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250 Million Years of Earth History in Central Italy

Celebrating 25 Years of the Geological Observatory of Coldigioco

Penrose 2017

COLDIGIOCO

Apiro, Italy

September 25-30, 2017

A Penrose Conference sponsored by

THE GEOLOGICAL SOCIETY OF AMERICA

THE BARRINGER CRATER COMPANY

LE MONTAGNE DI SAN FRANCESCO ASSOCIAZIONE 2012 COLDIGIOCO

Comune di Apiro

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250 Million Years of Earth History in Central Italy: Celebrating 25 years of the Geological Observatory of Coldigioco

September 25-29, 2017
Apiro, Marche Region, Italy

Conveners:

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Sponsored by:

GSA Foundation, Barringer Crater Company, Associazione Le Montagne di San Francesco

Description and Objectives:

Central Italy has been a cradle of geology for centuries. Since the beginning of the last century, the Triassic to Miocene carbonate succession exposed along the valleys of the Umbria and Marche (U-M) Apennines of Italy, has been a fertile playground for generations of Earth scientists, particularly paleontologists, sedimentologists, stratigraphers, geophysicists, and structural geologists, from all over the world. It is in this geological theater that pioneering studies in the most disparate disciplines of Earth sciences have led to the understanding of novel principles and natural phenomena of the past, the development of new methodologies and experimental research approaches, and ultimately to discontinuities in scientific thinking, with the birth of concepts such as Event Stratigraphy, Integrated Stratigraphy, and Cyclostratigraphy applied to astronomical tuning, let alone Quaternary Geology, Neotectonics and Speleogeology. The Umbria-Marche Apennines of northeastern Italy are a foreland fold-and-thrust belt, which was formed in the latest phase of the Alpine–Himalayan orogenesis. These mountains are entirely made of marine sedimentary rocks of the so-called Umbria–Marche (U–M) Succession, which represents a continuous record of the geotectonic evolution of an epeiric sea from the Early Triassic to the Pleistocene. Studies of these rocks have promoted sensational discoveries, particularly about major events that have punctuated the history of the Earth, such has the Cretaceous Oceanic Anoxic Events (OAE1 and OAE2), the Cretaceous–Paleogene (K–Pg) Boundary Event (with the global mass extinction caused by a catastrophic extraterrestrial impact), the events across the Eocene–Oligocene transition from a greenhouse to an icehouse world, the Messinian Salinity Crisis of the Mediterranean, just to name the most famous ones.

The objective of the meeting is to present an updated vision of 250 million years of Earth history as recorded in the sedimentary succession of the northern Apennine orogeny in central Italy. At the conference, besides keynote review presentations, original research works will be presented covering specific subjects of Tectonics and Structural Geology, Integrated Stratigraphy and Astronomical Tuning, Extraterrestrial Event Stratigraphy, and Quaternary Geology and Geo-Bio Speleology. These research works are either still in

progress or they were accomplished but never published before, all with the support of the Geological Observatory of Coldigioco, an independent research and educational center, which was founded in an abandoned medieval hamlet near Apiro in 1992 by Alessandro Montanari, Walter Alvarez, and David Bice.

Studies are now in progress about the recent tectono-seismic and structural history of the still active Umbria-Marche Apennines (as is exemplified by the recent seismic activity in 2016). More studies by international teams of stratigraphers are being conducted through long and continuous stretches of the U-M sedimentary succession, focusing on the integration of bio-magneto-chemostratigraphy and radioisotopic geochronology with astronomical tuning via multiproxy cyclostratigraphic analysis.

One of the primary results that have been derived from the U-M sedimentary succession in the past 25 years with the support of the Geological Observatory of Coldigioco has been the development of the subject of the role that extraterrestrial events, such as meteoritic impacts, comet showers and asteroidal breakups, had had in the biologic, environmental and climatic changes of planet Earth. Studies about this subject will be presented at the Penrose Conference.

Last but not least are the tremendous advancements in the studies on the Pleistocene and Holocene history of this part of the world, which were focused on the extraordinary speleologic record of the Frasassi hypogenic cave complex (i.e., karstic geomorphology, slack water deposits, extremophile sulfidic ecosystems, speleo-archeology). Interdisciplinary studies by international teams of speleo-geologists, geochemists, radioisotopic and cosmogenic geochronologists, biologists, and archeologists will be presented at the meeting.

The main topics that will be emphasized as part of the program include:

- Tectonics and Structural Geology.
- Integrated Stratigraphy and Astronomical Tuning.
- Extraterrestrial Event Stratigraphy
- Quaternary Geology and Geo-Bio Speleology.

Summary Schedule:

Day 0 | Sunday, September 24, 2017: 18:30 – 21:00, Icebreaker reception, Cingoli
Day 1 | Monday, September 25, 2017: 9:00 – 18:30, Oral and poster sessions, Apiro
Day 2 | Tuesday, September 26: 9:00 – 18:30, Oral and poster sessions, Apiro
Day 3 | Wednesday, September 27: 9:00 – 18:30, Oral and poster sessions, Apiro
Day 4 | Thursday, September 28: Field trip to Gubbio and surrounds
Day 5 | Friday, September 29: Morning: Field trip to Frasassi Gorge;
Afternoon: visit to and reception at Coldigioco, with music, art, and food
Day 6 | Saturday, September 30: Optional field trip to Monte Conero and Massignano

On Sunday, September 24, 2017, the ice breaker reception takes place at the Hotel Tetto delle Marche in Cingoli from 18:30 – 21:00.

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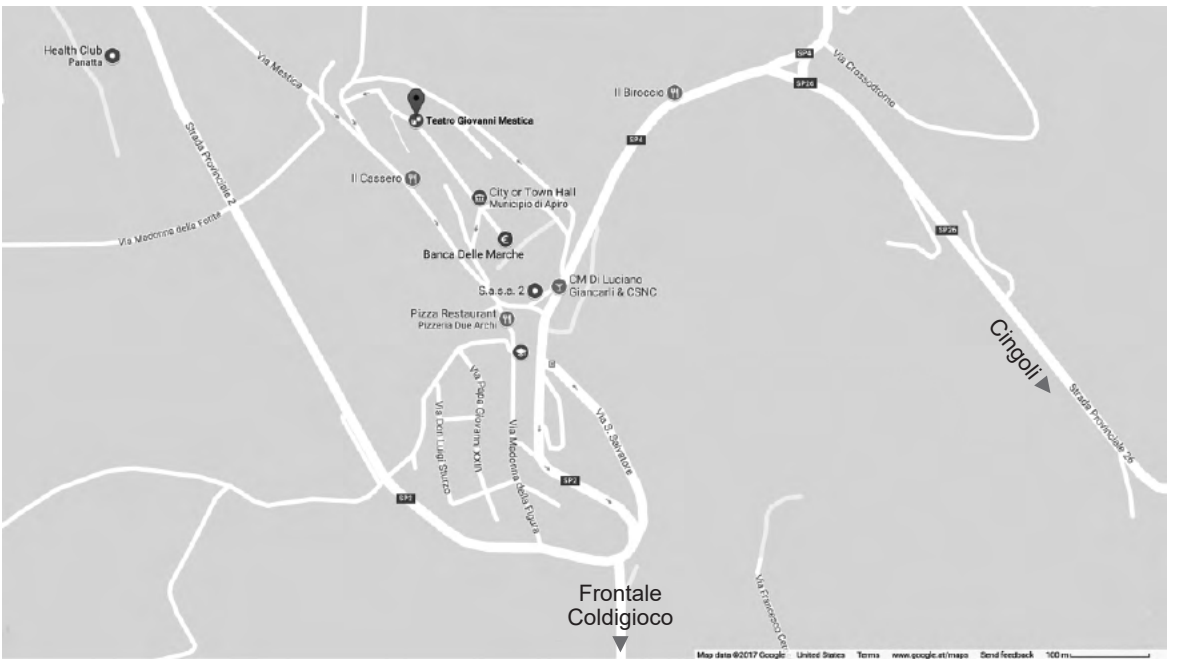
Venue:
The conference will be held in the historical Teatro Mestica in the medieval hilltop town of Apiro and the poster sessions will be set up in locales adjacent to the main theater auditorium. Lunch (included with the meeting fee) will be at "Il Biroccio", a typical Italian restaurant in Apiro in walking distance from the "Teatro". Coffee breaks and poster sessions will be held at the "Teatro" as well.



Accommodation:
Participants stay at the Hotel Tetto delle Marche in Cingoli (about 12 km from Apiro; half-board): www.hoteltettodellemarche.it
There will be bus shuttling in the morning and in the late afternoon to-and-from the conference site in Apiro. See the program for return times. In the morning (Mon-Wed) the bus leaves from the hotel at 8:30 a.m.

Those attendees not staying at the hotel in Cingoli, i.e., those with their own means of transportation (e.g., their own cars, rental cars), have to find their own parking in Apiro. Also they are requested to be at the hotel in Cingoli on Thursday morning and Friday morning at 8:20 for the field trip departures (which will be from the Hotel Tetto delle Marche in Cingoli at 8:30 a.m.).

Field Trips:
The field trips will visit classic geological sites (such as at Gubbio, where the asteroid impact hypothesis at the K-Pg boundary started, or the Frasassi caves, which are the largest show caves in Italy) and thus are of great importance for the work that is discussed at the meeting. See the schedule above for the two field trips that are included with the meeting fee. An optional all day field trip to Massignano near Monte Conero, where the GSSP of the Eocene-Oligocene Boundary is located, will be held on Saturday the 30th of September (extra cost). Field trips to Gubbio, Monte Conero, and Frasassi are organized with tourist busses, using local companies. Departure is at 8:30 a.m. from the hotel in Cingoli.

Emergency contact: Sandro mobile phone: +39 3200125225.

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Program Penrose Meeting: 250 Million Years of Earth History in Central Italy: Celebrating 25 years of the Geological Observatory of Coldigioco

Sunday, 24. September 2017

18:30-21:00	Ice breaker reception, Hotel Tetto delle Marche, Cingoli

Monday, 25. September 2017

9:00	Welcome and Introduction (A. Montanari, C. Koeberl)
9:15	Welcome address: Nadia Sparapani, Assessor of Culture of the Comune di Apiro
9:25	P. Kopsick: Cosa vedete? What do you see..? A brief history of Coldigioco and life
9:45	A. Montanari: Brief Review of the Umbria-Marche Sequence
	Session 1 (Chairs: D. Bice, R. Coccioni)
10:00	Keynote 1: W. Alvarez: Earth History Recorded in the Umbria-Marche Sequence - a Broad Perspective
10:30-11:00	Keynote 2: A. Montanari: Recent-Time Little Big History of Frasassi
11:00-11:30	Coffee break
11:30-11:50	M. Fiebig et al.: Some considerations about the reliability of OSL-datings in the Frasassi cave system
11:50-12:10	M. Lacroce et al.: Late Pleistocene tectonic tilting of the Frasassi anticline as measured from offset stalagmites in the Grotta Grande del Vento (Marche Apennines, Italy)
12:10-12:30	A.C. Pizzorusso: Caverns and Sanctuaries
12:30-14:00	Lunch at Biroccio
	Sesssion 2 (Chairs: J. Macalady, E.Tavarnelli)
14:00-14:30	Keynote 3: M.R. Barchi: The Seismicity of Central Italy in the Geological History of the Northern Apennines
14:30-15:00	Keynote 4: E. Tavarnelli: The role of structural inheritance in the evolution of fold-and-thrust belts: insights from the Umbria-Marche Apennines, Italy
15:00-15:20	P. Geiser: The problem of earthquake prediction: some reasons for its failure and a possible solution via tomographic fracture imaging (TFI)
15:20-15:40	L.S. Chan: Constraints on age and depth of occurrence of phreatic brecciation events in Hong Kong: Implications for the occurrence of seismogenic hydraulic fracturing
15:40-16:00	R.A. Bennett et al.: Characterizing abnormal sequences of normal earthquakes in central Italy: active fault creep, co-seismic stress transfer, and other possible controls
16:00-16:30	Coffee break
16:30-17:00	Keynote 5: M. Franceschi: Carbonate platforms of Adria across Early Jurassic carbon isotope perturbations
17:00-17:30	Keynote 6: F.J. Pazzaglia: Apennine Rivers and Fluvial Deposit Paleogeodetic Markers in the Study of Crustal Deformation and Exogenic vs. Autogenic Controls on Landscape Evolution

17:30-17:50	J. Weber et al.: Unifying several decades of GNSS/GPS measurements to study Adriatic microplate motion and neotectonics in the Southern Alps and northern Dinarides, Slovenia and surroundings
17:50-18:10	F. Mirabella et al.: Tectonically induced base-level change in the Quaternary revealed by alluvial fan shifts and rivers re-organization. A case study in the Northern Apennines of Italy
18:10-18:30	S.P. Lundblad: Evolution of small carbonate platforms (Calcare Massiccio and Corniola Formations) in the Umbria-Marche Apennines using strontium isotope stratigraphy: Implications for early Jurassic crustal structure
18:45	Return shuttle bus to Cingoli

Tuesday, 26. September 2017

	Session 3 (Chairs: K. Farley, F. Pazzaglia)
9:00-9:30	Keynote 7: R. Coccioni and A. Montanari: Thirty years of Lower Cretaceous to Miocene Integrated Stratigraphy in the Umbria-Marche Apennines (central Italy)
9:30-9:50	E. Tavarnelli: Factors controlling tectonic inversion
9:50-10:10	R.N. Mitchell et al.: A Late Cretaceous true polar wander oscillation
10:10-10:30	A. Montanari et al.: Pelagosite revisited: The origin and significance of a laminated aragonitic encrustation on Mediterranean supratidal rocks
10:30-11:00	Coffee break
11:00-11:30	Keynote 8: J. Smit: Tracing large impact events in Geological History
11:30-11:50	M.R. Rampino and K. Caldeira: Correlations among the ages of flood-basalt eruptions, extraterrestrial impacts, mass extinctions and times of ocean anoxia of the past 260 Myr
11:50-12:10	M.R. Rampino: A 26 Myr cycle in the ages of impact craters and mass extinctions of life?
12:10-12:30	T. Korbar: Cretaceous-Paleogene boundary tsunamite on Adriatic Carbonate Platform and implications on paleogeography of the western Tethys – a review
12:30-14:00	Lunch at Biroccio

