MagellanPLUS Workshop Series Programme

The life cycle of a microplate at a convergent margin – COSNICA

Workshop Report

authors: Walter Kurz (1), Steffen Kutterolf (2), Jennifer Brandstätter (1,#), Paola Vannucchi (3), Jonathan Obrist-Farner (4), Maria Sandoval (5), Martin Rojas-Barrantes (6), Julie Schindlbeck-Belo (2, #), Ann Dunlea (7, #).

(1) University of Graz, Institute of Earth Sciences, Heinrichstrasse 26, 8010 Graz, Austria.
(2) Dynamics of the Ocean Floor, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany.
(3) Dip.di Scienze della Terra, Universitá degli Studi Firenze, Italy.
(4) Department of Geosciences and Geological and Petroleum Engineering, Missouri S&T, McNutt, USA.
(5) Escuela Centroamericana de Geología, Universidad de Costa Rica.
(6) Directorate of Geology and Mines San José, Costa Rica.
(7) Woods Hole Oceanographic Institution, Massachussetts, USA
(#) early carreer scientist

Summary

The MagellanPlus workshop COSNICA was originally planned to be held in April 2020, however, had to be postponed several times due to the COVID 19 pandemic and related mitigation regulations. Finally, the workshop took place at the Institute of Earth Sciences, University of Graz (Austria), from September 27th to 30th 2022. The workshop was held in hybrid form (in person and online participation). In total it brought together 12 scientists from 6 countries that were interested in drilling-related exploration of oceanic microplates and the related convergent margins, using the example of the Cocos Plate and the adjacent Middle American Trench and volcanic arc.

The overarching workshop objective was to integrate several drilling projects offshore Nicaragua, Guatemala and Costa Rica (Figure 1) under a general umbrella theme, and to develop and brainstorm two IODP-pre-proposals targeting the Cocos Plate and the Costa Rican, Nicaraguan and Guatemalan fore arc region. The first objective was the result of unsolved questions arising from two IODP expeditions (Costa Rica Seismogenesis Project – CRISP) (Exp. 334 and 344), in the following being described as the Cocos Plate Enigma, the second objective has a potential amphibian component associated to the ICDP workshop held in March 2020 in Nicaragua to drill the terrestrial part of the Nicaragua depression.

These two drilling targets additionally complemented further proposed projects (Figure 1):

- At the Nicaraguan section of the incoming Cocos Plate bend faults were targeted during a successful Magellan workshop held in 2016 in London (Morgan et al. 2016).
- The Izabal pull-apart basin (Guatemala forearc) contains > 4 km of sediment, deposited since the Early Miocene, of which the uppermost 1500 m appear to have been deposited

continuously in a lacustrine environment. The basin sediments are targeted by the ICDP proposal LIBRE - Lake Izabal Basin Research Endeavour (Obrist-Farner et al., 2018).

- Moreover, the record of the frequency, magnitude, and composition (including alterations) of the volcanic ash in the marine sediments off Northern Central America was also implemented as workshop topic (Central American Volcanic Arc – CAVA).

Workshop description

During the past decades several international marine expeditions and two IODP expeditions have identified the Central American margin as one of the most active and fascinating margins in the world due to its unique components (subducting Cocos Ridge, young plate, faults, volcanism, tectonic evolution, hazards) and its social and economic implications for the local and international societies. Therefore, the COSNICA workshop was implemented to coordinate and integrate multiple research topics under the overarching theme: "The life cycle of oceanic microplates at convergent plate margins". The overarching goal is to integrate ideas and co-ordinate goals for two drilling proposals ("The Cocos Plate enigma" and "Seagoing part of Nica-Bridge") and how they are related to goals that have been developed during the Magellan workshop: "Bend-Fault Serpentinization: Oceanic Crust and Mantle Evolution from Ridge through Trench" in London 2016, the ICDP LIBRE workshop in 2018, and the CAVA ash project. Finally, the workshop will define overarching scientific goals leading to an umbrella proposal combining several single projects and proposals.

The Cocos Plate enigma:

