EOS meeting report "Evolution of Plate Tectonics" SUPPLEMENT

This supplement provides additional information beyond the brief EOS report.

The conference "Evolution of Plate Tectonics" was organized around four interrelated questions thought to be keys for answering the larger question of why Earth is the only body known to have plate tectonics:

1) When did plate tectonics start?
2) How did plate tectonics start?
3) What was Earth's convective and tectonic style before plate tectonics began? and
4) Why is it important to understand the evolution of plate tectonics?

Each of the four integral questions provided the focus of one day, with a Wednesday field trip to the Alpine suture zone allowing participants to learn about the fascinating geology of the region and interact more informally. The field trip guide can be downloaded from http://jupiter.ethz.ch/~plates/FIELD_GUIDE.pdf. Four mornings were devoted to talks by three invited experts with group discussions of the topics covered in these talks. On Monday, we addressed the question "Why is it important to understand the evolution of plate tectonics?" and talks on this topic were given by Shigenori Maruyama (Tokyo Institute of Technology, Japan "Earth history"), Nicolas Coltice (U. Lyon, France "Importance of plate tectonics for the geochemical evolution of Earth's mantle"), and Doris Breur (DLR, Germany "Is there plate tectonics on exoplanets?"). On Tuesday, we revisited the question "When did plate tectonics begin?" and keynote talks were given by Michael Brown (U Maryland, USA "Evidence from the metamorphic rock record for the onset of plate tectonics"), Mark Harrison (UCLA, USA "Geochemical evidence for early plate tectonics"), Kent Condie (New Mexico Tech, USA "The onset of plate tectonics on Earth: A planet in transition between 2 and 3 Ga"), and Jeronen van Hunen (Durham U., USA "Modeling the dynamics and observables of subduction in early Earth"). On Thursday, we explored the question "How did plate tectonics start?" with invited talks by Slava Solomatov (Wahington U., USA "Scaling of plate tectonics"), Yanick Ricard (U. Lyon, France "Onset of plate tectonics by accumulated lithospheric damage"), and Stephan Sobolev (GFZ, Germany "Plate tectonics initiation as running hurdles"). On the last day, we addressed "What was Earth's convective and tectonic style before plate tectonics began?" with invited talks by Elena Sizova (U Vienna, Austria "Plume tectonics and formation of tonalite, trondhjemite, and granodiorite in the Archean") and by Lyal Harris (INRS-ETE, Canada "Comparisons of Early Earth with Venus"). The meeting program can be downloaded from http://jupiter.ethz.ch/~plates/program.html

During lunch, students were invited to sit and discuss with the invited speakers. After lunch, poster presenters were given 3 minutes to introduce their posters, then the group spent the rest of the afternoon viewing posters before reconvening for group discussion and then dinner. Answers to a pre-meeting questionnaire about each of the four questions guided the afternoon discussions, and ideas shared during these discussions are also captured in the end-of-meeting questionnaire. A summary of the post-meeting responses is provided below.

For the question "Why is it important to understand the evolution of plate tectonics (PT)?", post-meeting responses included that this was an unsolved fundamental question in the history of our planet; that this understanding was needed to understand the evolution (and perhaps, origin) of life; the evolution of other planets and exoplanets; how every Earth cycle (and budget) evolved; the formation of Earth's surface environment, atmosphere, and habitability; mantle and core evolution; the origin of continents; and the origin of ore deposits and resources. These suggested "important reasons" were similar between pre- and post-meeting answers, but the aforementioned categories are sufficiently broad that a lot of ferment within each of these occurred over the course of the meeting.

For the question "When did PT start", most respondents that chose a date identified sometime in the Archean as the start date, in both pre- and post-meeting questionnaires; much smaller minorities chose the Hadean and the Neoproterozoic. The biggest change from pre- to post-meeting answers was that after the workshop, many more respondents opined that it was a more gradual process than heretofore appreciated; three examples of such responses follow. One participant wrote: "No particular date: this was a transitional/episodic/continuum process." Another offered: "First plate tectonic features probably started as early as Early Archean (or perhaps even Hadean) but 'modern-style' plate tectonic started sometime in the Proterozoic". A third answer was "Sometime in the Archean – although not the modern type of PT. The 'engine' probably initially was in 'stop and go' mode." This more nuanced appreciation of the problem is one of the most important results of the meeting.