	Session 4 (Chairs: R. Bennett, B. Schmitz)
14:00-14:30	Keynote 9: P. Claeys et al.: Chicxulub: old and recent results to document the best peak-ring crater on Earth
14:30-15:00	Keynote 10: D.M. Bice: Searching for signals in the noise: The Coldigioco approach to cyclostratigraphy in the Umbria-Marche Apennines
15:00-15:20	M. Sinnesael et al.: High-resolution multiproxy cyclostratigraphic analysis of environmental and climatic events across the Cretaceous-Paleogene boundary in the classic pelagic succession of Gubbio (Italy)
15:20-15:40	M. Sinnesael et al.: Applying and evaluating the use of portable X-ray fluorescence (pXRF) measurements on pelagic carbonates: Maastrichtian strata from the Bottaccione Gorge, Gubbio, Italy
15:40-16:00	L. Folco et al.: Impactor identification in tektites and microtektites using Ni, Co and Cr ratios: the case of the Australasian tektite/microtektite strewn field
16:00-18:30	Poster session with coffee & refreshments
18:45	Return shuttle bus to Cingoli

Wednesday, 27. September 2017

	Session 5 (Chairs: P. Claeys, J. Smit)
9:00-9:30	Keynote 11: B. Schmitz: Reconstructing the late history of the asteroid belt from sedimentary rock sections in the Apennines
9:30-9:50	E. Martin and B. Schmitz: Meteorite flux in the Late Cretaceous
9:50-10:10	D. Lenaz et al.: The terrestrial Cr-spinels in the Maiolica limestone: where are they from?
10:10-10:30	C. Koeberl et al.: Attempts to constrain the impactor composition from isotopic analyses of spinel-rich samples from Late Eocene impact ejecta at Massignano, Marche, Italy
10:30-11:00	Coffee break
11:00-11:30	Keynote 12: K.A. Farley: 80 million years of cosmic dust flux variations recorded in the Umbria-Marche Basin, including a now well-resolved multi-Myr ^{3}He event coincident with C33R-C33N at 80 Ma
11:30-11:50	D.M. Bice: Cyclostratigraphic analysis of the Late Cretaceous ^{3}He anomaly at Furlo, Italy
11:50-12:10	S. Lucas et al.: Using extraterrestrial ^{3}He concentration to examine changing sedimentation rates within a precession cycle
12:10-12:30	S. Boschi et al.: The Popigai impact ejecta layer recovered in a new Italian location, Monte Vaccaro section (Piobbico)
12:30-14:00	Lunch at Biroccio
	Session 6 (Chairs: C. Koeberl, S. Lundblad)
14:00-14:20	B.P. Glass: Could microtektites and shocked mineral grains from the Chesapeake Bay impact be found as far as Massignano, Italy?
14:20-15:00	Discussion: Extraterrestrial signals in the sedimentary record
15:00-15:30	Keynote 13: J.L. Macalady: Microbes Never Die - Lessons in Geochemistry and Astrobiology from 15 years of research at Frasassi

15:30-16:00	Coffee break
16:00-16:30	Keynote 14: D.M.P. Galassi: Stygobitic crustacean fauna in the hypogenic sulfidic caves of Frasassi (Italy): a challenge in a challenging environment
16:30-16:50	P. Ward and R. Mitchell: Mass extinctions and biodiversity: a view from 2017
16:50-17:30	General discussion: From Tectonics to the Frasassi Caves
17:30-18:00	Introduction to field trips (A. Montanari)
18:15	Return shuttle bus to Cingoli

Thursday, 28. September 2017

8:30	Departure for all-day field trip to Gubbio and surrounds from Hotel Tetto delle Marche, Cingoli; Lunch at Bottacione Gorge Restaurant; return to Cingoli ca. 18:30

Friday, 29. September 2017

8:30	Departure for half-day field trip to Frasassi Gorge from Hotel Tetto delle Marche, Cingoli; return to Cingoli ca. 13:00
16:30	Shuttle bus from Hotel Tetto delle Marche, Cingoli, to Coldigioco
17:00	Visit to and reception at Coldigioco, with music, art, and food, on the occasion of the 25th Anniversary of the „Osservatorio Geologico di Coldigioco“, until about
22:00	(return shuttle bus to Cingoli)

Saturday, 30. September 2017

9:00	Departure for optional field trip to Monte Conero and Massignano from Hotel Tetto delle Marche, Cingoli; lunch at Fortino Napoleonico in Portonovo, return to Cingoli ca. 18:30

250 Million Years of Earth History in Central Italy

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Abstracts

PREFACE

Cosa vedete? What do you see..? A brief history of Coldigioco and life

Paul Kopsick

Regent and Historian of Osservatorio Geologico di Coldigioco
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What do you see? It is possibly the most important question ever posed to man and it is particularly relevant to a geologist or any other scientist. What are you looking at and why is it there? What made it look like that?

For Coldigioco, the earliest question I had, although I did not know it at the time was in 1976, it was, "Who is that?" That was when I first met 'Gallo', a young Italian student who came to the USA with his future life mate Paula Metallo. In brief, what I saw was someone that I wanted to know more and who possessed innate skills and raw talent that I wanted to see develop and be a part of. An unexpected journey begins.

Pre-Villa K\T ruin and Piazza Itala in Coldigioco, 1993.

Skip ahead. "Where is it?" Was another question I was posed when in the summer of 1993, Sandro Montanari and I stood amongst the dirt and turkey droppings in the center of the decaying hamlet of Coldigioco in what is now Piazza Itala. The question was in response to him showing me the 'house' he wanted me to buy. Standing there and looking at the shell of a decades old assemblage of stones and clay tiles 'loosely' held together by mortar and gravity, I stared at the glassless windows, through the holes in the roof and floors and with surprising clarity somehow recognized, "Oh, there it is." A new phase of the journey begins. There and back again.

I was not the only one who has asked the same questions: “Who is that?” and “What am I looking at?” Walter Alvarez was faced with similar questions when he first met Sandro Montanari on an outcrop above Gola del Furlo, Italy in August 1978. By 1992, Walter had already responded to my second question and was setting up shop in the ‘Old School’ building that was to become the center of geologic research for hundreds of scientists and students. Walter had been asking similar questions throughout his accomplished career, like “Where did all the forams go?” and “What is that thin layer of clay?” The same can be said for anyone that has worked in Coldigioco.

Something else I learned very early while at Coldigioco was that ‘everything has a story.’ Everything! You just have to ask or figure it out for yourself. The motto on the logo for the Osservatorio Geologico di Coldigioco reads, “EX LIBRO LAPIDUM HISTORIA MUNDI” out of the book of rocks [comes] the history of the world [i.e., the Earth]

Indeed, each of the full-time and part-time inhabitants of Coldigioco have relied on their visual and mental talents to pose and answer a myriad of questions about what they see, why it is that way and just as importantly, how to explain it to others. Yes, these questions and talents are not unique to Coldigiocans. They are the basic tenants of life, learning and survival. However, through these last 25 years and hopefully for many more years to come, Coldigioco has lived up to the original ideals it was founded on and has become a nexus for creative thought, unfiltered science and enlightenment. The journey continues with a new generation of observers.

Villa K\T renovated and Piazza Itala in Coldigioco, 2017.

Keynote Presentations

Earth History Recorded in the Umbria-Marche Sequence — a Broad Perspective

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This keynote talk backs off from the scientific details of geological research in the Umbria-Marche Apennines to place that research (1) in the context of its human setting, notably the remarkable little medieval city of Gubbio, and (2) in its relation as geological research to research in astronomy, making the point that sometimes we do astronomy by looking down, and geology by looking up.

Gubbio has a rich history dating back to pre-Roman times, when it was called *Ikuvium*, Roman times with the name *Iguvium*, and Medieval times, when the current name came into use. The pre-Roman history lacks architectural monuments, and is represented most dramatically by the Eugubine Tablets, preserved in the municipal museum, which are written in Umbrian, the Italic language spoken in Gubbio before the Roman conquest. Roman Gubbio is represented by a well preserved theatre, still used for dramatic productions. Gubbio today is a gem of Medieval architecture, dominated by the Palazzo dei Consoli, and also including several major churches, a castle and defensive towers, and many residential buildings with distinctive architectural elements like the "doors of the dead."

The most dramatic manifestation of medieval Gubbio is the Festa dei Ceri, held on May 15 each year, and dominating the public life of the town. Statues of three saints — Sant'Ubaldo (patron saint of Gubbio), San Giorgio, and Sant'Antonio — mounted on tall wooden towers, are carried by their partisans at a dead run from the great piazza in front of the Palazzo dei Consoli, up a narrow zag-zag path to the Basilica of Sant'Ubaldo, 300 m higher, up the side of the mountain. The race, known as the Corso dei Ceri, is so wild and difficult that other Italians speak of these people as *i Matti di Gubbio*, the lunatics of Gubbio.

Part way up the path of the race, carried at high speed, the Ceri cross the level of a medieval aqueduct, built in the 14th century, to bring water from a reservoir behind a dam down through a canyon to the town. The reservoir, now almost completely silted up, is known by the fanciful name of *il Bottaccione*, "the big water barrel." The gorge cutting the mountain, which exposes pelagic limestones and marls dating from the Lower Cretaceous to the Miocene, is therefore called the Bottaccione Gorge. It is here that the amazing record of Earth history contained in pelagic carbonate rocks was first recognized.

This sequence was originally studied by the Gubbio geologist, Guido Bonarelli, at the beginning of the 20th century. In the 1930s, the young Swiss geologist, Otto Renz, first learned to identify planktic forams in thin sections of these hard limestones, which cannot be broken down to yield isolated foram tests. In the 1960s, the tecnhique of dating pelagic limestones with forams in thin section was perfected by Hanspeter Luterbacher and Isabella Premoli Silva, and this has made possible all of the subsequent studies of Earth history done in the Bottaccione Gorge and nearby exposures of the Umbria-Marche sequence, including the dating of the Cretaceous and Paleogene geomagnetic reversal sequence, the recognition of the KT boundary impact and extinction, and the many studies of paleontology, geochemistry, geochronology, and cyclostratigraphy that have enriched our understanding of Earth history.

The investigations of the record of large impacts on the Earth and of Milankovitch cyclostratigraphy are examples of what can be called "doing astronomy by looking down." They are based on finding proxies in the stratigraphic record for events in the Solar System or beyond that have affected the Earth. A recent example from elsewhere is the discovery of a 2.0-Ma anomaly of ^{60}Fe (half life ~2.6 Myr) in marine sediments, that appears to record a nearby supernova. In other examples, astronomers use the Earth as a filter or a detector, as in the case of the neutrino observatory in the deep Homestake Mine in South Dakota, and the LIGO observatories that recently detected gravity waves by observing the stretching of the Earth.

Another recent example is the research led by Birger Schmitz (this volume) which requires dissolving large samples (typically 1000 kg) of pelagic limestone to recover a few grains of chromite. Chromite is usually the only mineral of a meteorite that survives chemical alteration in marine sediments, and the trace-element content of chromite is diagnostic first of meteoritic vs. terrestrial origin, and in the former case, of the class of meteorite that supplied the chromite grain. The pelagic limestones of the Umbria-Marche sequence, particularly the very pure Maiolica limestone of the Lower Cretaceous, are ideal for this work, which holds the promise of identifying and dating collisions in the asteroid belt, recorded as changes in the kinds of chromite in the sedimentary record — a remarkable case of doing astronomy by looking down.

There are also cases of "doing geology by looking up." For example, much of what we know about the formation of the Sun and the Solar System comes from astronomical observations of brand-new stars just emerging from clouds of gas and dust, sometimes shooting out high-velocity Herbig-Haro jets in opposite directions along the spin axis of the new stellar system. Evidence for the still-controversial Late Heavy Bombardment comes primarily from the large, late impact craters on the Moon.

Perhaps the most dramatic and surprising case of "doing astronomy by looking down" took place early in the 20th century, when Hubble and Humason proposed that the Universe is expanding, beginning with what we now call the Big Bang. Inverting the expansion rate gave them a date for the origin of Universe of about 2 Ga. But early results from the then-new field of geochronology indicated that the Earth was at least that old, and probably older. Astronomers and geologists agreed that the Earth was unlikely to be older than the Universe, and as a result Hubble effectively retracted the discovery for which he is now famous. Astronomers later found that the cosmic distance ladder used by Hubble and Humason to measure the distance to receding galaxies was in error by a factor of about 7. When the cosmic distance ladder was later corrected, the age of the Universe was re-dated to 3 times the age of the Earth, and Hubble and Humason were posthumously shown to have been qualitatively correct, although quantitatively wrong.

Geology and astronomy have more overlap than is commonly recognized, and Gubbio and the Umbria-Marche Apennines are among the places where their interconnection has developed.

The Seismicity of Central Italy in the Geological History of the Northern Apennines

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Three destructive earthquakes (Colfiorito 1997-98, M_{max} = 6.0; l'Aquila 2009, M_{max} = 6.3; Amatrice-Norcia 2016-17, M_{max} = 6.5) occurred in Central Italy in the last 20 years, producing hundreds of fatalities, and widespread, dramatic damage of both villages and historical heritage. The progressively increasing quality of seismological data gives us detailed imaging of the activated faults, highlighting that, despite of their significantly different spatial and temporal evolution, all these seismic sequences were generated by complex systems of NNW-SSE trending normal faults, affecting the first ca. 10 km of the upper crust. Considering also older, lower-quality seismological data (covering the last century), historical seismicity (covering about 2 ka) and paleoseismological data, we can reconstruct the activity of the seismogenic fault systems back to a maximum of 10-20 ka.

In this talk, it will be discussed how the very recent tectonic history, highlighted by the seismic events, can be linked to the 250 Ma long history of the Umbria-Marche Apennines.

Last 2 Ma: it is largely accepted that the seismically active faults have strict connection with the Quaternary faults affecting the axial zone of the Northern Apennines, bordering extensional basins (grabens and half-grabens) whose distribution reflects the distribution of historical and instrumental seismicity. Seismogenic active faults and Quaternary faults are related to the same stress field (as also shown by focal mechanisms) and adjust the same strain field (as also imaged by geodetic, i.e. GPS and InSAR data). During the seismic events of 2016, clear surface ruptures were observed along the fault planes bordering the Quaternary Castelluccio basin.