The oceanic Cocos Plate offshore the western margin of Costa Rica has a complex tectonic history (e.g., Schindlbeck et al., 2016a-c; Brandstätter et al., 2016; Herbrich et al., 2015; Werner et al., 2003; Barckhausen et al., 2001). The northern part of the Cocos Plate, with generally smooth morphology, is generated by the East Pacific Rise (EPR), whereas the southern part is Cocos Nazca spreading center (CNS) generated crust with rougher morphology (Werner et al. 2003). After the breakup of the Farallon Plate at 23 Ma, Cocos Plate lithosphere was formed at the opened CNS-1 (Barckhausen et al., 2001). A major ridge jump at 19.5 Ma (CNS-2), and multiple southward ridge jumps after ~14.5 Ma resulted in segmentation of the Cocos Plate lithosphere. A further segmentation process is the overprint of the Cocos Plate by Galapagos hot spot magmatism (Barckhausen et al., 2001). Previous studies showed the tectonic complexity of the Cocos Plate (e.g., Barckhausen et al., 2001) and that Late Miocene to Pliocene magmatic processes that overprint of its igneous and sedimentary rocks (Brandstätter et al., 2016; 2018). The origin of the ~2 Ma old Cocos Island is discussed in several papers (e.g., Castillo et al., 1988; Schindlbeck et al, 2016a). The aseismic Cocos Ridge (CCR), orientated parallel to the recent movement direction of the underlying Cocos Plate (Walther, 2003), extends more than 1000 km from the CNS to the Cocos Plate - Caribbean Plate boundary at the Middle America Trench. It stands ≥ 2 km higher than the surrounding seafloor, is an asymmetric overthickened ridge of oceanic crust and has influenced the entire margin significantly. This crustal thickening reaches ranges from 8-10 km in the northwest to ~ 20 km beneath the center of the Cocos Ridge and is undoubtedly related to the Galapagos hot spot (Hoernle et al., 2002). The sedimentary deposits on the CCR and the surrounding ocean floor are less than 1 km thick (Walther 2003) and drill cores from several deep sea drilling expeditions (Exps. 170. 202, 334, 344) revealed very heterogenous stratigraphic records, sometimes only in a few km distance from each other (e.g., Schindlbeck et al. 2016b, Brandstätter et al. 2016, Harris et al. 2013, Kimura et al. 1997). These records comprise hiatuses versus continuous stratigraphy, exclusive Galapagos versus solely arc derived fallout tephras of the same age, and different magmatic basements etc. Pliocene to Late Miocene sediment hiatuses, for example, occur at Sites U1381 and 1242 although these are located next to Site U1414. The latter has a continuous and homogenous sedimentation with arc-derived tephras. The causes for this discrepancy are subject of ongoing investigations (Schindlbeck et al., 2016b), and, more detailed investigations will be required to explain these inconsistencies. Therefore, the main aim of that workshop is to identify drilling locations and possible sites to reveal the internal Cocos Plate structure and the boundary between hiatus-non hiatus sites, and the processes that brought these sites so close together.

The seagoing part of NICA-BRIDGE:

In March 2020, a workshop took place to develop a scientific drilling project in Lakes Nicaragua and Managua, Nicaragua. Both are located and originated in a half graben that developed at least since the Pliocene due to tectonic changes at the Central American margin and the subducting Cocos Plate. The lakes are uniquely suited for multidisciplinary, globally important scientific investigation of long, continuous sediment profiles because of its: 1) long tectonic record (>3 Myr) of terrestrial and connected marine basin development at the Southern Central American margin, 2) alternating lacustrine and marine environments, 3) proximity to two (older and younger) volcanic arcs, 4) significance as an endemic hot spot, 5) strategic location to study the great American biotic interchange, and 6) the interactive combination of seismological, volcanological, paleoclimatological, paleoecological, and paleoenvironmental studies in both the ocean and on land. The Sandino basin offshore Nicaragua is the oceanic continuation of this depression and complements the lake drilling to understand the evolution of the complex margin. The COSNICA workshop served to define, complement, and compare scientific objectives of the lake drilling project proposal in the ocean. It will address topics such as (a) development of a Neotropical environmental and paleoclimate record that will extend presently available late Pleistocene-Holocene records back to Miocene times, (b) determination of the times and rates of marine transgressions and regressions, their tectonic and climatic controls and ecological consequences, (c) investigation of recurrence rates and magnitudes of natural hazards such as explosive volcanic eruptions, (d) basin evolution of a tectonic influenced multi stage forearc, and (e) linkages between long-term terrestrial and marine environmental records.

Bend Fault Serpentinization

In the middle America region, bend-faulting using reactivated mid ocean ridge normal faults is associated with bright fault-like reflectors that continue from surface bend-faults through the crust and into the upper mantle (Ranero et al., 2003). The normal mantle, seismic P-wave speeds ~ 8 km/s, away from regions of plate bending does not have bright reflectors. The bright reflectors in this region are conjectured to be caused by partial serpentinization around a fault, which would result in a lower seismic wave velocity. Seismic refraction and tomographic delay-inferred wave velocities for the Middle American region are all consistent with ~10-20% serpentinization (Ranero et al., 2004; Ivandic et al., 2008; 2010; van Avendonk et al., 2011).

