line 23: Change “in the westernmost margin” to “just west” of the ophiolite. The Mesozoic cherts are not found in the ophiolite itself, but in mélange-type shear zone material west of the ophiolite.
The limited distribution of these cherts maybe more aptly described with “in the westernmost margin” rather than “just west” of the ophiolite.

Page 3 Line 23-25: Besides Queano et al. 2017, you should also cite Hawkins and Evans (1983) who first described these cherts and Encarnacion (2004) who provides additional description of the shear zone.
Additional references added - Hawkins and Evans (1983), Karig et al., (1986) and Encarnacion (2004).

Page 3 Line 24: The shear zone is not “buried;” it is well-exposed in several places.
Sentence modified

Page 4 Lines 2-4: You might want to note that the idea that the San Antonio massif is a displaced block from the north is disputed by Encarnacion et al. (1999) for lack of convincing evidence.
I re-visited the Encarnacion et al., (1999) paper but I can’t seem to find the lines that dispute idea that the San Antonio massif is a displaced block from the north.
In Encarnacion (2004) page 119, it is stated that “Except for some possible tectonic displacements of locally derived blocks (Yumul et al, 1998) the ophiolite is a coherent slab…”.

Page 4 Line 18: You may want to add that the arc affinity of the Acoje block is also consistent with radiogenic isotope data (Pb, Sr, and Nd), which indicate hydrous fluid enrichment (Encarnacion et al., 1999).
This reference is cited in the discussion section 6.2

Page 4 Line 24: What rock types were the “bedding planes” measured on?
Bedding planes were measured primarily on pillow lavas and tuff breccias.

Page 4 Line 26: Change to “…NW-plunging anticline just south.”
Seems ok to us.

Page 4 Line 28: What does “conjugate intrusive directions” mean? (Intruded into conjugate fractures sets?). Please clarify.
(Dikes with) conjugate intrusive directions pertain to obliquely intruding dikes.

Line 32: Change to “subaqeous fall-out deposits” (?)
Changed.

Page 5 Lines 3-4: Do the terms “Strombolian to Hawaiian fire fountaining” apply to subaqeous/submarine volcanics? I would think not(?) Are these deposits in fact subaerial? If so, that would be a very important finding! It would imply that portions of the Zamabales ophiolite in fact contain what might be actual subaerial island arc crust, which would substantially change the paleogeography of Luzon. Please clarify.
Here we are referring to submarine Strombolian to Hawaiian-type fire fountaining. Sentence is modified and a reference discussing deep submarine pyroclastic eruptions (Head and Wilson, 2003) is added.

Page 5 Line 12: What are the “upright structures”? Sedimentary/volcaniclastic bedding? Please clarify.
“Upright structures” include flattened flow lobes in the summit of the recognized pillow volcano shown in Fig3d (inset).
“Upright” is used in page 5 line 12 to describe the primary igneous structures (emplacement-related) in the synclinal area in a broad sense. It is used in contrast to post-ophiolite emplacement folding affecting the volcanic section and overlying sedimentary sequences.

Page 6 Line 1: Change “12” to “Twelve.” (Avoid numerals at the beginning of a sentence.)
Sentence modified.

Page 6 Line 2: Add “Standard JB-2 and JB-3 …”
Sentence modified.

Page 7 Line 15: Change to “The Cs, Rb, … and Mn contents in …”
Sentence modified.

Page 8 Line 16: Change to “…MORB for most trace elements…”
I think this is not necessary.

Page 10 Line 32: Please add a few words summarizing the general consensus on boninite genesis. (“…there is general consensus on boninite petrogenesis, namely that…”
Sentence modified.

Page 12 Line 3: Change semi-colon to a period.
Sentence modified.

Line 7: Change “Ma” to “Myr.” (You are referring to differences in ages, not a point in time.)
Sentence modified.

Page 13 Lines 2-5: Regarding the paleomagnetic data, do the declinations support a Philippine Sea Plate connection as well? The Philippine Sea Plate has been inferred to have rotated clockwise. There are additional previous paleomagnetic studies (for

example, Fuller et al., 1991, J. Asian Earth Sciences) that appear to demonstrate counterclockwise rotation for Luzon.
Declination-based interpretations of the Cenozoic rotation history of Luzon and Zambales are contentious; Fuller et al., (1991) argues for CCW rotation while McCabe et al., (1987) calls for CW rotation.
As discussed by the Queano et al., (2007), the use of declination data in tectonic models of Luzon and Zambales might be of limited use since the CW and CCW directions cannot be unambiguously ascribed to either local or major plate rotations.