Last 20 Ma: extensional tectonics, presently active in the axial region of the Apennines (as well as the contemporaneous compressional earthquakes active in the Adriatic-Po Plain foreland), represent the last, present-day stage of a long-lived tectonic process, active since Early Miocene, where a compressional-extensional couple migrated eastward through time across the Italian peninsula, as testified by the ages of synchronous hinterland (extensional) and foreland (compressional) basins.

Last 200 Ma: more complex and controversial is the relation between the distribution of present-day seismicity and the older periods of the Umbria-Marche geological history. Quaternary faults act on a structurally complex upper crust, whose rocks are pervaded by previous faults and discontinuities, which may affect the localization and segmentation of the seismogenic faults. In some cases, seismogenic faults have been hypothesised to re-activate previous faults (e.g. Late Miocene thrust faults of the Apennines mountain belt, or syn-orogenic normal faults accomplishing the flexure of the Apennines foreland). More often, previous compressional and/or strike-slip faults seem to have a major effect on the segmentation of the extensional fault system. Finally, it is not less important to consider the role of the mechanical stratigraphy, determining the superposition of rocks with different rheological behaviour and, after all, the thickness of the seismogenic layer. By studying seismic reflection profiles crossing this region, it has been observed that most of the earthquakes occur within the sedimentary cover, with mainshocks located at the base of this layer.

In conclusion, while innovative technologies and improved density of the instrumental networks provide impressive advance on the detailed reconstructions of the seismogenic faults, the contribution of more general studies of stratigraphy, tectonics and geomorphology is still required for a better understanding of these phenomena in a correct and comprehensive regional framework.

Searching for signals in the noise: The Coldigioco approach to cyclostratigraphy in the Umbria-Marche Apennines

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The Umbria-Marches Apennines have provided a remarkable opportunity to explore and understand the role of astronomical cycles in controlling the Earth's climate over that past ~200 myr. Over this time span, a largely pelagic sequence of mainly marls and limestones accumulated in a relatively deep Tethyan continental margin basin. The early development of a magetostratigraphy and radioisotopic dates from numerous volcanic ashes provided a chronological framework to independently evaluate the periods of stratigraphic cycles, expressed through lithology, geochemical proxies, magnetic susceptibility, and color. Over the past 20 years of research at the Osservatorio Geologico di Coldigioco (OGC) in tight collaboration with Alessandro Montanari (an expert stratigrapher and pelagic carbonate sedimentologist), I have sought to identify and understand these cycles through the use of spectral analysis techniques run with MatLab scripts that I have developed and refined in a quest to find the meaningful signals through the noise. The stratigraphic record is noisy for several reasons: 1) the Earth's climate system is noisy, 2) the proxies we use are imperfect, and 3) we at OGC generally assume that sedimentation rates are constant, though we know this cannot be the case. Seeing through this noise is challenging and given the fact that we are genetically conditioned to find patterns in nature, I have adopted a skeptical approach, using a variety of techniques to help isolate meaningful signals of paleoclimatic cycles. At OGC we begin with careful field work to make sure our sections are measured as carefully as possible, with sample collection designed to minimize the effects of bioturbation and provide the temporal resolution needed to identify the highest frequency signals. We also try to utilize as many different proxies as possible. In order to find meaningful signals, we have developed a set of strategies to create and analyze random data sets to provide a 95% confidence level to compare with the real data. If meaningful signals are identified, we carefully apply band-pass filters to isolate these signals to compare them with the stratigraphy in order to understand how these cycles are expressed in the rock record. We also use these band-passed signals to examine amplitude modulations using Hilbert transforms. The cycles of amplitude modulations allow us to evaluate whether the apparently significant signals are likely to be expressions of astronomical cycles, whose amplitude modulations are well-known. In addition, we use the band-passed signals to compare with each other in order to test whether signals that we suspect are the expressions of precession and eccentricity in the stratigraphy have the same relationship that is observed in the astronomical cycles. We have applied this approach to a broad range of data, including historical climate records, tree rings, varves, and stratigraphic proxies ranging in age from the Jurassic to the Miocene, and have come to believe that this careful, thorough, and skeptical application of the tools of spectral analysis have resulted in significant contributions to our understanding of the history of climatic cycles on Earth.

Chicxulub: old and recent results to document the best peak-ring crater on Earth

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The Chicxulub crater in Yucatan (Mexico) results from the asteroid or comet impact that is linked to the K-T (or K-Pg) boundary mass extinction. The Chicxulub structure has a diameter between 190 and 210 km and lies buried under several hundred meters of Cenozoic sediments, onshore and offshore the Yucatan Peninsula (Hildebrand et al. 1991). Chicxulub is the one of the largest terrestrial craters and, based on geophysical imaging, certainly the best-preserved peak-ring basin on the planet. From the PEMEX oil exploration wells around the sixties, in search of an extension to the highly-productive Cantarell oil field, to the 2016 IODP-ICDP expedition 364, Chicxulub has been subject to several drilling exploration programs, together with various geophysical campaigns (Fig. 1). The abstract reviews existing data in the light of the recent developments regarding the cratering process and K-T boundary deposits. The PEMEX exploration program extended from the fifties to the late 1970's and about 8 holes were drilled, which remain among the deepest within the structure (Perez-Drago, et al. 2008). Being dry holes, limited studies were carried out and today very little core material remains. Well Yucatan-6 (1631 m), located on the onshore part of the peak-ring yielded a succession of suevite (Claeys et al. 2003), and below it, coarse impact melt-breccia which was used to confirm the impact crater origin (Kring and Boynton, 1992). Well Chicxulub-1 (1582m), close to the crater center, bottomed in fine impact-melt rock, and provided the first ^{40}Ar-^{39}Ar ages linking Chicxulub to the K-T boundary (Swisher et al. 1992). In the 1990's, the Universidad Nacional Autónoma de México (UNAM) drilled several shallow (700 m) wells outside the crater rim (Urrutia-Fucugauchi et al., 1996). They revealed a proximal ejecta blanket composed of suevite, and thick carbonate- and evaporite-breccias. Seismic experiments, conducted in 1996 and 2005 imaged the different impact lithologies down to the bottom of the crust and highlighted the well-preserved 80-km in diameter peak-ring morphology of the structure (Morgan et al. 1999; Gulick et al. 2008). The seismic data also illustrate pre-impact conditions and advocate deeper-water conditions and thicker Mesozoic sediments in the northeast quadrant. In 2001-2002, the International Continental Drilling Project (ICDP) drilled in the trough zone, outside the peak-ring (Urrutia-Fucugauchi et al., 2004). The recovered core is composed of Cenozoic carbonates (from 404 m where coring started down to 795 m), a thin impactite succession (795 – 895) most likely spilled over from the peak-ring area, and a down to 1511 m, carbonate and evaporite units from the upper part of the target rock. Their preserved stratigraphic orientation indicates that this (or these) or mega-block(s) gently "slid" inward from the rim zone (Belza et al. 2012). Drill core M0077A was recovered in April 2016, by the International Ocean Discovery Program (IODP) and ICDP into the peak ring of Chicxulub offshore the Yucatán Peninsula. Three main lithological units encountered are: 1) Paleogene sedimentary rocks (Post-Impact section), 2) Suevite and impact melt rock (Upper Peak ring section), and 3) Granitic peak ring rocks intruded by pre-impact dikes and intercalated with suevites and impact melt rocks (Lower Peak Ring section). The recovered highly shocked granitic rocks, originating from deep within the Yucatan basement, support the dynamic collapse model to explain the formation of the uplifted peak-ring zone (Morgan et al. 2016).

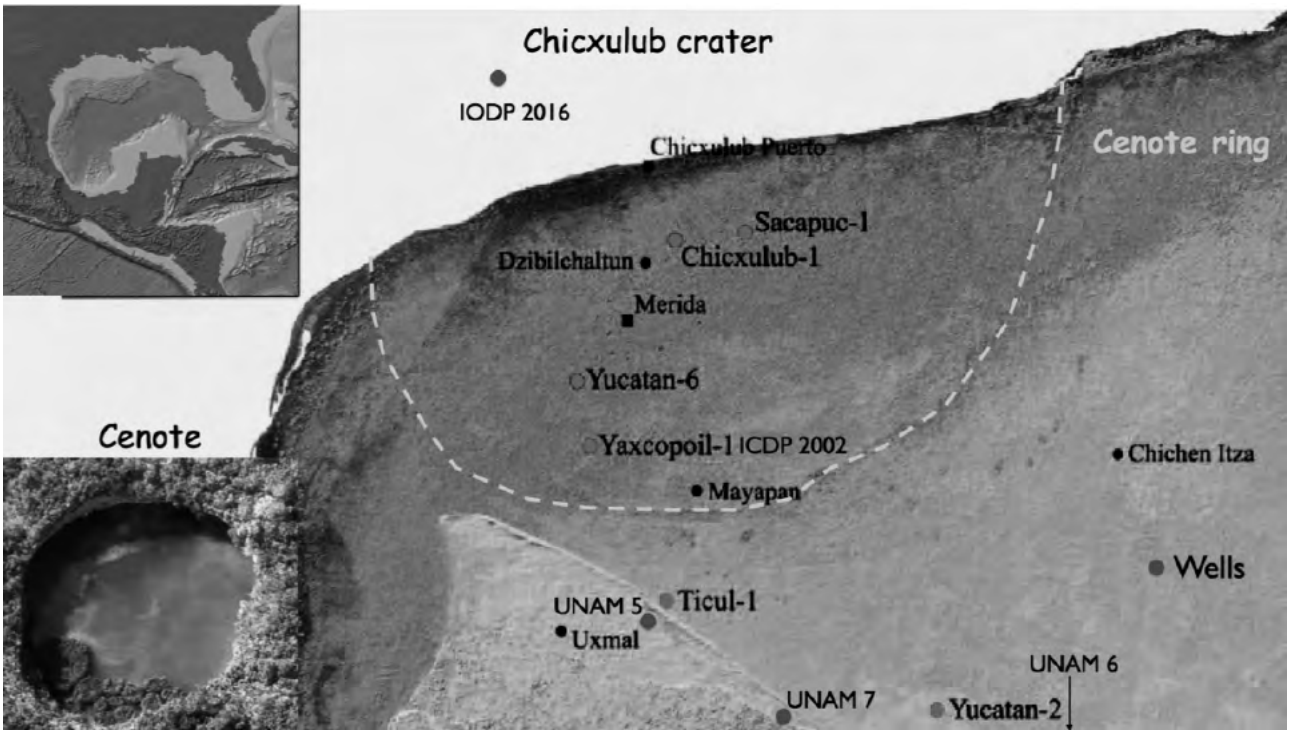

Fig. 1 - Localization of the wells drilled in and around the Chicxulub structure

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Thirty years of Lower Cretaceous to Miocene Integrated Stratigraphy in the Umbria-Marche Apennines (central Italy)

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This keynote presentation aims to highlight the application of Integrated Stratigraphy in the Umbria-Marche (U–M) Apennines of central Italy, which has resulted from our continual involvement in the geological research of this area for the last thirty years within the framework of cooperative international research projects as a key tool for the study of the U–M Lower Cretaceous to Miocene pelagic sedimentary successions. The features of this essentially continuous and complete succession make it an unique venue for documenting the geologic history of Earth through the application of a multi–disciplinary approach, which is valuable not only to sedimentologists, paleontologists, and paleoclimatologists, but is also useful to more specialized biostratigraphers, magnetostratigraphers, chemostratigraphers as well as geo– and astrochronologists who address their effort to reach an ever improving global chronostratigraphy. Our use of Integrated Stratigraphy has followed broad purposes, such as: identification of potentially useful sections for the definition of chronostratigraphic units, forward recommendations on the choice of particularly interesting sections and points for the refinement of the chronostratigraphic time scale (GSSP: Global Boundary Stratotype Section and Point) including the GSSPs for the base of the Rupelian, Chattian, and Tortonian Stages, detailed reconstruction of the tectono–sedimentary evolution of the U–M basin, and paleoenvironmental, paleoclimatic, paleogeographic and paleoceanographic reconstructions. As stratigraphic methods improved in both precision (resolution) and accuracy, the integrating of various component aspects of stratigraphy has resulted in major improvements in our understanding of the nature, sequence, and chronology of events in Earth history, and in placing Earth history in a truly historical context. Here we show the most significant examples of our multi–disciplinary approach.

80 million years of cosmic dust flux variations recorded in the Umbria-Marche Basin, including a now well-resolved multi-Myr ^{3}He event coincident with C33R-C33N at 80 Ma

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The slowly accumulating and uninterrupted deep marine carbonates of the Umbria-Marche Basin (UMB) have been critical for the development of a nearly complete 100 Myr record of the cosmic dust flux, using ^{3}He as a tracer. The idea to study ^{3}He in the UMB originated with Gene Shoemaker, who proposed using the method to confirm his belief that a comet shower occurred in association with the large Late Eocene impacts (Chesapeake Bay, Popigai). In 1996 we [1] sampled the Massignano section, and analysis of the resulting samples revealed the first known episode of an extended period (3 Myr) of enhanced cosmic dust flux. We took the temporal evolution of the ^{3}He peak and its coincidence with previously discovered impact indicators as confirmation of the comet shower hypothesis, though this conclusion has been challenged and an asteroid shower offered as an alternative [2]. The Maastrichtian and the remainder of the Paleogene were sampled at Bottacione Gorge, but no additional ^{3}He peaks were discovered [3]. Apparently the K/T impactor was not associated with enhanced inner solar system dustiness [4]. More recently, a 3 Myr episode of enhanced ^{3}He flux at ~8 Ma, attributed to the collisional destruction of the parent body of the Veritas asteroid family [5], was confirmed at Monte di Corvi, near Ancona [6]. In addition, the Bottaccione Gorge sampling was extended back to ~100 Ma, and three additional cosmic dust events were tentatively identified, in the Campanian, the Santonian, and the Turonian stages [7]. Most notable of the three possible Cretaceous events, the Campanian peak (called K1) is identified by an abrupt increase in ^{3}He associated with a lithologic change (the R1 to R2M transition), the C33R-C33N boundary, and the first appearance of syndepositional slumping and faulting in the UMB. These characteristics suggest sediment disturbance and missing section, making it difficult to interpret the ^{3}He data. A new, high temporal resolution Campanian ^{3}He record from an apparently complete and undisturbed section (Apiro, ~40 km east of Gubbio) reveals a well developed >3 Myr-duration ^{3}He peak, with a maximum amplitude ~10x above pre-event levels. To within a few cm the ^{3}He maximum coincides with the C33R-C33N transition. This pattern was also found in the nearby Furlo locality. The temporal evolution of this event is similar to the late Eocene comet (or asteroid) shower. The synchroniety of K1, the magnetochron boundary, and the onset of sedimentary disturbances (turbidities) attributed to eustasy-induced seismicity [8] encourages speculation of a causal link, perhaps through comet-shower related bolide impact(s). The possibility of impact-induced magnetic field changes has been noted previously [9]. A few minor impact craters (Lappajarvi, Wetumpka [10]) are plausibly coincident with K1, but apparently other impact indicators of this age are unknown. These data invite closer scrutiny of events in the early to middle Campanian.