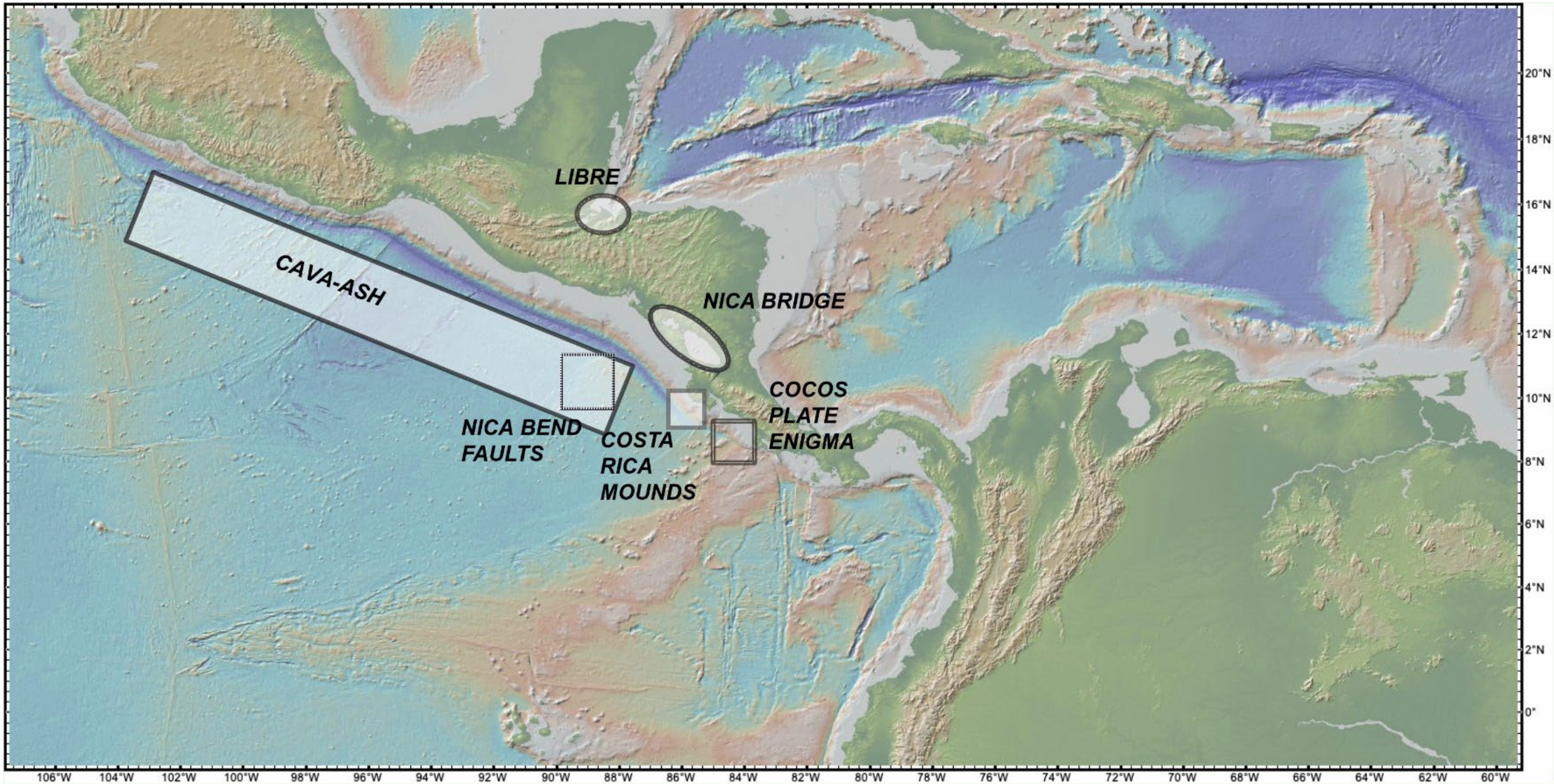

Figure 1: Bathymetric map of the COSNICA workshop target area with several sites of proposed investigation indicated.

Regional heat flow above this area of active bend-faulting is only ~20% of the conductive heatflow expected for lithosphere of the studied age (Grevemeyer et al., 2005; Iyer et al., 2012). This low conductive heatflow implies large-scale regional hydrothermal inflow into the faulting region. Finally, electromagnetic imaging of the Middle American region suggests an increasing of porosity along bending-fault planes, which might act as fluid pathways required for serpentinization of the uppermost mantle (Key et al., 2012; Naif et al., 2015). In addition to this region being one of the best-characterized bend-faulting regions, it is the shallowest exemplar of well-developed bend-faults and BFS. It also provides a unique opportunity to ultimately drill a compact 'flowline' from the East Pacific Rise, through an off-axis EPR-lithosphere MoHole reference site to characterize on and off-axis chemical transformations, to a BFS site that documents the final chemical transformations and interactions between seawater, crust, and mantle before the plate subducts into the mantle.