Page 13 Line 20: By “rapid emplacement” do you mean “rapid formation”? If not, what do you mean by “rapid emplacement”?
We do not mean rapid formation. Rapid emplacement is inferred based on the reasoning that juvenile arc magmatism progressed only up to boninite; that it is a case of “failed’ subduction initiation or arrested arc development. On the other hand, the IBM forearc which can be described as a case of “successful” subduction initiation that produced an intra-oceanic arc with calc-alkaline lavas (41-35 Ma) after boninite (48-44 Ma) and proto-arc basalt (52-48 Ma).

Page 13 Line 20: Change to “The timing of the proposed subduction inititation…”
Sentence modified.

Page 13 Lines 21-35 to lines 1-3 of page 14: This section discusses the relationship between the Zambales ophiolite and Eocene (Angat) and Cretaceous ophiolites in the east Luzon area. The authors state that the similarity in ages of the Zambales and Angat ophiolites presented in Encarnacion et al. (1993) “does not necessarily prove and affinity” between the two. But Encarnacion et al. (1993) (and Encarnacion et al., 1999, and Encarnacion, 2004) did not use the ages alone in arguing that the Zambales and Angat ophiolites (and Cretaceous ophiolites) are contiguous (not exotic/allochthonous to each other). The geology and stratigraphy as well are consistent with the Zambales-Angat ophiolite forming adjacent to the Cretaceous ophiolite in the east, which was the main point of Encarnacion et al., 1993 (and reiterated/amplified in Encarnacion, 2004).

We disagree with the interpretations of Encarnacion et al. (1993).

In particular, we invite the reviewer to place the west dipping Cretaceous-Eocene subduction zone east of Sierra Madre that produced a late Cretaceous arc and an Eocene arc-backarc basin pair (presumably the Zambales ophiolite) shown in Fig.12 of Encarnación, (2004) in current global and regional plate reconstructions of SE Asia and the western Pacific region (Wu et al., 2016; Zahirovic et al., 2014, 2016).

Indeed, age constraints were not the sole parameter used in arguing that the Zambales and Angat ophiolites (and Cretaceous ophiolites) are contiguous. But the Eocene volcaniclastic sequence, as shown in Fig.6 of Encarnación, (2004), overlies the Angat (Eocene) and Montalban (Cretaceous) ophiolites and not the Zambales ophiolite. Bachman et al., (1983) notes that there is marked lithological difference between the east and west flanks of the Luzon Central Valley Basin (CVB); he further characterized the CVB as a forearc basin.

Regarding the issues mentioned above, I think suggesting that the Zambales is exotic to east Luzon causes greater problems with the proposed model, because the east Luzon ophiolites and arc crust are in-between the Zambales and the Philippines Sea Plate. In other words, if one wants to separate the Zambales ophiolite from east Luzon, shouldn't it also be separate from the Philippine Sea Plate?

On the contrary, we find no problem if east Luzon ophiolites and arc crust are placed in-between the Zambales ophiolite and the Philippine Sea Plate.
With regards to Zambales ophiolite being "separated" from the Philippines Sea Plate, this is the case in earlier tectonic reconstructions which follows the arc- backarc basin scenario where Zambales ophiolite is alternatively placed east of the Celebes Sea Basin in contact with the western margin of the Philippine Sea Plate (Fig.5 of Rangin et al., 1990a and Plate 2 of Rangin et al., 1990b).

In its present form, the G-Plates based reconstruction in Fig 10b using the unfolded slab data, plate polygons and rotation file of Wu et al. (2016) is actually compatible with Encarnacion (2004) in a broad sense. If Zambales ophiolite was formed by the proposed incipient subduction on the western margin of the Philippine Sea Plate, one can argue that Zambales ophiolite can be contiguous with basement of Luzon and that it is relatively autochthonous (with respect to Luzon) (Encarnación, 2004); albeit highly displaced (relative to its present position) caused by transport along a plate boundary (Pubellier et al., 2004). A back-arc origin for Eocene ophiolites associated with Cretaceous arc in eastern Philippines is compatible with Fig. 10b as well.
Arguments against a backarc basin origin for Zambales are given in section 6.3; the only contention would then be the relationship of Angat to Zambales ophiolite.

Page 14 Lines 5-7: Why is doubly-vergent subduction "feasible"? Please elaborate.