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Carbonate platforms of Adria across Early Jurassic carbon isotope perturbations

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During the Early Jurassic, Earth experienced major palaeogeographic and biologic modifications. The Pangea mega-continent underwent a progressive break-up and after the mass-extinction at the Triassic/Jurassic boundary, life in the seas gradually recovered. The reorganization of continental masses under the effects of rifting brought to the widening of the Tethys Ocean at tropical latitudes and created ample extensions of shallow seas where large carbonate platforms developed. In deep waters, a key event that would have had far-reaching implications was the expansion of pelagic biocalcification, which commenced sometimes in the Late Triassic and became abundant in the seas during Early Jurassic, for reasons that are not yet fully understood.

The Early Jurassic also witnessed global perturbations of the carbon cycle that appear associated to environmental changes and that are attributed to the emission of large amounts of greenhouse gases into the atmosphere-ocean system. Major modifications in the shallow water carbonate environments and shifts in the δ13C record are associated to such perturbations.

The Apennines and the Alps expose thick successions of carbonate rocks that testify for the extended platforms, separated by deep basins, which occupied the southern margin of Tethys, in those times. Spectacular examples are the Calcare Massiccio and the Calcari Grigi. The rocks of these units tell of the evolution of shallow water carbonate environments across global carbon isotope perturbations in the Sinemurian–Pliensbachian when the thus far dominant microbial carbonates underwent an abrupt demise.

The comparison to similar events in a deeper past (Carnian Pluvial Episode) reveals similarities that suggest common underlying mechanisms in the interplay between environmental changes in times characterized by disturbances in the carbon isotope record and the shallow water carbonate factory. This may have significant implications on the understanding the contribution of marine calcium carbonate precipitation to the global carbon cycle and the advent of pelagic biocalcification.

Research to tackle these questions is much needed and the application of integrated stratigraphy in the spectacular playground of the carbonate successions of the Apennines could provide some of the keys for their understanding.

Stygobitic crustacean fauna in the hypogenic sulfidic caves of Frasassi (Italy): a challenge in a challenging environment

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The Frasassi cave system in central Italy hosts one of the few known examples of a groundwater metazoan community that is supported by sulfur-based lithoautotrophic microbes. Despite the challenging conditions represented by high concentrations of toxic hydrogen sulfide (H_2S) and low concentrations of oxygen, this cave system is home to many invertebrate species, including Rotifera (Montanari, 2000), Mollusca Gastropoda (Bodon and Cianfanelli, 2012), Platyhelminthes (Montanari, 2000; Stocchino et al., 2017, *in press*), and an extraordinarily diversified community of Crustacea including Amphipoda (Dattagupta et al., 2009; Karaman et al., 2010; Bauermeister et al., 2012), Ostracoda (Peterson et al., 2013), and Copepoda (Galassi et al., 2017).

If some amphipod and ostracod species are able to live in strict contact with the microbial mats in the benthic layers of the sulfidic lakes, this is not the case for the copepods. The distribution of the copepods is described herein by analyzing spatial and temporal variations in the assemblages inhabiting both sulfidic lakes and non-sulfidic dripping pools in the Frasassi cave system, in order to explain which environmental conditions regulate the spatial distribution of these microcrustaceans. Particular attention is addressed to copepod assemblages of sulfidic lakes under conditions of both high and low H_2S concentrations. Cluster analysis and canonical correspondence analysis separated the copepod assemblages inhabiting dripping pools from those living in sulfidic lakes, with the stygoxene species living almost exclusively in the non-sulfidic karst. H_2S concentration, pH and O_2 concentration were identified as the main factors regulating the community structure. These results indicate that the distribution of groundwater copepods within the cave system is ecologically and spatially structured. Sulfidic lakes showed lower Simpson dominance, higher Shannon diversity and higher Pielou equitability at higher H_2S concentrations. The complex community structure of the copepods of the Frasassi cave system suggests that a chemosynthetically produced food source facilitated the colonization of sulfidic groundwater likely due to preadaptive traits of the ancestral populations which made them able to overcome harsh environmental conditions.

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Microbes Never Die – Lessons in Geochemistry and Astrobiology from 15 years of research at Frasassi

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The spectacular microbiota native to sulfidic caves in the Frasassi Gorge has been a focus of our research since 2003. The challenges of carrying out research underground have been met by Penn State caver-scientists, logistical support from the Osservatorio Geologicio di Coldigioco, long-term collaborations with Italian speleologists, and continuous funding from NASA and NSF. Our combined efforts have resulted in more than 25 scientific publications and 60 conference abstracts so far. The publications and related ongoing work address fundamental questions in biogeoscience, including how microbes make a living from chemical energy (Jones *et al.* 2014, Hamilton *et al.* 2015), how fluid flow dynamics interact with chemistry to control microbial growth (Macalady *et al.* 2008, Jones *et al.* 2015), the timescale for development of microbe-animal symbioses (Dattagupta *et al.* 2009), rates of microbial evolution versus physical transport (Jones *et al.* 2016), the origins of microbial populations in the terrestrial subsurface (Mansor *et al.* 2016), how signatures of past microbial life are preserved in minerals (Zerkle *et al.* 2015, Harouaka *et al.* 2016, Mansor *et al.* 2017), and how microbes influence cave formation (Jones *et al.* 2015). These studies rely equally on geological and geochemical field observations and the analysis of microbial genes and gene products (RNA, lipids, proteins), which combine in a powerful approach known as "environmental omics" or "microbiome science". Important mysteries remain for future research at Frasassi, including the age and origin of the anoxic microbial ecosystem deep within the aquifer. Due to past scientific investment at Frasassi, it is now more than ever an extraordinary natural laboratory for exploring early Earth biogeochemistry, microbial evolution, and the search for reliable biosignatures of life in the universe.

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Recent-Time Little Big History of Frasassi

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Apart the many of its marvels, which have been keeping busy a number of speleologists, geologists, hydrogeochemists, geomorphologists, zoologists, microbiologists, and archeologists from allover the world, the Frasassi cave complex offers a unique opportunity to study and understand the Little Big History of this part of the world through the past couple million years (i.e., most of the Pleistocene and the Holocene epochs). In fact, when admiring the dramatic scenarios of the Frasassi gorge, with its 400 m high shear vertical limestone cliffs (from Latin *Infra Saxa* = in between stones), or the intricate and fabulously decorated maze of the cave system, which carves the insides of the mountain on either side of the gorge, an earth scientist has a clear perception of time and geologic history. The Sentino River has obviously incised the Frasassi gorge, from its top down to the present bottom thanks to a combined process of antecedence and superposition ensured by the continual orogenic uplifting of the Apennines and fluvial erosion, punctuated by glacial-interglacial episodes, a process that started as far back as the latest Miocene, i.e. the time of emersion of this region from the sea. As for the cave, Frasassi is a hypogenic sulfidic cave complex (as opposed to a classic epigenic karst), meaning that the massive limestone making up the core of the Frasassi-Valmontagnana blind-thrust anticline, is dissolving mostly below water table, i.e. below piezometric (base) level, which corresponds to the mean river level flowing through the gorge. This is because sulfidic water upwelling from the Triassic Burano anhydrites, a formation resting below the karstified lower Jurassic Calcare Massiccio Formation, meets the carbonate aquifer at or just below piezometric level, where H_2S gets oxidized forming sulfuric acid (H_2SO_4), an extremely aggressive agent, which brutally corrodes the encasing limestone. Production of sulfuric acid is facilitated by the metabolism of sulfur-oxidizing bacteria, which thrive at the chemocline (the interface between sulfidic-anoxic water coming from below and carbonate-oxygenated water percolating from above). Locally, where the hydrogen sulfide exhales out of phreatic pools into the cave atmosphere, the vaults of the cave are subject to fast carbonate corrosion, with the formation of instable slush masses of gypsum, leading to the enlargement of cave spaces (i.e. formation of vertical shafts and tall rooms).

The organization of the cave system in 7 main hypogean subhorizontal floors connected by subvertical shafts, suggests that the speleogenic process evolved through phases of dissolution along an horizontal plane alternated with phases of localized dissolution forming vertical shafts. The uppermost horizontal floors, which are the oldest, are found at elevations around 500 m above sea level (asl), whereas the lowermost floor, where dissolution is presently occurring at or just below water table, runs at about 200 m asl, which is the mean elevation of the Sentino River flowing at the bottom of the Frasassi gorge (the thalweg). This implies that parts of the Frasassi hypogenic cave system, which formed across and below the thalweg, would have been incised by the Sentino River in its slow process of erosion and deepening of the gorge, forming new entrances to the cave system now open on the carved gorge's cliffs. Therefore, at times the river floods the cave, freely flowing through these newly incised cave entrances, and transporting sediment into the cave maze. Close to the cave entrance it will be poorly sorted sediment, like gravel and sand mixed with

clay and silt. In inner parts of the cave, the sediment will be sorted out to just limey clay.

Slackwater sedimentary deposits preserved in the cave, thus, represent periods of deposition in a normal stratigraphic sequencing. In a near entrance space in the cave, like in a shaft or a depression of the rocky cave floor, the oldest sediment layer found at the bottom of one such slack water deposits represents the first river flood through the newly breached cave entrance, whereas the top in the same deposit the last flood, after which the river could no longer reach the sill of the cave entrance because of the continual deepening of the thalweg do to the tectonic uplifting coupled with incision of the gorge. Eventually, these slackwater deposits may be removed by erosion, or covered by debris fallen from the vaults of the cave, or even concealed by speleothems and flowstones. Nevertheless, wherever these slackwater deposits can be recognized and reached, they provide a sedimentary-stratigraphic record of events pertaining to the environmental history of the Frasassi gorge and Sentino River. First of all, detrital silicates contained in the stratified slackwater sediment such as quartz and feldpar grains can be dated with a certain precision and accuracy using the Optical Stimulated Luminescence (OSL) method back to 200-250 ka. Cosmogenic nuclides ^{10}Be-^{26}Al can be used to date even older sediments back to 1 Ma or older. Thus, the age of the top sediment of one such near-entrance deposit would give the age of when the river was last flowing at that elevation, whereas the age of the bottom sediment layer in that deposit will give the age of the first breaching of the cave vault by the eroding river, thus the age of when the river was flowing at the height of the vault of the incised cave entrance. Practically, dating slackwater deposits at near-entrance of caves at different elevations on the gorge cliffs provides the means for assessing the tectonic uplifting rate of this part of the Apennines with unprecedented precision and accuracy.

Moreover the fine fraction of these slackwater sediments contains shells of river mollusks and ostracods, which provide the means for proxying the temperature and organic matter productivity of the paleoriver water via oxygen and carbon isotope analysis. Quantitative taxonomic analysis of these fossils would also provide insight about the faunal and environmental-climatic evolution of this riverine environment. The sediment also contains pollen, which bears information about the evolution of the flora of this area. All together, the slackwater deposits in the Frasassi cave complex promise to be a novel subject for reconstructing the recent-time Little Big History of this part of the world with the application of analytical methods and techniques normally used in the integrated stratigraphic studies of deep-time sedimentary successions.

Apennine Rivers and Fluvial Deposit Paleogeodetic Markers in the Study of Crustal Deformation and Exogenic vs. Autogenic Controls on Landscape Evolution

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The Osservatorio Geologico di Coldigioco has long been a geographical and intellectual venue for process geomorphology studies, using the tectonic, climatic, and geologic setting of the Apennines as a natural laboratory. The focus of this presentation will be on Apennine rivers and their deposits that serve as both paleogeodetic markers of crustal deformation as well as archives of paleoenvironmental change through the Quaternary. Promoted by the multi-national NSF-funded RETREAT collaboration and continuing with numerous subsequent projects, at least three major results and advances in our thinking on these topics have emerged in the past 25 years. The first major result, building upon a large body of work by both American and Italian geomorphologists, is that rock type and soil mantles integrated across an entire drainage basin drive non-uniform and unsteady geomorphic responses to the same climate change, as recorded in river deposits and the degree of river incision. Rivers underlain primarily by siliciclastic bedrock develop a hydrology and sediment flux that widens valleys and carves broad strath terraces. In contrast, the hydrology of carbonate valleys promotes a sediment flux that alternately narrows/deepens and buries/excavates bedrock gorges, leaving behind a record of mostly inset fill terraces. These outcomes lay the foundation for how river deposits can be used in subsequent tectonic and paleoenvironmental studies. The second major result is that crustal shortening continues along the leading edge of the Apennine orogenic wedge, a conclusion supported by recent, large thrust-sense earthquakes, and this shortening is part of a larger coupled sub-lithospheric system that is driving uplift of the entire wedge at a rates approaching ~ 1 mm/yr. Mapping and dating of fluvial terraces preserved along foreland-slope draining rivers from Emilia-Romagna through Le Marche regions shows that the Apennine mountain front is probably cored by a crustal-scale, blind reverse fault accommodating up to ~3 mm/yr of GPS-geodetically measured shortening since the middle Pleistocene. Local deformation and offsets of terrace straths further attest to active folds and faults embedded within the uplifting wedge. Mean rates of river incision locally exceed cosmogenically- and thermochonometrically-determined modern and paleo erosion rates by 0.1-0.5 mm/yr, indicating that relief is continuing to grow in the Apennine landscape. The third major result is that through the application of rock-magnetic cyclostratigraphy of fluvial-deltaic growth strata, fault slip in the Apennine wedge can be demonstrated to be unsteady at short (10^4- 10^5yr) time scales and distinguishable from orbitally-forced paleoenvironmental change. Fault slip unsteadiness is consistent with a number of well-documented intrinsic, rheological properties of deforming rock and the research contributes to our understanding of the degree of dynamic coupling between surficial and deep Earth processes in growing orogens. Collectively, these three major conclusions are being used to seed two new research projects, both of which directly address the legacy and challenges of active seismicity in Italy. One new project addresses the problem of the apparent disconnect between historic, damaging earthquakes and the lack of a clear geomorphic expression of active seismicity, as is the case for many parts of the Umbria-Marche region that straddle the transition in crustal shortening to extension. In this context, rivers and terraces can be used to test emerging geodynamic models of Apennine orogenesis that include an active, low-angle decollement. A second project addresses the problem of deconvolving exogenic, high-frequency tectonic forcing, such as earthquakes, from exogenic climatic forcing and autogenic process shredding in recently uplifted Pleistocene fluvial deposits using cyclostratigraphy.