Lake Izabal Basin Research Endeavour (LIBRE)

The Cocos Plate interacts with the North American and Caribbean plate boundary across a diffuse triple junction where the Cocos, North American, and Caribbean plates interact. The North American and Caribbean plates are separated across a diffuse shear zone called the Polochic-Motagua Fault System (PMFS) in Guatemala (Lyon-Caen et al., 2006). The four main faults of the PMFS, the northernmost Ixcán Fault, the northern Polochic Fault, the central Motagua Fault, and the southern Jocotán-Chamelecón Faut, are seismically-active faults and have caused devastating earthquakes in the past (White, 1984; 1985; Plafker, 1976). Contemporary tectonic analysis indicates that the PMFS accommodates ~ 20 mm/yr of left-lateral displacement, with most of the slip occurring along the Motagua Fault, minimal slip along the Polochic Fault, and no slip along the Ixcán and Jocotán-Chamelecon faults (Ellis et al., 2019).

Lake Izabal in eastern Guatemala is in an active pull-apart basin located along the Polochic-Motagua fault system, the inland extension of the North American and Caribbean plate boundary. Preliminary data suggest that the basin contains > 4 km of sediment, deposited since the Early Miocene, of which the uppermost 1500 m appear to have been deposited continuously in a lacustrine environment. These sediments contain a unique continental record in the northern Neotropics that is long enough to improve our understanding of regional tectonics and associated geohazards, paleoclimatic perturbations and tropical feedback on climate change across multiple glacial-interglacial cycles, and associated paleoenvironmental and paleobiological changes.

Central American Volcanic Arc (CAVA)

The Central American Volcanic Arc (CAVA) is one of the most active volcanic arcs on our planet and responsible for a considerable number of devastating Plinian and ignimbrite forming eruptions in the last hundreds of thousand years. Even more, there is multiple evidence that the arc system is active even since at least the Miocene contributing to marine and lacustrine depositional facies with deposits from an ancient arc system that experienced phases of increased volcanism and ignimbrite flare ups in the Neogene (Ehrenborg, 1996, Carr et al., 2007; Schindlbeck et al. 2016a,b, 2018, Jordan et al. 2007a). Whereas volcanic ash from multiple arc volcanoes in the Upper Peistocene has been distributed by prevailing stratospheric easterly winds, across the Pacific Ocean where resulting ash layers provide valuable marker horizons in the mostly non-erosive submarine environment, it is also known that large Neogene eruptions distributed the related eruption products (mostly co-ignimbrite ash) also into the Caribbean Sea (Jordan et al. 2006).

The volcanism at the Central American subduction zone is strongly characterized by variations in the nature of the incoming plate (Hoernle et al., 2002), in the upper-plate crustal thickness and composition (Carr, 1984), and the tectonic setting. These variations lead to characteristic along-arc variations in the composition and magnitude of the erupted volcanic products (Carr, 1984; Carr et al., 2007; Feigenson et al., 2004; Hoernle et al., 2008; Patino et al., 2000; Rose et al., 1999). Another important feature that influences the volcanism especially in the southern part of the CAVA is the subduction of material from the Galapagos hotspot track as well as its explosive traces in the overlying sediments (Schindleck et al. 2015, 2016c) culminating in the collision and subduction of the 2 km thick Cocos Ridge. All this led to compositions ranging from normal calc-alkaline basalt through rhyolite to alkaline rock series.

Workshop programme

Tuesday, September 27th 2022	
17:30	Registration, Welcome Icebreaker
Wednesday, September 28th 2022	***Plenary Sessions***
09:00	Workshop Introduction, Workshop goals (Walter Kurz)
09:30	Central American tectonics (Paola Vannucchi, Udo Barckhausen)
10:00	The Cocos Plate enigma (Walter Kurz, Jennifer Brandstätter)
Coffee break	
11:00	Bend-fault serpentinization (Jason Morgan; online presentation)
11:30	The Nica Bridge (Steffen Kutterolf)
Lunch break	
13:30	The LIBRE Project (Jonathan Obrist Farner)
14:15	The southern flank of the Cocos Ridge (Martin Rojas Barrantes)
Coffee break	
15:30	The CAVA ash project (Ann Dunlea; online presentation)