We speculate that the location of Philippine Sea Plate (PSP) in the nexus of Pacific, Indo-Australian and Eurasian plates and their long-term Cenozoic plate motion makes doubly-vergent subduction initiation along its margins feasible. The northwestward translation and clockwise rotation of the Philippine Sea Plate starting in the early Eocene had to be accommodated by the adjoining oceanic domain east of southern Eurasia (e.g. East Asian Sea); hence, its interaction with the oceanic leading edge of the Philippine Sea Plate is expected (Wu et al., 2016; Zahirovic et al., 2016) and likely led to incipient subduction (Fig. 10).

Page 14 Line 29: Change to "By studying the Zambales ophiolite…"
Sentence modified.

Page 14 Line 29: Delete "(SI)"
Deleted.

Page 14 Line 29: It is stated that subduction initiation is a "plate-scale process." I'm not sure what the purpose of this statement is. When is it not a plate-scale process? Please clarify.
The purpose of the statement is to emphasize that subduction initiation may not be localized in the eastern margin of the Philippine Sea Plate. The doubly-vergent SI configuration presented here is distinct from current SI scenarios solely based on the

IBM forearc which mainly focuses on the problem of whether subduction initiation is spontaneous or induced (e.g. Arculus et al., 2016; Keenan and Encarnación, 2016).

Figure 2: The caption should include the references for the ages shown in the figure.
References added.

Figure 2: Page 5 says the 44.1 Ma age is from a sill. This isn't clear or indicated in the stratigraphic column.
It is shown in the stratigraphic column.

Figure 10: In panel "b", what are the diamonds, inverted triangles, and squares?
Captions modified.

References

Arculus, R. J., Ishizuka, O., Bogus, K. A., Gurnis, M., Hickey-Vargas, R., Aljahdali, M. H., Bandini-Maeder, A. N., Barth, A. P., Brandl, P. A., Drab, L., do Monte Guerra, R., Hamada, M., Jiang, F., Kanayama, K., Kender, S., Kusano, Y., Li, H., Loudin, L. C., Maffione, M., Marsaglia, K. M., McCarthy, A., Meffre, S., Morris, A., Neuhaus, M., Savov, I. P., Sena, C., Tepley III, F. J., van der Land, C., Yogodzinski, G. M., Zhang, Z., Keenan, T. E., Encarnacion, J., Arculus, R. J., Ishizuka, O., Bogus, K. A., Gurnis, M., Hickey-Vargas, R., Aljahdali, M. H., Bandini-Maeder, A. N., Barth, A. P., Brandl, P. A., Drab, L., do Monte Guerra, R., Hamada, M., Jiang, F., Kanayama, K., Kender, S., Kusano, Y., Li, H., Loudin, L. C., Maffione, M., Marsaglia, K. M., McCarthy, A., Meffre, S., Morris, A., Neuhaus, M., Savov, I. P., Sena, C., Tepley III, F. J., van der Land, C., Yogodzinski, G. M., Zhang, Z., Keenan, T. E. and Encarnacion, J.: Unclear causes for subduction, Nat. Geosci., 9(5), 338 [online] Available from: http://dx.doi.org/10.1038/ngeo2703, 2016.
Arfai, J., Franke, D., Gaedicke, C., Lutz, R., Schnabel, M., Ladage, S., Berglar, K., Aurelio, M., Montano, J. and Pellejera, N.: Geological evolution of the West Luzon Basin (South China Sea, Philippines), Mar. Geophys. Res., 32(3), 349–362, doi:10.1007/s11001-010-9113-x, 2011.
Bachman, S. B., Lewis, S. D. and Schweller, W. J.: Evolution of a forearc basin, Luzon Central Valley, Philippines, Am. Assoc. Pet. Geol. Bull., 67(7), 1143–1162, 1983.
Encarnación, J.: Multiple ophiolite generation preserved in the northern Philippines and the growth of an island arc complex, Tectonophysics, 392(1–4), 103–130, doi:10.1016/J.TECTO.2004.04.010, 2004.
Fuller, M., Haston, R., Lin, J. L., Richter, B., Schmidtke, E. and Almasco, J.: Tertiary paleomagnetism of regions around the South China Sea, J. Southeast Asian Earth Sci., 6(3–4), 161–184, doi:10.1016/0743-9547(91)90065-6, 1991.
Head, J. W. and Wilson, L.: Deep submarine pyroclastic eruptions: theory and predicted landforms and deposits, J. Volcanol. Geotherm. Res., 121(3–4), 155–193, doi:10.1016/S0377-0273(02)00425-0, 2003.
Karig, D. E.: Accreted terranes in the northern part of the Philippine archipelago, Tectonics, 2(2), 211–236, doi:10.1029/TC002i002p00211, 1983.
Keenan, T. E. and Encarnación, J.: Unclear causes for subduction, Nat. Geosci., 9(5), 338–338, doi:10.1038/ngeo2703, 2016.
McCabe, R., Kikawa, E., Cole, J. T., Malicse, A. J., Baldauf, P. E., Yumul, J. and