Reconstructing the late history of the asteroid belt from sedimentary rock sections in the Apennines

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Almost nothing is known about the variations through deep time in the types of meteorites arriving at Earth. In an ongoing project we are searching ancient sediments from ten different time periods through the Phanerozoic for relict extraterrestrial spinel grains from micrometeorites (Schmitz, 2013). Samples, 300-1500 kg large, of slowly formed pelagic limestone are dissolved in acids leaving a residue of refractory extraterrestrial spinels. The time periods studied include the middle Cambrian, Ordovician before and after the breakup of the L-chondrite parent body, late Silurian, late Devonian, middle Jurassic, early and late Cretaceous, early Paleocene and late Eocene. Most of our studies for the late Mesozoic and the Cenozoic are based on rock sections in the Apennines (e.g., Schmitz et al., 2017). The approach builds on complex methodological considerations. A thorough understanding also of the spinel fraction in recent meteorites is necessary. In order to obtain some insights into the changes in the meteorite flux carefully calibrated analyses of the isotopic and elemental composition of the recovered spinel grains as well as consistent data treatment is required for the different time windows. Our results indicate that the background meteorite flux has varied significantly through the Phanerozoic. The results so far, based on three time windows, tentatively suggest that there may have been a gradual long-term (on the order of hundred million years) turnover in the meteorite flux from achondrite-rich assemblages in the early Phanerozoic to assemblages dominated by ordinary chondrites in the late Phanerozoic. This trend may have been interrupted at times by short-term (a few million years) meteorite cascades from single asteroid breakup events. This scenario, however, is very preliminary, and may change as results from additional time windows are considered. We show also that the breakup of the L-chondrite parent body in the mid-Ordovician stands out like the most prominent event in the asteroid belt registered in Earth's sedimentary record for the past 500 million years.

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Tracing large impact events in Geological History

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Statistics predict that at least four Chicxulub-sized impact events should have happened during the Phanerozoic. Yet almost four decades after the discovery of the iridium anomaly in the Italian Apennines (Alvarez et al., 1980) and Spain (Smit and Hertogen, 1980) at the KPg boundary, few traces have been found of additional large impacts that also could have caused a mass-extinction. What should we look for? Popigai and Manicouagan are fairly large (diam. ca.100km) impact events, but any trace of a mass-extinction is lacking, although the ejecta are globally distributed. On the other hand, large igneous provinces (LIPS) seem to roughly coincide with mass-extinctions, in particular the P/T, Tr/J and J/K boundaries. Also oceanic anoxic events (the Cenomanian-Turonian -OAE2- with a foraminiferal mass-extinction, (Caron, 2006) coincide with LIPS.

New discoveries and insights open a new vista on the relation between impacts and mass-extinctions. De Graaff et al. (2017) demonstrated a small iridium anomaly in a single 1cm thick clay layer precisely at the ∂13C anomaly and mass-extinction at the Tr/J boundary in the Canj section, Montenegro (Crne et al. 2010). More importantly perhaps is the non-changing facies at Canj during the late Rhaetian, and the extremely sudden transition to the Hettangian. Rhythmically bedded (probably precession-eccentricity cycles) pelagic cherty limestones bear an uncanny resemblance to the rhythmically bedded Maastrichtian Scaglia Rossa in the Umbre-Marche basin of Italy. Such pelagic carbonate sections are highly susceptible to oceanographic or climate changes, as shown by the response of pelagic carbonate deposition to variations in solar input. The admixed hemi-pelagic clay component is dependent on the variations of riverine run-off or wind-blown dust from nearby continental landmasses. Dust or run-off depends an the amount of rainfall. Annual rainfall is influenced at low latitudes by the position of the ICTZ, largely governed by the precession cycle. Both sub-systems in pelagic sediments are therefore highly sensitive to small climate changes. LIPS extrusions like Deccan traps or CAMP (Hasselbo et al. 2002), held responsible for the climate changes resulting in mass-extinctions should therefore be visible as slight changes in carbonate pelagic sedimentation. Yet neither at the KPgB nor at TrJB such traces are discernible in sediments preceding the stratigraphic boundary. Moreover, CAMP extrusions postdate, not predate the TrJB.

What else should we look for? Large craters are easily eroded or filled completely, making identification difficult, as demonstrated by the late discovery of the Chicxulub crater. Ejecta of such impacts should be found worldwide, but diminish to a few mm in thickness from about 5000 km from the crater, making their identification difficult if not accompanied by the lithologic change resulting from mass-extinction. The majority of such mega impacts should have occurred in the ocean basins, may be all except the Chicxulub impact. The lack of a solid -'physical-' ejecta component, such as impact spherules or shocked minerals at TrJB could indicate such oceanic impact.

Impact induced tsunamigenic sediments caused by impact should be another impact indicator to look for, and have probably been overlooked and/or explained as a different process, such as a turbidite. Three out of four impact derived sediment layers

in the early Proterozoic Hamersley basin in Australia show clear evidence of sedimentation induced by tsunamis (Simonson et al. 1998). The stratigraphy of Gulf coast tsunamites at the KPgB are quite similar to these Proterozoic examples. A characteristic feature is their uniqueness in most stratigraphic sections, in combination with their content of various types of impact ejecta. Recently DePalma et al (2017) described an important extention of KPgB impact induced tsunamigenic sediments.

At Tanis, N. Dakota, a seiche deposit contains e.g. impact event induced sediments, various types of ejecta, a mixture of marine and continental fossils and direct impact victims, such as sturgeon and paddlefish fossils with Chicxulub impact spherules caught in the gills. The timing problem, raised by the simultaneous arrival of ejecta and tsunami/seiche waves precludes direct arrival of a tsunami from the Gulf of Mexico, that would have taken days to arrive in the Dakotas. An elegant solution to this problem might be the coupling of seismic waves to a 'resonance' in a nearby body of water, like the western interior seaway (WIS). Seismic waves from the 2011 Tohoku, Japan 9.2m earthquake have caused seiches in several fjords in Norway, 8000 km away, within half an hour of the quake (Bondevik et al. 2013). The much higher amplitude seismic waves from the Chicxulub impact on a shorter distance could have caused a much larger seiche within half an hour, simultaneous with the arrival of ejecta. We should be on the lookout of such mega wave sediments even far away from the point of impact.

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The role of structural inheritance in the evolution of fold-and-thrust belts: insights from the Umbria-Marche Apennines, Italy

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Fold-and-thrust belts, which developed at the expense of previously rifted regions, commonly expose both stratigraphic and structural records of earlier episodes of extension. Cross-section restoration from the Appalachians (Thomas, 1982), the Alps (Butler, 1989) and the Apennines (Barchi et al., 1989; Tavarnelli, 1996) has shown that pre-existing faults strongly influence the geometry of developing thrusts. The restored two-dimensional (2D) geometry of extension structures which preceded thrusting is often similar to that of structures observed in seismic profiles across passive continental margins (Gillcrist et al., 1987). However, the three-dimensional (3D) geometry of the extension structures that predated contraction is generally poorly constrained, and field information about the patterns of normal faulting in basin-derived mountain ranges is surprisingly rare (Alvarez, 1990).

The Umbria-Marche fold-and-thrust belt, in the northern Apennines of Italy, provides excellent opportunities to evaluate the structural heritage of the opening of the Mesozoic Tethys Ocean in the 3D geometry of the Neogene compressional structures related to the Alpine Orogeny. The structure and evolution of parts of this orogenic belt are described as field examples, and the kinematics along well-exposed Mesozoic extension structures are provided. Cross-section restoration shows a close coincidence between these extension structures and the Neogene thrust ramps, thus suggesting that the geometry of the latter was controlled by the map distribution of the former. Sequential balancing also allows for the definition of the geometrical pattern of pre-existing normal faults, which were produced in response to a uni-directional extension stress field. The inferred direction of principal extension, corrected for the effects of late deformation, is consistent with that proposed for the northern margin of the Adria Promontory in global-scale plate tectonic reconstructions.

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Oral Presentations

Characterizing abnormal sequences of normal earthquakes in central Italy: active fault creep, co-seismic stress transfer, and other possible controls

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The tectonic fault system in central Italy is responsible for notably destructive earthquakes—such as the M6.3 2009 L'Aquila and M6.2 2016 Amatrice events—and complex earthquake sequences that may last for several months or even years. The processes that control the spatial and temporal clustering of these earthquakes are currently poorly understood as they are not well explained by models for aftershock decay or Coulomb stress transfer. One proposed mechanism for fault interaction and earthquake clustering is that some faults or portions of faults slip without producing ground shaking seismic waves, transferring stress to locked faults in the process. Studies of micro-earthquakes in and laboratory experiments on fault rocks from central Italy indirectly support this slow aseismic slip hypothesis, but direct measurement of slow aseismic fault slip has been difficult to obtain because specialized instrumentation is required to detect the small amplitude and slow speeds of ground motions associated with such events. Other possible explanations include temporal evolution of co-seismic Coulomb stress due to viscoelastic relaxation in the lower crust and/or upper mantle, or migration of high pressure pore fluids. To explore these questions further we are developing a network of multi-sensor instruments in shallow boreholes over the Alto Tiberina low angle normal fault near Gubbio. The network should be capable of detecting very small signals associated with slow aseismic fault slip, which is thought to characterize this fault. The new data that we collect will complement the existing TABOO borehole and surface infrastructure and the resulting data sets will address several first order questions: (1) Do aseismic faults load stress on earthquake prone faults steadily or episodically through time? (2) Does the pattern of aseismic slip correlate with the pattern of micro-seismicity on or near aseismic faults? (3) What are the spatial and temporal characteristics of aseismic fault slip, including slip magnitudes, rates, propagation directions and rates, and event durations? Numerical calculations will also allow us to assess the importance of Coulomb stress changes on upper crustal faults over time caused by viscoelastic relaxation. These questions bear directly on our understanding of fault friction and mechanics, and earthquake hazards. We also plan to incorporate data from the borehole network and other geophysical networks into the Accessible Earth Study Abroad (AE) curriculum. Based in Orvieto, Italy, AE is a capstone course for college juniors, seniors, and graduates around the world. It aims to increase diversity among geoscientists by making geoscience as accessible and inclusive as possible for all students. We will present a review of existing geophysical data sets pertaining to aseismic fault slip in central Italy, outline our plans for a network of multi-sensor borehole instruments, and provide a brief summary of student opportunities through the Accessible Earth Program.

Cyclostratigraphic analysis of the Late Cretaceous ^{3}He anomaly at Furlo, Italy

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We used magnetic susceptibility as a climate proxy to investigate whether the significant K1 ^{3}He anomaly identified by Farley et al. (2012) in the Late Cretaceous Scaglia Rossa Formation was associated with a disruption in the recording of Milankovitch cycles. The ^{3}He anomaly was first identified in the Bottaccione section near Gubbio, Italy and we correlated its location using magnetostratigraphy to the better exposures in Furlo, some 40 km away from Gubbio. Our approach was to analyze the cyclicity before and during the ^{3}He anomaly to see if there was an observable effect that might be attributable to the enhanced influx of interplanetary dust particles that the anomaly represents. The Scaglia Rossa Fm. at Furlo contains a number of turbidites that complicate the stratigraphic record, necessitating an approach to account for these episodic events, which disrupt the normal, steady rate of sediment accumulation, before a cyclostratigraphic analysis could be undertaken. We first excised the turbidites from the section and then experimented with varying amounts of erosion associated with each turbidite until we minimized the spectral noise of the magnetic susceptibility data; this led to an optimized stratigraphic record for the sampled portions of the Furlo sequences. Analysis of our optimized stratigraphic sections shows that before the ^{3}He anomaly, the magnetic susceptibility reveals clear signals of the short eccentricity and the precession, with a weaker obliquity, but that after the onset of the ^{3}He anomaly, the Milankovitch cycles are poorly recorded. We suggest that this decline in the clarity of orbitally controlled climatic cycles (which are typically quite clear in the Scaglia Rossa) is due to stochastic climate forcing related to the influx of interplanetary dust particles, which obscures the climate forcing from normal, highly periodic orbital cycles. We note that a similar relationship pertains to the Late Eocene ^{3}He anomaly, which is related to an asteroidal bombardment (Brown et al., 2009), and to the Tortonian ^{3}He anomaly, which was caused by the Veritas asteroidal breakup (Montanari et al., 2017).

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The Popigai impact ejecta layer recovered in a new Italian location, Monte Vaccaro section (Piobbico)

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The Popigai (100 km in diameter) and the Chesapeake Bay (40-85 km) impact structures formed within a time span of 10-20 kyr and characterize together with a ^{3}He interplanetary dust anomaly the Late Eocene (Priabonian) enhanced flux of extraterrestrial matter to Earth. The Popigai impact structure is located in Siberia and has a radiometric age of 35.7±0.5 my. The ejecta from the impact crater has been recovered in Late Eocene sediments in the Massignano section, near Ancona, Italy (Montanari et al., 1993). The ejecta layer in the Massignano section is not represented by a distinct bed and can thus be difficult to demarcate in the field. The impact layer is associated with an iridium anomaly, shocked quartz, and abundant altered clinopyroxene-bearing spherules called pancake spherules. Recently we showed that the ejecta is also associated with a significant enrichment of H-chondritic chromite grains (>63 μm) possibly representing unmelted fragments of the impactor (Boschi et al., 2017).Here we report the first discovery of the Popigai ejecta located in another locality in Italy; the Monte Vaccaro section, 90 km northwest of Ancona, at the same biostratigraphic level as that of the Massignano section. The Monte Vaccaro biostratigraphy was established on calcareous nannoplankton and allowed the identification of a sequence of distinct bioevents, showing a good correlation with the Massignano section. The Popigai ejecta layer in the Monte Vaccaro section contains shocked quartz, abundant pancake spherules and an iridium anomaly. The peak iridium concentration measured with the new triple coincidence Ir-spectrometer in Lund, lies at 686±69 ppt, which is a factor three times higher than the iridium anomaly in the Massignano section. The limestone at Monte Vaccaro contains fewer terrestrial spinel grains (200 grains in 450 kg) than at Massignano, which makes searches for extraterrestrial grains easier. So far, however, only 7 extraterrestrial grains (>63 μm) have been recovered in the 30 cm section starting 15 cm above the ejecta layer. Hence, the data are not statistically robust enough to support an H-chondritic enrichment as shown for the Massignano section. In future works in Monte Vaccaro we will search also for extraterrestrial chromite grains in the size fraction 32-63 μm. This size fraction tends to be richer in grains (10-30 times more) than the >63 μm fraction. The grains from the smaller size fraction might confirm the Massignano results or indicate a more complex scenario.