16:15	The Tectonic and Stratigraphic development of the Sandino Forearc Basin from Guatemala to Costa Rica (César Raneiro; online presentation)
	Breakout Sessions
16:45	Breakout session Introduction: Perspectives of a combined strategy (Steffen Kutterolf)
17:15	free collecting of drilling objectives/perspectives/ideas (Sedimentology, Paleoclimate (ecology) and (Bio-) Stratigraphy; Structural geology, Tectonics, and Geophysics; Igneous Petrology, volcanology and geochemistry) brainstorm the potential specific scientific goals and identify possible overlap/common targets between the COSNICA proposals
18:00	*End of Day 1*
Thursday, September 29th 2022	***Plenary Sessions***
09:00	Available Platforms (Anna Joy Drury)
10:00	Available Platforms (Online Presentation of the ESO Science Manager **Dave McInroy)**
Coffee break	
	Breakout Sessions
11:00	Breakout session 1 (continued): free collecting of drilling objectives/perspectives/ideas brainstorm the potential specific scientific goals and identify possible overlap/common targets between the COSNICA proposals
Lunch break	
13:30	Breakout session 2: Synergies of previous proposals Umbrella target and which are the hypothesis to be tested
Coffee break	
15:30	Breakout session 2 *(continued)* Synergies of previous proposals
18:00	*End of Day 2*

Friday, September 30th 2022	***Breakout Sessions***
9.00 – 12:00	Breakout session 3 (umbrella proposal): Strategic plan to get Central America as target area for future scientific drilling; results from the breakout sessions Proposal and research phases, technical aspects for proposal implementations. discussion: set up of a priority list of sites and targets Assign teams and team leaders for each section for a pre-proposal **conclusion and end of workshop**
Lunch	

Workshop results

The workshop aimed to integrate the working hypotheses of the proposals and projects described above into an umbrella topic that is aimed to provide an overarching drilling proposal including a series of sub-proposals.

Workshop discussions resulted in the definition of a general umbrella topic for the target area and the definition of sub-themes and sub-hypotheses that altogether are aimed to be further developed and finally to end up in a white paper going to be published in, e.g., Scientific Drilling.

In general, the target area (Figure 1) is a distinguished case example for the interaction of plate tectonics at a convergent margin, hot spot magmatism, subduction and related volcanic arc magmatism, climate evolution and oceanography. The life-cycle of the Cocos plate therefore has cascading effects on Earth system processes due to the physical, mechanical, and chemical alterations of a plate approaching to and during subduction affecting on geochemistry, climate, and life.

The role of Cocos Plate tectonics for global climate, environment and ecological systems is closely related to the final Isthmus of Panama closure around 3.5 Ma as a response to changes in regional tectonic processes, particularly in the subduction system. The process of closing the Isthmus of Panama resulted in spatial / temporal heterogenous hydroclimate, paleo-oceanographic and paleo-ecological response in Central America.

During IODP Expedition 344, two Sites, U1414 and U1381, were drilled on the incoming Cocos Plate. Although the distance between these two sites does not exceed 11 km, Pleistocene to mid-Miocene sediments are missing at Site U1381, whereas at Site U1414 a continuous sedimentation from Mid Miocene times is documented (Harris et al., 2013a). Altogether drill cores from several deep sea drilling expeditions (Exps. 170. 202, 334, 344) revealed very heterogenous stratigraphic records sometimes only in a few km distance from each other (e.g., Schindlbeck et al. 2016b, Brandstätter et al. 2016, Harris et al. 2013, Kimura et al. 1997). These records comprise hiatuses versus continuous stratigraphy, exclusive Galapagos versus solely arc derived fallout tephras of the same age, and different magmatic basements etc. The causes for this discrepancy will be subject of ongoing investigations. Additional drilling sites along the western flank of the Cocos Ridge, with high resolution sedimentary and tephra stratigraphy as well as paleomagnetic analysis should enable to identify a potential short-lived spreading center in the area of these sites.

Bend-faults play a key role to slab hydration by providing high-permeability pathways for seawater to flow into the oceanic crust and uppermost mantle. Bend-fault hydration depends on various conditions such as temperature, the state of stress, and rock and fault permeability to fluid flow. In order to deepen our understanding of bend-fault hydration processes and their effects on changing in physical properties in incoming oceanic plates in subduction zones we aim to obtain and analyze in-situ physical properties, lithofacies, biofacies, and fluids in active bend-fault systems by ocean drilling in the middle America region of oceanic plate subduction.

Bend Faulting Serpentinization and fluid sediment cycle in the subduction zone also influences the seismic behavior and volcanic arc magmatism. In consequence, alterations of volcanogenic material affect the sediment and crustal compositions being subducted and re-erupted in the arc and play a major role in the carbon and silica cycles.