There was also considerable discussion about the definition of PT that is useful for answering the question; the purely kinematic definition of Earth's lithosphere being broken into multiple fragments, each of which moves independently, is of limited use in a controversy where isotopic, geochemical, and petrologic lines of evidence are important. Workshop participants mostly agreed that an updated definition of PT that included the key role of subducting slabs in driving plate motions is needed in order to make progress.

Responses to the question "How did PT start?" were split between those who weren't sure and those who focused on ways to weaken strong oceanic lithosphere. Three principal ways to do this were mentioned: mantle plumes, bolide impacts, and accumulation of lithospheric damage. One respondent suggested that "bottom-up or top-down impacts on a stagnant lid" was responsible. Several respondents focused less on a single mechanism than a continuum of processes: one respondent to the question opined "hesitantly, intermittently, episodically". Another respondent suggested that there was a "long transition period where PT (mainly subduction) started several times and plume-lid tectonics and modern-style PT operated side-by-side." A third comment was "…any one of several processes: plumes, impacts, or convective drag." Many of these comments rephrase the increasing sense of the community that modern-style PT may be the result of multiple conditions and stimuli acting over a long time.

The question "What happened before PT?" elicited a range of responses, but there was remarkable commonality in answers, considering that this meeting was the first time that the question was considered explicitly. There was consensus that a magma ocean stage occurred early in Earth history, but that some kind of "stagnant lid" occurred after the magma ocean stage and before global PT began. Most responses focused on what this intermediate style was. Common themes focused on the roles of mantle plumes interacting with some kind of a stagnant, deformable, and magmatically active lid, known as "plume-lid tectonics". Several respondents mentioned that a "proto-PT" might have occurred episodically or that regions of stagnant lid might co-exist with regions where proto-PT occurred. The group was not happy with use of the term "stagnant lid", a concept that was developed to explain the present tectonic regime of Venus. This term suggests a lack of deformation and igneous activity, so answers from the group included "soft lid", "stable lid", "active stagnant lid", "deformable stagnant lid", "some kind of lid regime", "magmatic stagnant lid". These terms try to capture the idea of a single-plate planet that was nevertheless quite active in terms of deformation and magmatism, or was so from time to time. One important outcome of this workshop is the need to better understand the different convective and magmatic styles that a single-plate silicate planet like Venus, Mars, or the pre-PT Earth may go through.

In summary, the meeting accomplished many but not all of its goals. It brought together a broad geoscientific and planetary community and made good progress in addressing three of the four key questions: Why is it important to understand the evolution of PT?, How did PT begin? and What was Earth's tectonic/convective style before PT? We made less progress on resolving the controversy of When did PT begin?, but perhaps this question is less important because there may not have been a single moment when the PT regime "turned on". Instead, PT may have truly evolved over much of Earth history. We are well on our way to answering the question of Why is it important to understand the evolution of PT? but we may never be able to definitively answer the other three key questions. Nevertheless, there is a lot of "low-hanging fruit" to be harvested in the future. One of the most important opportunities is that this exploration can help bring the many subdisciplines of the geosciences together to learn from each other, and to engage planetary sciences and evolutionary biologists. Perfect balance among the geoscientific and planetary science subdisciplines is not expected in a small workshop like this. The Ascona meeting benefitted from strong participation of geodynamic modelers and the European geoscientific community, but we also had good participation by geologists and geochemists. More participation by experts in some other subdisciplines – such as isotope geochemistry, rock mechanics, and economic geology – would have provided useful additional perspectives. The workshop would also have benefitted if there were more geoscientists from Asia and the Third World.