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Constraints on age and depth of occurrence of phreatic brecciation events in Hong Kong: implications for the occurrence of seismogenic hydraulic fracturing

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The Jurassic-Cretaceous magmatism in Hong Kong region was followed by multiple hydrothermal episodes during the Late Cretaceous through Cenozoic. The hydrothermal events resulted in widespread deuteric mineralisation and silicification. A few hydrothermal episodes, possibly postdating the late Mesozoic fold and thrust events as well as an Eocene sedimentary formation, are found to be associated with phreatic breccia pipes and silicification of older host rock. The mineralogy and structure of the phreatic features in several localities in Hong Kong were studied in order to determine age, temperature, and depth of the occurrence of the events.

At one locality (Ping Chau in Mirs Bay), authigenic aegirine are found to replace zeolite and earlier minerals in an Eocene-age mudstone and biogenic sedimentary sequence. Relict bedding and stromatolitic structures observed in a silicified siltstone layer are evidence for hydrothermal alteration. The aegirine, attributable to hydrothermal events, suggests an alteration temperature at about 300°C.

At a second locality (Double Island in Double Haven), folded sediments of Late Cretaceous age were silicified within a phreatic breccia pipe. The geometry of the pipe resembles an inverted cone, with a silica-rich core zone and brecciated fragments on the margin. The core zone was about 50 m in width. Field studies of similar pipe-like structures in the vicinity reveal a diameter of less than a few meters in the root zone. Silica veins, stockworks and pockets of breccia fragments are commonly present at the contact with the host rocks.

At a third locality (Lantau Island), fractures exhibiting radiating patterns are observed in a 3 m thick quartz dike. The fractures, a few cm in length, nucleate from a central point. The lack of a preferred orientation of the fractures argues against formation in a deviatoric stress system. They probably resulted from explosive events associated with sudden vaporization of ground water. The conversion of superheated groundwater from liquid to vapor state could have produced a shock wave through the rock, overcoming the tensile strength of the rock and causing the fractures to form and propagate outward from the nucleating points of vaporization. This process resembles the boiling liquid expanding vapor explosion (BLEVE) that leads to gas tank explosions. If so, the hydraulic fracturing process may enable us to estimate the depth at which the fracturing occurred, based on thermodynamic consideration of the phase relation between water and gas as well as the geostatic gradient of the crust. Given the known supercritical point of water and a geostatic pressure gradient of 27 MPa/km, the fracturing probably occurred at a depth of 300-500 m. The physical conditions and depth of the fracturing can be better constrained if the tensile strength of the quartz dike is known.

The study may have important implications for the occurrence of hydraulic breccias in general, including the Maiolica breccia wall in the Northern Apennines, Italy.

Some considerations about the reliability of OSL-datings in the Frasassi cave system

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In this presentation results available for four Optical Stimulated Luminescence samples (OSL) from the Frasassi cave system are discussed. Two samples of the SDS profile and two samples of the CDC profile were taken. The ages for the two samples from the SDS profile (age range 129-101ka, VLL-02264-L and VLL-0265-L) are in good agreement within error, just like the two samples from the CDC profile (age range 217-158 ka). From a methodological point of view, the ages determined for both profiles must be considered as reliable. Different OSL dating protocols were used to determine the age for each individual sample. By applying this comparative approach, and taking the luminescence characteristics of the samples into consideration (quartz OSL, different feldspar OSL signals), the ages could be based on the most robust measurement protocol. The ages presented here were all derived from measurements using the post Infrared signal of potassium-rich feldspar stimulated at a temperature of 225 °C (pIRIR225). Incomplete bleaching of the luminescence signal prior to deposition, leading to age overestimation when not detected and corrected for, was not a significant factor for the samples under investigation, because ages calculated for luminescence signals with different bleachability yielded results in agreement within error. Bleaching can therefore be assumed to have been sufficient before the samples entered the cave system.

Considering the altitude of the samples above present thalweg, it seems puzzling that the samples show a difference in age (SDS – Marine Isotope stage 5-6) and CDC (Marine Isotope Stage 6-7) but both are about on the same altitude level. This may point towards an extrinsic source of error, not inherent in the dating approach, influencing the accuracy of the dating results. A number of geological factors may spring to mind (redeposition of material within the cave, sediment routing independent from the main drainage along the former thalweg level, etc.).

However, identifying or even quantifying such factors seems challenging. Because of that, the results from OSL dating were compared with age determinations from the Frasassi cave system performed by the group of Alessandro Montanari and co-workers in different areas of the cave complex by using the respective uplift rates calculated from these ages as a tool for normalization. For this approach, ranges of uplift rates were calculated based on the error intervals of the dating results. Using only the central age values without considering the error range could lead to misinterpretations caused by forcing the ages to an unrealistically high level of precision. Table 1 shows the results from these calculations with the majority of uplift rates falling into a coherent range. In two cases the calculated ranges deviate from the general trend with possible implications put up for discussion in Table 1.

We are aware that the identified outliers in calculated uplift rates from different thalweg levels may also represent actual changes in uplift rate over time. More discussion about different approaches to uplift calculations seems necessary. However, our comparative approach may help identifying outliers especially when samples were analyzed from identical thalweg levels, as those OSL dated for the SDS and CDC profiles. Nevertheless, the SDS ages may still indicate a change in uplift rate; with the ages from the CDC profile representing a different event imported to this thalweg level (see sources of extrinsic errors

above). To address these uncertainties, additional analyses and dating efforts using independent methodology or investigation of additional sites from the ~30 m thalweg level may help to clarify these contrasting results.

Table 1: Uplift calculation using error ranges in relation to altitude above thalweg.

Location	**Altitude (above present thalweg)**	**Dating error range (method)**	**Uplift calculation (altitude versus dating range)**	Possible implications
CDC	**32 m**	**158-217 ka (OSL)**	**= 0,15-0,2 mm/a**	These OSL-dating-ranges fit the general uplift trend in the cave system and could be considered more reliable because of the coherent relation to other dates.
SDS	**29 m**	**101-129 ka (OSL)**	**= 0,22-0,29 mm/a**	These OSL-dates point to a higher calculated uplift-rate compared to other dates in the cave system. Additional analyses from independent sites and/or methodology may be used to validate the reliability of the ages.
GBV	**119 m**	**490-1010 ka (cosmo)**	**= 0,12-0,25 mm/a**	
	119 m	**450-850 ka (cosmo)**	**= 0,14-0,26 mm/a**	
	119 m	**500-780 ka (integrate cosmo+paleomag)**	**= 0,15-0,24 mm/a**	
Section 2.1	**130 m**	**394-438 ka (U/Th)**	**= 0,3 - 0,33 mm/a**	These calculated up-lift values seem to be higher than the general trend. So probably the dated chunk of speleothem falling from the ceiling on to the floor of the cave is younger than the formation of the cave level in 130 m above present thalweg.
BDR	**170 m**	**780-900 ka (Paleomag)**	**= 0,19-0,22 mm/a**	

Impactor identification in tektites and microtektites using Ni, Co and Cr ratios: the case of the Australasian tektite/microtektite strewn field

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We present a case study of projectile identification in Australasian microtektites using Ni, Co, and Cr ratios (Fig. 1) to discuss the potential and limits of this geochemical method for projectile identification in tektites and other impact melt rocks - a topic that could be of interest for the study of the 250 million years long collisional history of Earth recorded in the geological sequences in Central Italy (e.g., the North American microtektite layer associated with the 35.3 ± 0.1 Myr old, 90-km-diameter Chesapeake Bay impact structure and the Massignano record).

The nature of the impactor that generated the Australasian tektite/microtektite strewn field, i.e., the largest Cenozoic strewn field (~15% of the Earth's surface), the youngest (~0.78 Myr old) on Earth, and the only one without an associated impact crater so far, is an outstanding issue. Based on the variations of the Cr, Co and Ni ratios in a Co/Ni versus Cr/Ni space of 77 normal and high-Ni Australasian microtektites (size ramge: ~200 to 700 μm) from within 3000 km of the hypothetical impact location in Indochina (~17°N, 107°E; [9]) we identify a chondritic impactor signature (Fig. 1). Despite substantial overlap in Cr/Ni versus Co/Ni composition for several meteorite types with chondritic composition (chondrites and primitive achondrites), regression calculation based on ~85% of the studied microtektites best fit a mixing line between crustal compositions and an LL chondrite. Eight high Ni/Cr and five low Ni/Cr outlier microtektites (~15% in total) deviate from the above mixing trend, perhaps resulting from incomplete homogenization of heterogeneous impactor and target precursor materials at the microtektite scale (nugget effect), respectively.

This result has implications for studies of the flux to Earth of the kinds of large impactors over the Cenozoic and impact scenario. Together with previous evidence from the ~35 Myr old Popigai and the ~1 Myr old Ivory Coast microtektites, our finding suggests that at least three of the five known Cenozoic distal impact ejecta were generated by the impacts of large stony asteroids of chondritic composition, and possibly of ordinary chondritic composition. The impactor signature found in Australasian microtektites documents mixing of target and impactor melts upon impact cratering. This requires target-impactor mixing in both the two competing microtektite formation models in literature proposed for the Australasian: the impact cratering and low-altitude airburst plume models.

The case study presented here identifies the potential and limits of the adopted geochemical method in projectile identification studies. In particular, we propose that the study of the variations of the Cr, Co and Ni ratios of impactites enriched in these elements relative to background crustal levels in a Co/Ni versus Cr/Ni space (Fig. 1) is an additional tool for identification of impactor contaminations and discrimination between iron, chondritic and differentiated impactors. Furthermore, this geochemical method can help to constrain chondritic impactor signatures down to the meteorite type. The resolution of the method is limited by substantial compositional overlap amongst several types of meteorites with chondritic compostion (chondrites and primitive achondrites), yet it could be strategic if combined to other geochemical and isotopic methods mainly based on highly siderophile elements including PGE [e.g., 6] , and Cr isotope systematics (e.g., [10]) which can help to discriminate between carbonaceous, enstatite and ordinary chondrite groups. The method also relies on the repre-

sentativeness of the Cr, Co and Ni data set currently available. There is in fact little statistics for several types of chondritic meteorites (e.g., CB, K, winonaites). Also the large spread in Cr/Ni and Co/Ni ratios in Acapulcoites-Lodranites likely due to a sampling issue (see discussion above) should be further investigated.

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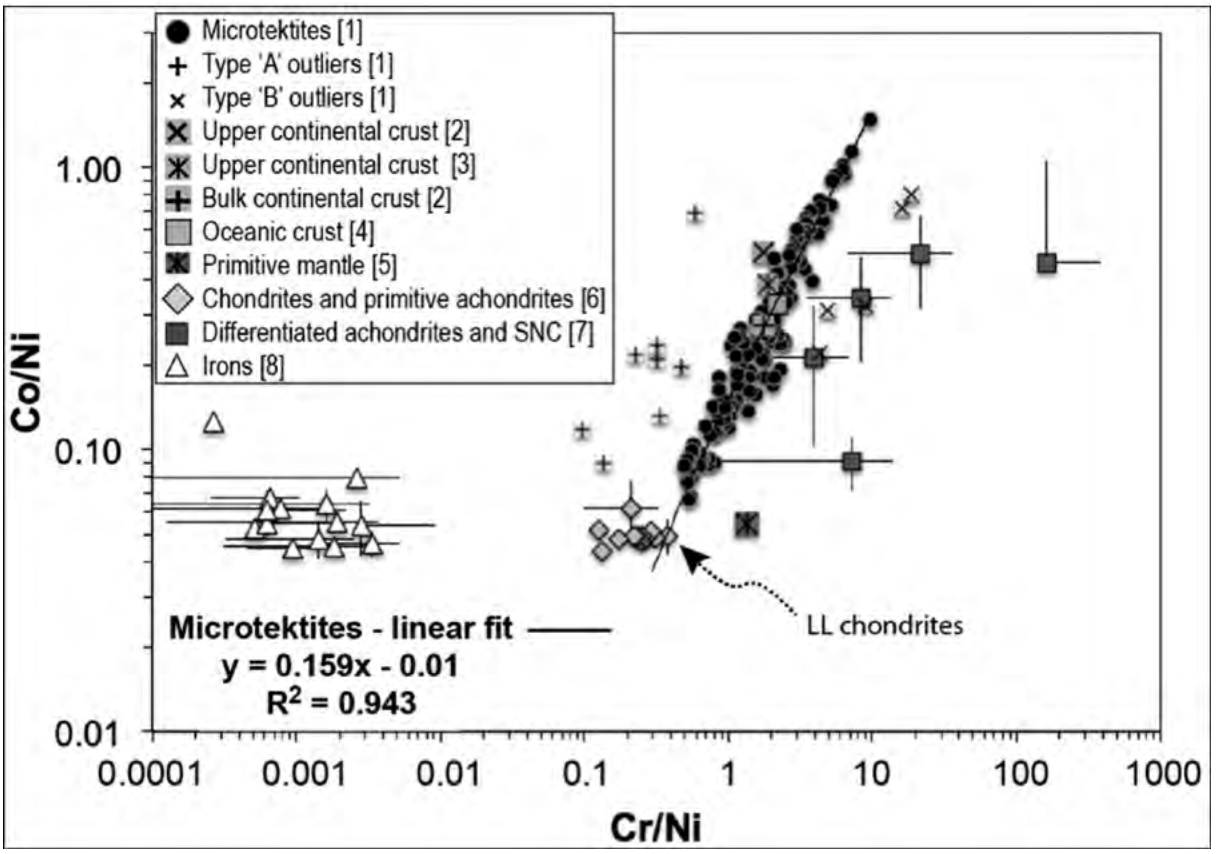

Fig. 1. - Cobalt/Ni versus Cr/Ni plots for normal and high-Ni Australasian microtektites (139 LA-ICP MS spot analyses from 47 microtektites analyzed in this work and 31 INAA bulk compositions of microtektites from literature) and terrestrial geochemical reservoirs, chondrites, achondrites and iron meteorites. About 85% Australasian microtektites define a mixing line between crustal metarials and primitive compositions (chondrites and primitive achondrites). Regression calculation based on these main trend microtektites best fit a mixing line between crustal compositions and an LL chondrite. Type A and B outliers (see text for discussion) were not used to calculate the trend line (solid black line).