Knowing the detailed long-term Quaternary and Neogene record of explosive eruptions is essential to evaluate systematic changes in both, frequency and composition through time and possible external trigger mechanism that may control or modulate them. The geographic separation of the ancient Neogene and recent arc system in the Southern CAVA due to the slab roll back centered in the region of Nicaragua should facilitate the use of marine and lacustrine sediment records to better constrain the time frames of arc migration as well as the explosive record and magmatic compositions of different age segments. Long time series of explosive eruptions, established by comprehensive tephrochrono-stratigraphy, provide the data base to investigate episodic variations in the abundance of marine tephras and therefore the history of explosive volcanism. Central America is a perfect place to test this and a new catalogue of highly explosive eruptions established within the proposed projects can be perfectly statistically evaluated (running average, frequency and multitaper spectral analysis). In detail LIBRE, NICA-BRIDGE, CAVA-ASH, COCOS-ENIGMA, SANDINO BASIN sediment cores will contribute to:

- a high-resolution tephrostratigraphic framework that will enable layer-wise correlation among the drill cores and identification of widespread ash markers that occur in Lake and marine sediments, thereby enabling direct regional comparison of records that can be linked to paleoclimate proxies in the same records.
- establish most complete and continuous high-resolution eruptive time series for the Central America region that can be statistically analyzed for simple reccurrence rates, eruption frequencies and periodicities
- combine the spatial distribution of co-temporal tephras for magma volume calculation and derive into a mass eruptive time series that can be explored regarding complex eruptive magnitude dependent periodicities of CAVA volcanism
- compare and elaborate on climatic versus tectonic controls on extended periods dominated by erosion versus those dominated by volcanic activity.

Workshop participants

Table 1 Workshop Participants (online participants in *italic,* (#) early carreer scientist)

Surname	Name	Institution	Country
Bauersachs	Thorsten	IFM Geomar Kiel	Germany
Belo	*Julie (#)*	IFM Geomar Kiel	Germany
Dunlea	*Ann (#)*	Woods Hole Oceanographic Institution	USA
Kurz	Walter	University of Graz	Austria
Kutterolf	Steffen	IFM Geomar Kiel	Germany
Morgan	*Jason P.*	SUS Tech Shenzhen	China
Obrist-Farner	Jonathan	Missouri S&T	USA
Raneiro	*César*	Instituto de Ciencias del Mar, Barcelona	Spain
Rojas Barrantes	Martin	ICE San Jose	Costa Rica
Sandoval	Maria	Universidad de Costa Rica, San Jose	Costa Rica
Vannucchi	Paola	Univ. Firenze	Italy
Piller	Werner	University of Graz	Austria
Stegmüller	Georg	Technical support University of Graz	Austria

in person participants (from left to right: Martin Rojas-Barrantes, Maria Sandoval, Steffen Kutterolf, Paola Vannucchi, Walter Kurz, Jonathan Obrist-Farner, Werner Piller)

References:

Barckhausen, U., Ranero, C. R., von Huene, R., Cande, S. C., & Roeser, H. A. (2001). Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models. Journal of Geophysical Research, 106, 207–220, doi:10.1029/2001JB000238.

Brandstätter, J., Kurz, W., Krenn, K., & Micheuz, P. (2016). Fluid inclusion petrology and microthermometry of the Cocos Ridge hydrothermal system, IODP Expedition 344 (CRISP 2), Site U1414. Geochemistry, Geophysics, Geosystems, 17, doi:10.1002/2015GC006212.

Brandstätter, J., Kurz, W., Richoz, S., Cooper, M. J., Teagle, D. A. H. (2018). The origin of carbonate veins within the sedimentary cover and igneous rocks of the Cocos Ridge: Results from IODP HoleU1414A. G3: Geochemistry, Geophysics, Geosystems: an electronic journal of the earth sciences, 19, https://doi.org/10.1029/ 2018GC007729. DOI: https://doi.org/10.1029/ 2018GC007729, 2018.

Carr MJ (1984) Symmetrical and segmented variation of physical and geochemical characteristics of the Central American volcanic front. J. Volcanol. Geotherm. Res. Vol. 20:p. 231-252

Carr MJ, Saginor I, Alvarado GE, Bolge LL, Lindsay FN, Milidakis K, Turrin BD, Feigensohn MD, Swisher III CC (2007) Element fluxes from the volcanic front of Nicaragua and Costa Rica. Geochem Geophys Geosys 8:doi:10.1029/2006GC001396

Ehrenborg, J. (1996). *A new stratigraphy for the Tertiary volcanic rocks of the Nicaraguan Highland. Geological Society of America Bulletin, 108(7), 830–842.* doi:10.1130/0016-7606(1996)108<08

Ellis, A., DeMets, C., McCaffrey, R., Briole, P., Cosenza Muralles, B., Flores, O., Guzmán-Speziale, M., Hernández, D., Kostoglodov, V., LaFemina, P., Lord, N., Lasserre, C., Lyon-Caen, H., Rodriguez Maradiaga, M., Molina, E., Rivera, J., Rogers, R., Staller, A. & Tikoff, B. (2019) Gps Constraints on Deformation in Northern Central America from 1999 to 2017, Part 2: Block Rotations and Fault Slip Rates, Fault Locking and Distributed Deformation. Geophysical Journal International, 218, 729-754.