What should we do in the future to advance our understanding of the evolution of PT? The progress that we made at Ascona strongly suggests that we should not wait another 10 years to gather again and continue the exploration. We aim to have another meeting in 2-3 years. The Ascona meeting was advertised widely and we accepted all bona fide applicants; we plan to continue this approach at the next meeting. Matt Leybourne from Laurentian U. in Sudbury, Canada offered to host the next meeting there, which would have the advantages of more engagement of economic geologists and a possible field trip to an Archean greenstone belt in the Canadian Shield. Sudbury lies on the shoulder of the 1.85 Sudbury Impact Crater and hosts some of the largest Ni-Cu-PGE deposits in the world. In addition to discussing advances in our understanding of when and how plate tectonics started, the 2018 workshop will involve discussions on the relationships between plate tectonics and mineral deposits.

Figure 1S: Workshop participants. Upper image shows workshop participants on lawn outside the conference center with Lago Maggiore and southern Alps in the distance. B identifies individuals by number: 1= Charitra Jain (ETH, Switz.); 2= Jie Liao (ETH, Switz.); 3= Jean-Pierre Burg (ETH, Switz.); 4= Maxim Ballmer (ETH, Switz.); 5 = Stefan Braendli (ETH, Switz.); 6= Taras Gerya (ETH, Switz.); 7= Bob Stern (UT Dallas, USA); 8 = Jean-Francois Moyen (Jean Monnet U., France); 9= Muriel Gerbault (Inst Research for Development, France); 10 = John Saul (France); 11 = Christoph Heubeck (U Jena, Germany); 12 = David Willis (Monash U., Australia); 13 = David Mole (CSIRO, Australia); 14 = Jeroen van Hunen (Durham U, UK); 15= Doris Breuer (DLR, Germany); 16 = Fabio Crameri (Oslo, Norway); 17 = Carol Frost (NSF, USA); 18 = Antoine Rozel (ETH, Switz.); 19 = Nicolas Coltice (U Lyon, France); 20= Diogo Lourenço (ETH, Switz.); 21 = Matt Leybourne (Laurentian U., Canada); 22 = Craig O'Neill (Macquarie U., Australia); 23 = Paul Tackley (ETH, Switz.); 24 = Anoinette Grima (UCL, UK); 25 = Michael Brown (U Md, USA); 26= Kent Condie (NM Tech, USA); 27 = Scott King (Va Tech, USA); 28 = Caroline Dorn (Uni Bern, ETH, Switz.); 29 = Isra Ezad (UCL, UK); 30 = Dan Bower (ETH, Switz.); 31 = Dave Stegman (UCSD, USA); 32 = Tim Lichtenberg (ETH, Switz.); 33= Xin Zhou (ETH, Switz.) 34 = Kiran Chotalia (UCL, UK); 35 = Adrien Vezinet (U Jean Monnet, France); 36 = Gautier Nicoli (Lorraine Nancy U., France); 37 = Frank Wagner (ETH, Switz.); 38 = Stephan Sobolev (GFZ, Germany); 39 = Christine Houser (ELSI, Japan); 40 = Jana Schierjott (ETH, Switz.); 41 = Matthew Mayne (U Jean Monnet, France); 42 = Tatsuki Tsujimori (Tohoku U., Japan); 43 = Dave Bercovici (Yale, USA); 44 = Maxime Maurice (DLR, Germany); 45 = Martina Ulvrova (UCB Lyon, France); 46 = Yanick Ricard (ENS de Lyon, France); 47 = Bettina Baitsch Ghirardello (ETH, Switz.); 48 = Elena Sizova (U. Graz, Austria); 49 = Veronica Sanchez (TAMU Kingsville, USA); 50 = Claudia Stein (Muenster, Germany); 51 = Anne Davaille (CNRS/U Paris, France); 52 = Walter Mooney (USGS, USA); 53 = Ulrich Hansen (U Muenster, Germany); 54 = Ria Fischer (ETH, Switz.); 55 = Richard From (U Manitoba, Canada); 56 = Shigenori Maruyama (Tokyo Tech, Japan); 57 = Slava Solomatov (WUSTL, USA); 58 = Lyal Harris (INRS, Canada); 59 = Andrea Piccolo (JGU Mainz, GER); 60 = Matthias Schmitz (University of Jena, Germany). Not shown: Mark Harrison (UCLA, USA), John Hernlund (ELSI, Japan).

Fig. 2S: Ms. Kiran Chotalia, winner of best student contribution award during the CSF Conference "Origin and Evolution of Plate Tectonics