Almasco, J.: Paleomagnetic results from Luzon and the central Philippines, J. Geophys. Res., 92(B1), 555, doi:10.1029/JB092iB01p00555, 1987.
Pubellier, M., Monnier, C., Maury, R. and Tamayo, R.: Plate kinematics, origin and tectonic emplacement of supra-subduction ophiolites in SE Asia, Tectonophysics, 392(1–4), 9–36, doi:10.1016/J.TECTO.2004.04.028, 2004.
Queano, K. L., Ali, J. R., Milsom, J., Airchison, J. C. and Pubellier, M.: North Luzon and the Philippine Sea Plate motion model: Insights following paleomagnetic, structural, and age-dating investigations, J. Geophys. Res., 112, 2007.
Queaño, K. L., Marquez, E. J., Dimalanta, C. B., Aitchison, J. C., Ali, J. R. and Yumul, G. P.: Mesozoic radiolarian faunas from the northwest Ilocos Region, Luzon, Philippines and their tectonic significance, Isl. Arc, 26(4), e12195–n/a, doi:10.1111/iar.12195, 2017a.
Queaño, K. L., Dimalanta, C. B., Yumul, G. P., Marquez, E. J., Faustino-Eslava, D. V, Suzuki, S. and Ishida, K.: Stratigraphic units overlying the Zambales Ophiolite Complex (ZOC) in Luzon, (Philippines): Tectonostratigraphic significance and regional implications, J. Asian Earth Sci., 142, 20–31, doi:10.1016/j.jseaes.2016.06.011, 2017b.
Rangin, C., Jolivet, L. and Pubellier, M.: A simple model for the tectonic evolution of Southeast Asia and Indonesia region for the past 43 m.y, Bull. la Soc. Geol. Fr., VI(6), 889–905, doi:10.2113/gssgfbull.VI.6.889, 1990a.
Rangin, C., Pubellier, M., Azema, J., Briais, A., Chotin, P., Fontaine, H., Huchon, P., Jolivet, L., Maury, R., Muller, C., Rampnoux, J. P., Stephan, J. F., Tournon, J., Cottereau, N., Dercourt, J. and Ricou, L. E.: The quest for Tethys in the western Pacific; 8 paleogeodynamic maps for Cenozoic time, Bull. la Soc. Geol. Fr., VI(6), 907–913, doi:10.2113/gssgfbull.VI.6.907, 1990b.
Reagan, M. K., Pearce, J. A., Petronotis, K., Almeev, R. R., Avery, A. J., Carvallo, C., Chapman, T., Christeson, G. L., Ferré, E. C., Godard, M., Heaton, D. E., Kirchenbaur, M., Kurz, W., Kutterolf, S., Li, H., Li, Y., Michibayashi, K., Morgan, S., Nelson, W. R., Prytulak, J., Python, M., Robertson, A. H. F., Ryan, J. G., Sager, W. W., Sakuyama, T., Shervais, J. W., Shimizu, K. and Whattam, S. A.: Subduction initiation and ophiolite crust: new insights from IODP drilling, Int. Geol. Rev., 59(11), 1439–1450, doi:10.1080/00206814.2016.1276482, 2017.
Wu, J., Suppe, J., Lu, R. and Kanda, R.: Philippine Sea and East Asian plate tectonics since 52 Ma constrained by new subducted slab reconstruction methods, J. Geophys. Res. Solid Earth, 121(6), 4670–4741, doi:10.1002/2016JB012923, 2016.
Zahirovic, S., Seton, M. and Müller, R. D.: The Cretaceous and Cenozoic tectonic evolution of Southeast Asia, Solid Earth, 5(1), 227–273, doi:10.5194/se-5-227-2014, 2014.
Zahirovic, S., Matthews, K. J., Flament, N., Müller, R. D., Hill, K. C., Seton, M. and Gurnis, M.: Tectonic evolution and deep mantle structure of the eastern Tethys since the latest Jurassic, Earth-Science Rev., 162, 293–337, doi:10.1016/J.EARSCIREV.2016.09.005, 2016.