Feigenson MD, Carr MJ, Maharaj SV, Bolge LL, Juliano S (2004) Lead Isotope Composition of Central American Volcanoes: Influence of the Galapagos Plume. Geochem. Geoph. Geosy. 5(6):1-14

Grevemeyer, I., Kaul, N., Diaz-Naveas, J.L., Villinger, H.W., Ranero, C.R. and Reichert, C. (2005): Heat frlow and bending-related faulting at subduction trenches: Case studies offsore of Nicaragua and Central Chili. *Earth and Planetary Science Letters, 236,* 238-248.

Harris, R. N., et al. (2013). Expedition 344 summary. In N. Harris et al. (Eds.), Proceedings of IODP, (Vol. 344). Texas: College Station, Integrated Ocean Drill. Program. doi:10.2204/iodp.proc.344.101.2013.

Herbrich, A., Hoernle, K., Werner, R., Hauff, F., van den Bogaard, P., & Garbe-Schönberg, D. (2015). Cocos Plate Seamounts offshore NW Costa Rica and SW Nicaragua: Implications for large-scale distribution of Galápagos plume material in the upper mantle. Lithos, 212/215, 214–230. https://doi.org/10.1016/j.lithos.2014.10.014.

Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Alvarado, G. E., & Garbe-Schönberg, C.-D. (2002). Missing history (16–71 Ma) of the Galápagos hotspot: Implications for the tectonic and biological evolution of the Americas. Geology, 30, 795–798, doi:10.1130/0091 27613 (2002) 030<0795:MHMOTG>2.0.CO;2.

Hoernle K, Abt DL, Fischer KM, Nichols H, Hauff F, Abers GA, van den Bogaard P, Heydolph K, Alvarado G, Protti M (2008) Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. Nature 451(7182):1094-1097

Ivandic, M., Grevemeyer, I., Berhorst, A., Flueh, E.R. and McIntosh, K. (2008): Impact of bending related faulting on the seismic properties of the incoming oceanic plate offshore of Nicaragua. *Journal of Geophysical Research,* **113,** B05410, doi:10.1029/2007JB005291.

Ivandic, M., Grevemeyer, I., Bialas, J. and Petersen, C.J. (2010): Serpentinization in the trench-outer rise region offshore of Nicaragua: constraints from seismic refraction and wide-angle data. *Geophysical Journal International,* **180,** 1253-1264.

Iyer, K., Rüpke, L.H., Morgan, J.P. and Grevemeyer, I. (2012): Controls of faulting and reaction kinetics on serpentinization and bouble Benioff zones. *Geochemistry Geophysics Geosystems,* **13,** Q09010, doi:10.1029/2012GC004304

Jordan BR, Sigudsson H, Carey SN, Rogers R, Ehrenborg J (2006) Geochemical correlation of Caribbean Sea tephra layers with ignimbrites in Central America. In: Siebe C, Macías JL, Aguirre-Díaz GJ (eds) Neogene-Quaternary Continental Margin Volcanism: A Perspective from México. pp 175-208

Jordan BR, Sigurdsson H, Carey SN, Rogers R, Ehrenborg J (2007) Geochemical variation along and across the Central American Miocene paleoarc in Honduras and Nicaragua. Geochimica et cosmochimica acta 71(14):3581-3591

Key, K., S. Constable, T. Matsuno, R. Evans, and D. Myer (2012), Electromagnetic detection of plate hydration due to bending faults at the middle america trench. *Earth and Planetary Science Letters,* **351,** 45-53.

Kimura, G., Silver, E.A., Blum, P., et al. (1997). Proc. ODP, Init. Repts., 170: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.170.1997.

Kutterolf, S., Brenner, M., Freundt., A., et. Al. (2016). Neogene environmental and geological evolution of the Central American bridge between two continents and oceans (NICA_BRIDGE). ICDP, the International Continental Scientific Drilling Program, Proposal, 2016.

Lyon-Caen, H., Barrier, E., Lasserre, C., Franco, A., Arzu, I., Chiquin, L., Chiquin, M., Duquesnoy, T., Flores, O., Galicia, O., Luna, J., Molina, E., Porras, O., Requena, J., Robles, V., Romero, J. & Wolf, R. (2006) Kinematics of the North American–Caribbean-Cocos Plates in Central America from New Gps Measurements across the Polochic-Motagua Fault System. Geophysical Research Letters, 33.

Morgan, J.P., Fujie, G., Grevemeyer, I., Henstock, T., Morishita, T., Teagle, D. (2016). Bend-Fault Serpentinization (BFS+H-ODIN): Oceanic Crust and Mantle Evolution from Ridge through Trench, MagellanPlus Workshop report.

Naif, S., Key, K., Constable, S, Evans, R.L. (2015): Water-rich bending faults at the Middle America Trench. *Geochemistry, Geophysics, Geosystems,* 16, 2582– 2597, doi:10.1002/2015GC005927.