The problem of earthquake prediction: some reasons for its failure and a possible solution via tomographic fracture imaging (TFI©)

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Seismogenesis is a highly complex multidimensional, multiphase phenomenon whose parameters are space, time and energy. A principal goal of Earthquake Seismology is sufficient knowledge of seismogenesis to allow prediction. To date this remains an elusive hope one not even known if possible. To understand the reason for the lack of success, I introduce the notion of a ***coherent*** data set and propose that its present absence, imposed by the tools currently used to study the phenomenon, can at best, only provide a limited understanding of the seismogenic process. A ***coherent*** data set is one where all the parameters controlling a phenomenon can be directly related to one another in the coordinate frames in which they actually operate and in the near real time in which they interact. As an example of a technology that can provide a coherent data set for the study of seismogenesis, I discuss the recent development and application of TFI© by the Oil and Gas industry. TFI© is a transformational tool for examining crustal deformation and fluid movement in terms of space, time and energy at scales spanning micro to macro, in near real time and with a degree of accuracy and precision as high as ± 8 m.

Existing tools for seismogenic analysis: There are three types of tools; **geodetic** for surface deformation, **microseismic** for subsurface failures and **fabric studies** for rock deformation. Fabric studies of cores and outcrop, are sparse, static two-dimensional data. Geodetics measures surface strains of the Earth's crust but not the strain mechanisms. Microseismic studies provide information on failure mechanisms and the stress field but are limited by the log-normal distribution of failure events causing most to be undetectable by standard hypo-central methods. None of the forgoing technologies can supply objective information on the permeability field. Further they cannot be temporally connected. Accordingly, the data available from these tools do not form a coherent data set and thus can provide only limited and incomplete information on seismogenic mechanisms almost certainly precluding the possibility of prediction.

TFI: Providing the missing data: TFI© is a 5D, [space (x,y,z), time (t) and energy (E)], imaging technology for the deformation processes of the brittle crust. It can provide the following *coherent* data critical to understanding the seismogenic mechanism in near real time: **1]** Records data across much or perhaps all of the fracture size spectrum; **2]** can relate data from the micro to macro scale; **3]** can measure the energy associated with brittle failure; **4]** Can be inverted to determine 3D stress at the 100 m scale; **5]** Direct imaging of fractures/faults and the permeability field; **6]** is capable of accuracy and precision of ± 8m. Thus TFI© can provide a coherent data set for the seismogenic deformation mechanisms and processes. As such it offers the opportunity for a quantum jump in our understanding of the seismogeneic process.

How Does TFI Work?: TFI© uses three fundamental properties of the Earth's brittle crust:

1] Critical Earth (Leary, 1997; Zoback, 2007): The Earth's crust is in a constant state of near failure on pre-existing fractures. Ziv and Rubin (2002) show that stress drops of < 0.02 bars are sufficient to cause failure on pre-existing fractures; **2] Damage zones**: All physical discontinuities in the brittle crust are surrounded by damage zones where fracture density increases geometrically as the discontinuity is approached (Vermilye and Scholz , 1998). **3] Log normal distribution of fracture size**: Most of ambient seismic energy in the crust is the product of fractures below the resolution of hypo-central methods.

Given a velocity model, TFI© uses beam forming surface and/or buried arrays for continuous recording of seismic energy. Fracture/faults emitting seismic energy are spatially stable. Application of basic signal processing methods for weak, spatially stable signals, namely temporal data stacking in this case using semblance as an energy proxy, allows signal extraction. Seismic energy emissions increase with crack density. Damage zone crack density increases geometrically towards the mechanical discontinuity. Thus fracture/faults are embedded in clouds of seismic energy that is maximum at the discontinuity. The discontinuity is roughly parallel to the medial surface of the semblance cloud. Extraction of the medial surface of the semblance cloud provides the image of the fracture/fault surface.

Towards a deeper understanding of the seismogenic mechanism: A sufficiently dense TFI© capable, seismic array along a known earthquake fault, can monitor the mechanisms and processes of all phases of the earthquake cycle. As earthquake prediction is not currently possible, capturing the pre-seismic and co-sesimic phase is the largest problem. The current approach is to instrument an active earthquake fault and hope that a co-seismic event occurs. To date this has not met with much success. However, we can be certain of one phase of any given earthquake fault, i.e., immediately following an earthquake when a fault is post-seismic. At this time, rapid placement of a surface array, would capture most of the post-seismic phase and the following inter-seismic, unfortunately capturing the pre-seismic and co-seismic phases would remain dependent on luck. An innovative solution to this problem has been proposed by the SEISMs group (seisms@ldeo.columbia.edu) which is to instrument a known seismogenic fault and induce an earthquake. This could allow monitoring the complete earthquake cycle.

Summary: From both societal and scientific standpoints, seismogenesis and earthquake prediction is one of the most important unsolved geological/geophysical problems. Despite this and the significant time, money and effort spent to solve it, so far, all attempts have failed. I claim the cause of this failure is because available technology can only collect incoherent data on seismogenesis. Incoherent data is insufficient for identifying and monitoring the seismogenic mechanisms and the processes that they drive. TFI© represents a transformative, proven imaging technology capable of collecting coherent data on seismogenesis. It is proposed that by instrumenting earthquake faults with TFI© capable seismic arrays under controlled conditions, all phases of the earthquake cycle can be imaged and analyzed thus allowing both a qualitative and quantitative breakthrough in understanding the seismogenic mechanism and therefore significantly advancing our understanding of earthquake prediction.

Could microtektites and shocked mineral grains from the Chesapeake Bay impact be found as far as Massignano, Italy?

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The late Eocene was a time of global cooling (e.g., [1]), significant stepwise faunal and floral turnovers [2], and several large impacts, including two of the three largest known in the Cenozoic (last 65 Ma). The craters produced by two of these impacts are the ~100 km diameter Popigai crater in Northern Siberia and the ~90 km diameter Chesapeake Bay crater (some authors assign a diameter of 40 km to this structure [3]) at the mouth of the Chesapeake Bay located on the East Coast of the U.S.A. The Popigai crater has been dated at ~35.7 ± 0.8 Ma [4] and the Chesapeake Bay crater at 35.3 ± 0.2 Ma [5]. The Popigai crater is believed to be the source of the clinopyroxene-bearing (cpx) impact spherule layer found around the Earth ([6] and references therein). Ejecta from the Chesapeake Bay crater include the North American (N. A.) tektites found in Georgia, Texas, and Cuba; and microtektites and shocked mineral grains found in marine sediments in the western Atlantic off New Jersey, on Barbados, and in the Caribbean Sea and the Gulf of Mexico [7]. The cpx spherules contain Ni,Cr-rich spinel crystallites. An Ir anomaly has been found associated with the cpx spherule layer at numerous sites around the globe and shocked quartz grains have be found associated with the layer at a site off the Philippine Islands, which is farther from Popigai than is Massignano. The N.A. microtektite layer is not associated with an Ir anomaly, but shocked mineral grains (including shocked quartz) are found in the layer [7]. It has been suggested that these two large impact events may have played a role in the climatic and the biotic changes that occurred near the end of the Eocene [6,8].

Montanari et al. [9] reported finding two Ir anomalies at Massignano, Italy: one at 5.61 m with an age of 35.7 ± 0.4 Ma and one at ~6.2 m with an age of ~35.55 Ma. However, more recent astronomically derived chronology for this section [10] suggests ages for the Ir anomalies of 35.27 and 35.21 Ma, respectively, and indicates an age difference of ~60 ka. Shocked quartz grains with planar deformation features and pancake-shaped spherules with Ni-rich spinels were found associated with the older, lower (5.61 m) Ir-rich layer [11-13]. The pancake-shaped spherules have been interpreted as impact spherules that were diagenetically altered to a clay mineral and then flattened by compression due to the overburden [12,13]. The age of the Ir anomaly and the presence of diagenetically altered impact spherules containing Ni-rich spinel crystallites suggest that this layer is part of the cpx spherule layer and thus most likely from the Popigai crater [8,13]. It has been suggested that the overlying smaller Ir anomaly at ~6.2 m may be from the Chesapeake Bay impact [8], but no microtektites or shocked mineral grains have been found at this height in the section. The age difference between the cpx spherule layer and the N. A. microtektite layer is not well established. The relationship between the two layers is best shown in Core RC9-58 from the Caribbean Sea [14]. Here the peak abundances for the two layers are separated by 25 cm. An Ir anomaly is associated with the cpx spherule layer but not with the N.A. microtektite layer. Unfortunately, the sedimentation rate is not known for this core, but using the sedimentation rate for this stratigraphic interval in a nearby core, indicates an age difference of ~80 ka, which is close to the estimated age difference between the two Ir anomalies at Massignano mentioned above.

If the Ir anomaly at ~6.2 m is from the Chesapeake Bay impact, why haven't any microtektites or shocked mineral grains been found at that stratigraphic level at Massignanao? At the time of the impact, Italy was ~5500 km from the Chesapeake Bay impact site. Could we expect shocked mineral grains and/or microtektites to be thrown that

far? Assuming the source crater for the Australasian microtektite layer is located somewhere in Indochina, as proposed by several researchers (e.g., [15]), the microtektites from this impact have been found as far 11,000 km from the proposed source crater location [17]. And for a given distance from the source crater, the North American microtektites are slightly more abundant than are the Australasian microtektites. At a distance of 5500 km in the Australasian strewn field, we find ~20 microtektites per cm^2. We could expect at least that many North American microtektites at the same distance. Shocked quartz and coesite have been found up to ~9700 km from the Popigai crater [6]. However, how far unmelted shocked mineral grains can be found from the source crater depends on crater size. Present data suggest that unmelted shocked grains can only be found up to ~100 crater diameters from the source crater. If the Chesapeake Bay crater is really 90 km in diameter, then we would expect to find shocked mineral grains up to 9000 km from the Chesapeake Bay crater. However, some authors suggest that if the impact had taken place on land, the diameter would have been ~40 km [3,18]. Unmelted shocked mineral grains would probably not have reached Italy from the Chesapeake Bay crater if it had a diameter of 40 km. However, even if microtektites and shocked mineral grains could have been thrown as far as Massignano, they may not have fallen in that area, as there are data that suggest ejecta are not thrown equally in all directions. The Australasian microtektite strewn field may have been deposited in lobes [19] and the cpx and North American strewn fields along rays ([6,20], respectively). So, even though we can expect microtektites from the Chesapeake Bay impact to be thrown as far as Massignano, that area may have been between rays or lobes.

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Attempts to constrain the impactor composition from isotopic analyses of spinel-rich samples from Late Eocene impact ejecta at Massignano, Marche, Italy

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The late Eocene is marked by multiple bolide impact events, possibly related to a comet or asteroid shower over a duration of about 2-3 million years, which may have played an important role related to the deterioration of the global climate at the end of the Eocene. Upper Eocene marine sediments around the world contain evidence for at least two closely spaced impactoclastic layers – i.e., layers containing impact debris, such as tektites and microtektites and shocked minerals and rock fragments (for references see, e.g., Montanari and Koeberl, 2000; Koeberl, 2009). Initially, it was thought that there is only one layer known from the eastern U.S. coast, the Caribbean, and the Gulf of Mexico, which is correlated with the North American tektite strewn field. This layer contains microtektites (i.e., glassy, not recrystallized spherules), shocked minerals, and high-pressure phases (e.g., coesite), but no marked siderophile element anomaly. This upper layer correlates with the North American tektite strewn field (with the 85-km-diameter Chesapeake Bay crater (USA) as its source crater). A second, lower, microkrystite-bearing layer (with clinopyroxene-bearing spherules) was then found at many locations as well layer and was most likely derived from the 100-km-diameter Popigai impact crater (Russia). At least five impact structures with late Eocene ages are known. The Eocene/Oligocene GSSP is located at Massignano, Italy, and below the boundary in the late Eocene 5.61-meter-level shocked quartz and pancake-shaped smectite spherules that contain Ni- and Cr-rich spinel crystals are found. These are associated with a positive Ir anomaly in upper Eocene deposits with the same age as the Popogai-derived cpx spherule layer. This layer is overlain by another Ir-rich layer, probably representing the NA-tektite event. The pancake spherules appear to be diagenetically-altered and flattened cpx spherules About 50 kg of "pancake-bearing" rock from was collected, largely dissolved, and then the pancakes extracted mostly by hand-picking, leaving a few hundred mg of this spinel-rich material. About 120 mg of the unspiked sample was analyzed for tungsten isotopic composition, resulting in a barely resolvable negative anomaly of about -0.2 ε^{182}W, which is in line with a meteoritic admixture to the pancake sample. Chromium isotopic measurements were done on two separate batches of the "pancake-concentrate", giving values of around -0.4 to -0.5 ε^{54}Cr, which distinctly point to an ordinary chondritic impactor. This result supports the asteroid impact interpretation but not the comet impact hypothesis.

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Cretaceous–Paleogene boundary tsunamite on Adriatic Carbonate Platform and implications on paleogeography of the western Tethys - a review

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Note: This abstract will be presented as an oral presentation on Tuesday 26 at 12:10, replacing the "*Preliminary report on a distinct Cretaceous Paleogene boundary event bed in the NW part of the Adriatic Carbonate Platform (Pivka area, Kras region, SW Slovenia)*", which will be given as a poster presentation.