Obrist-Farner, J., Oboh-Ikuenobe, F.E., Douglas, P.M.J., Brenner, M., Curtis, J.H., Lodolo, E., Pérez Alvarado, L.C., and Bhattacharya (2018). LIBRE – Lake Izabal Basin Research Endeavour (Central America, Guatemala, Lake Izabal). ICDP, the International Continental Scientific Drilling Program, Proposal, 2018.

Patino LC, Carr MJ, Feigenson MD (2000) Local and regional variations on Central American arc lavas controlled by variations in subducted sediment input. Contrib Mineral Petrol 138:265-283

Plafker, G. (1976) Tectonic Aspects of the Guatemala Earthquake of 4 February 1976. Science, 193, 1201.

Ranero, C.R., Morgan, J.P. and Relchert, C. (2003): Bending-related faulting and mantle serpentinization at the Middle America Trench. *Nature,* **425,** 367-373.

Ranero, C.R. and Sallarés, V. (2004): Geophysical evidence for hydration of the crust and mantle of the Nazca plate during bending at the north Chile trench. *Geology,* **32,** 549-552.

Ranero, C. R., Villaseñor, A., Phipps Morgan, J., and Weinrebe, W. (2005). Relationship between bend-faulting at trenches and intermediate-depth seismicity, Geochem. Geophys. Geosyst., 6, Q12002, doi:10.1029/2005GC000997.

Rose WI, Conway FM, Pullinger CR, Deino A, McIntosh K (1999) An improved age framework for late quaternary silicic eruptions in nothern Central America. Bull. Volcanol. 61:106-120

Schindlbeck, J. C., Kutterolf, S., Straub, S. M., Andrews, G. D. M., Wang, K.-L., & Mleneck-Vautravers, M. J. (2018). *One Million Years tephra record at IODP Sites U1436 and U1437: Insights into explosive volcanism from the Japan and Izu arcs. Island Arc, 27(3), e12244.* doi:10.1111/iar.12244

Schindlbeck, J.C., Kutterolf, S., Freundt, A., Andrews, G. D. M., Wang, K.-L., Völker, D., et al. (2016a). Alkalic marine tephra layers at ODP Site 1241 - Major explosive eruptions from an oceanic volcano in a pre-shield stage?, Journal of Volcanology and Geothermal Research, 328, http://dx.doi.org/10.1016/j.jvolgeores.2016.10.009

Schindlbeck, J. C., S. Kutterolf, A. Freundt, G. E. Alvarado, K.-L. Wang, S. M. Straub, S. R. Hemming, M. Frische, and J. D. Woodhead (2016b), Late Cenozoic tephrostratigraphy offshore the southern Central American Volcanic Arc: 1. Tephra ages and provenance, Geochem. Geophys. Geosyst., 17, 4641–4668, doi:10.1002/2016GC006503.

Schindlbeck, J.C., Kutterolf, S., Freundt, A., Straub, S.M., Vannucchi, P., & Alvarado, G.E. (2016c). Late Cenozoic tephrostratigraphy offshore the southern Central American Volcanic Arc: 2. Implications for magma production rates and subduction erosion, Geochem. Geophys. Geosyst., 17, 4585–4604, doi:10.1002/2016GC006504.

Schindlbeck, J. C., Kutterolf, S., Freundt, A., Eisele, S., Wang, K.-L., & Frische, M. (2018). *Miocene to Holocene marine tephrostratigraphy offshore northern Central America and southern Mexico: Pulsed activity of known volcanic complexes. Geochemistry, Geophysics, Geosystems.* doi:10.1029/2018gc007832

Van Avendonk, H.J.A., Holbrook, W.S., Lizarralde, D. and Denyer, P. (2011): Structure and serpentinization of the subducting Cocos plate offshore Nicaragua and Costa Rica. *Geochemistry Geophysics Geosystems,* **12,** Q06009, doi:10.1029/2011GC003592

Walther, C. H. E.(2003). The crustal structure of the Cocos ridge off Costa Rica, J. Geophys. Res., 108 (B3), 2136,doi:10.1029/2001JB000888.

Werner, R., Hoernle, K., Barckhausen, U., & Hauff, F. (2003). Geodynamic evolution of the Galápagos hot spot system (Central East Pacific) over the past 20 m.y.: constraints from morphology, geochemistry, and magnetic anomalies. Geochemistry, Geophysics, Geosystems, 4 (12). http://dx.doi.org/10.1029/2003GC000576.

White, R.A. (1984) Catalog of Historic Seismicity in the Vicinity of the Chixoy-Polochic and Motagua Faults, Guatemala. Open-File Report.

White, R.A. (1985) The Guatemala Earthquake of 1816 on the Chixoy-Polochic Fault. Bulletin of the Seismological Society of America, 75, 455-473.