The Chicxulub asteroid impact triggered a global mass extinction and extraordinary sedimentary perturbations around the Gulf of Mexico region at the Cretaceous–Paleogene (K–Pg) boundary some 66 million years ago (Alvarez et al., 1980; Schulte et al., 2010; Renne et al., 2013). Moreover, the seismic shock was probably able to trigger giant landslides and submarine failures of the SE continental margins of North America and/or the islands in the Caribbean region, possibly generating a trans-Atlantic mega-tsunami, which propagated to the east. Such a tsunami would certainly affect shallow-marine and coastal sedimentation on continental margins of the SW Europe and NW Africa, presumably also along the margins of the western Tethys Ocean (Korbar et al., 2015, and references therein).

The peri-Adriatic area was part of a continental microplate called Adria - a promontory of Africa pointing to the north into the western-central Tethys during the Mesozoic (Channell et al., 1979). The Cretaceous to Paleogene tropical carbonate platform successions in the peri-Adriatic region exhibit a more or less extended hiatus around the K–Pg boundary (e.g., Eberli et al., 1993; Bosellini et al., 1999; Korbar, 2009). This is probably a supra-regional hiatus since it is recorded also on Panormide platforms (Zarcone et al., 2010), as well as within shallow-water successions of the NW African epicontinental basins opened to the central-eastern Atlantic Ocean (Marzoqi & Pascal, 2000). Thus, there are very few continuous K–Pg boundary shallow-marine successions in the region reported to date: one from Tunisia (Adatte et al., 2002) and two from the SW part of the Adriatic Carbonate Platform (ACP) in the present day Dalmatian archipelago (Adriatic Sea, Croatia - Korbar et al., 2015, 2017a). Both ACP successions include event beds at the K–Pg boundary, which imply sedimentological perturbations related to the Chicxulub impact. Although there is no modern analogue for a broad and isolated tsunamite in a carbonate platform interior (e.g. Shiki et al., 2008), both ACP K–Pg boundary event beds were probably deposited from a major tsunami (Korbar et al., 2017b). Furthermore, in spite of the reported hiatus that include the K–Pg boundary within shallow-marine successions in the NW part of the ACP (Ogorelec et al., 2007), the latest discovery from the Kras (Karst) plateau could confirm a contemporaneous tsunami event also on that remote part of the ACP (Korbar et al., this volume).

Reported deep-marine successions in the region lack any disturbance within the K–Pg boundary interval. Both Umbria-Marche (Italy) and Adriatic-Ionian (Albania) basinal K–Pg successions are characterized by many major debrites and slumps above and/or below the K-Pg boundary, but lack any within the narrow boundary interval (Montanari et al., 1989; Rubert et al., 2012). Thus, the tsunami must had a source in a more distant region. An unexpected and hypotethical K–Pg boundary seismic shock in north Africa, which would trigger north-directed tsunami, is not probable, since it would affect also the outer shelf deposition of the well-known Tunisian successions (Adatte et al., 2002). Yet, the only reported inner-neritic Tunisian Seldja succession is characterized by a relativelly thick, coarse-grained event bed containing ripped-up clasts of the underlaying terminal Maastrichtian marls, along with abundant and various bioclasts (Adatte et al., 2002), that could be deposited from the same K–Pg boundary intra-Tethyan tsunami. However, the tsunami could be triggered also by an European (Iberian) source. To be consider is that potential key-localities are situated in the eastern African continental

margins of Morocco (Marzoqi & Pascal, 2000), facing hypotetical trans-Atlantic tsunami triggered by the Chicxulub impact.

If the K–Pg boundary trans-Atlantic tsunami indeed existed, a known general paleogeography of the western Tethys, which is interpretated according to the most relevant geodynamic reconstructions of the Cenozoic Alpine orogenesis in the western Mediterranean (Lowrie & Alvarez, 1974; Rosenbaum et al., 2002), would be confirmed. Such a major intercontinental tsunami would imply a wide paleo-Gibraltar strait, and a very broad deep-marine area of the western Tethys without any archipelago acting as a barrier for the proposed trans-Atlantic K–Pg boundary tsunami. If so, the tsunami was finally broken down on the western coasts of the peri-Adriatic carbonate platforms, some 10-20 hours after the Chicxulub asteroid impact, at the end of its almost 10,000 km destructive run.

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Preliminary report on a distinct Cretaceous–Paleogene boundary event bed in the NW part of the Adriatic Carbonate Platform (Pivka area, Kras region, SW Slovenia)

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The area of Pivka in the easternmost Kras region of SW Slovenia paleogeographically belongs to the NW sector of the Adriatic Carbonate Platform (ACP), which was tectonically incorporated in the NW part of the External Dinarides during Cenozoic Alpine orogenesis (Otoničar, 2007; Korbar, 2009). The Kras region is built predominantly of Cretaceous to Paleogene carbonates (Jurkovšek et al., 2016), that are mainly characterized by a small hiatus spanning Cretaceous–Paleogene (K–Pg) boundary (Ogorelec et al., 2007). Although the hiatus is a common feature of almost whole ACP (Vlahović et al., 2005), there are at least two known exceptional sections in the SW part of the ACP (present day Dalmatian archipelago) that are characterized by a continuous K–Pg succession and by an unusual deposit at the K–Pg boundary interpreted as a major tsunamite (Korbar et al., 2015, 2017), related to the Chicxulub asteroid impact (Schulte et al., 2010).

Kras region is a type locality of the Liburnian formation (Drobne et al., 1989), which i s characterized by >100 m meters thick innermost-platform succession of predominantly dark -grey lime mudstones deposited on tidal-flats and protected brackish lagoons in the NW part o f the ACP with rare intercalations of supratidal breccias and coal beds (Jurkovšek et al., 1996; 2016 and reference therein). In the easternmost part of the region (Pivka area) within the form ation succession we recognized an unusual >1 m thick intercalation of a massive coarse-grain ed limestone that is underlain and overlain by typical mudstones of the Liburnian formation. L ower boundary of the intercalation is sharp and erosional, Overlain by >70 cm thick bioclastic -skeletal-intraclastic packstone to grainstones containing very diversified association of benthi c foraminifera, including larger benthic foraminifera (*Orbitoides* sp., *Siderolites* sp., *Lepidorbi toides* sp.) atypical for the inner-platfom lagoon, as well as abundant bioclasts of rudists, echi noderms, corals, bryozoans, and other fossil remains that are absent from the underaying and overlaying strata. There are also rounded mudclasts and abundant muddy matrix similar to tha t of the underlaying lagoonal mudstones. The upper part of the intercalation is characterized b y fining-upward succession and up to 30 cm thick mudcap. The mudcap is characterized by fl oatstone containing up to 2 cm long bioclasts of radiolitid and requieniid rudists bivalves, as well as by Maastrichtian benthic foraminifera association: miliolids, *Cuvillierinella* sp., *Rhapy dionina* sp., *Murciella cuvilieri* FURCADE, *Cuneolina pavonia* d'ORBIGNY, *Stensioeina sur rentina* TORRE, *Bolivinopsis* spp., and *Dargenioella* sp. (Vicedo et al., 2011; Fleury, 2014, 20 16). The uppermost few cm of the mudcap is wackestone with various tiny microfossils and m icromudclasts, including rare planktonic foraminifera *Muricohedbergella* sp. The mudstones t hat directly overlay the mudcap contain ostracods and rare tiny benthic foraminifera *Rotorbin ella* sp. (cf. *hermi/skoulensis*) and *Kartalina* sp., indicating Paleocene age (Hottinger, 2014; Si rel, 2015). However, one tiny stylolith separate the Maastrichtian and Paleocene mudstones, i ndicating substantial dissolution (probably up to a few cm) of the original limestone successio n. Nevertheless, this is the first report of the K–Pg boundary in the shallow-marine succession s of the NW part of the Adriatic Carbonate Platform that is not characterized by a hiatus. Furt hermore, the event bed could be interpreted as a tsunamite according to criteria discussed in K orbar et al. (2015, 2017). With this respect additional detail field studies are planned.

The event bed will be mapped and the expected new sections will be analyzed lateraly. If confirmed, the reported K–Pg boundary event bed discovered on the NE part of the Kras

region could be the ultimative evidence of a contemporaneous tsunami event on the whole western part of the ACP.

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Late Pleistocene tectonic tilting of the Frasassi anticline as measured from offset stalagmites in the Grotta Grande del Vento (Marche Apennines, Italy)

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The massif of Jurassic limestone making up the core of the Frasassi-Valmontagnana blind thrust anticline, hosts a large hypogenic sulfidic cave complex, which, due to Pleistocene tectonic uplifting, has been incised by the Sentino River forming the deep Frasassi Gorge. Being a hypogenic cave that formed below base level (i.e., below water table), the Frasassi cave complex is organized in seven horizontal hypogean "floors", the youngest presently active at piezometric (river) level, the oldest some 200 m above the Sentino thalweg. Therefore, the Frasassi cave complex records the tectonic uplifting history of this still active Apennine mountain belt (e.g., Cattuto, 1976; Mariani et al., 2007). In addition to an uplifting rate of about 0.55 mm/yr for the Holocene, Mariani and co-workers revealed, via radioisotopic dating and surveying of phreatic calcite deposits, an overall tilting of the Frasassi anticline of about 0.2° angle to the East for the past 9000 or so years. In our study aimed at a better determination of this tectonic tilting (Lacroce, 2015), we focused on a group of 30 stalagmites found at the bottom of the Abisso Ancona of the Grotta Grande del Vento (the largest room in the Frasassi complex, about 10^6 m^3 bell shaped cavity with a floor area of about 10^4 m^2), all of which appear to have grown offset from the center toward a southeastern direction, thus appearing as though the stalagmites have been recording the tilt over time, giving them the name "paleotiltmeters". From U-Th dating of these paleotiltmeters, we concluded that the Frasassi anticline has been tilted by about 0.3° over the past 32 ky, and the tilting has been gradually increasing. The 60° (NE) direction of strike slip faults in this area, and the local focal mechanisms of recent seismic activity, are adequate evidence to suggest that the titling is caused by the strike slip zone south of the Frasassi anticline. The gradual increase in tilt suggests that the strike slip fault zone is presently active. Howerver, the strike slip fault zone should be further investigated to find out whether it constitutes a seismic hazard, and if fault activity is still increasing. Therefore further geophysical and seismo-tectonic examination of the strike slip zone is needed to conclude that the strike slip zone is the main cause or a concause of the tilting. The unique setting of the stalagmites provided us with an opportunity to interpret structural data from this rare occurrence. Our findings positively demonstrate that stalagmites can be used to calculate the tilt angle of a fault, and can act as a paleotiltmeter.

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The terrestrial Cr-spinels in the Maiolica limestone: where are they from?

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We focus here on a part of the Lower Cretaceous (145–133 Ma) Maiolica limestone in central Italy. This pelagic limestone presents very low contents of terrestrial detrital mineral grains, making it useful for reconstructions of the micrometeorite flux even in the small spinel size ranges. Samples were collected from 12 beds in two stratigraphically separated groups along the 240-m-thick Monte Acuto section of the Maiolica limestone in central Italy (43°27.83′N, 12°40.27′E) spanning from Berriasian to the early Hauterivian. One additional sample comes from the early Berriasian Bosso section, 12 km northwest of Monte Acuto.

Schmitz et al. (2017), from a total of 1652 kg of limestone from the earliest Berriasian to early Hauterivian Maiolica Formation, recovered about one hundred extraterrestrial spinel grains. Among them about 80% originated from ordinary chondrites with ratios between the three groups of ordinary chondrites, H, L, LL, ~1:1:0.2 that is similar to the present. About 10% of the grains in the Maiolica originate from achondritic meteorite types that are very rare (<1%) on Earth today. In addition there are the terrestrial spinels that are easily discriminated from the extraterrestrial grains by their low V_2O_3 content, usually below 0.5 wt. %.

According to the most used parameters in spinels classification, terrestrial spinels from Bosso show Cr#, i.e. Cr/(Cr+Al), in the range 0.35-0.64 and Mg#, i.e. Mg/(Mg+Fe^{2+}), in the range 0.38-0.70. Other spinels along the section show Cr# in the range 0.14-0.94 and Mg# 0.16-0.81. The TiO_2 content is comprised between 0.39 and 1.61 wt.% for Bosso spinels and between 0.07 and 3.60 wt. % for the others. The highest V_2O_3 content is 0.44 wt.%.
In order to find out the most suitable source for the studied spinels we used the Cr# vs. Mg#, the Fe^{3+}/(Fe^{3+}+Al+Cr) vs. Mg# and the Cr-Fe^{3+}-Al triangular diagrams by Barnes and Roeder (2001). Even if there are several similarities between the compositional fields of spinels from tholeiitic basalts and those from ophiolites, the high Fe^{3+} content suggests a derivation from an ophiolitic source. When using the TiO_2 vs Al_2O_3 diagram (Lenaz et al., 2000; Kamenetsky et al., 2001) it looks that an ophiolite generated in a MORB tectonic setting is the most suitable for the Bosso spinels moving to a supra-subduction zone ophiolite for the younger spinels given the presence of some spinels from BABB, Arc and OIB.

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Using extraterrestrial ^{3}He concentration to examine changing sedimentation rates within a precession cycle

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Use of extraterrestrial ^{3}He concentration as a proxy for sedimentation rate in marine sediments allows the construction of high-resolution timescales. An instantaneous sedimentation rate is determined for each sample measured, allowing this method to be used in investigating changing sedimentation rates on a sub-precessional scale, as well as constructing timescales over sections with rapid fluctuations in lithology.

We build on the techniques established by Patterson and Farley [1] by releasing helium from samples using a laser heating system in order to reduce blanks, and expand the range of lithologies to which this method has been applied to include organic-rich black shales. We construct a $^3He_{ET}$ age model through an interval with a known timespan, a precession cycle, as this allows us to check our determination of background $^3He_{ET}$ flux, one of the largest potential sources of error in a $^3He_{ET}$ age model.

The study area, the Umbria-Marche basin in the northeastern Apennines of Italy, has long been of palaeoclimatological interest because extensive pelagic cyclically bedded successions spanning the Late Jurassic to the Miocene are encoded with records of rapid climate perturbation (for example the Mesozoic Oceanic Anoxic Events).

In the Cenomanian (Late Cretaceous) Scaglia Bianca Formation, cycles of limestone and black cherts and/or thin black shales have been interpreted as precession cycles [2]. A high-resolution timescale has been constructed over one such cycle, to investigate how its 21ka timespan is apportioned within these different lithologies. Variation in sedimentation rate within the limestone unit, which makes up the bulk of the cycle by thickness, is examined in detail and compared with other sedimentological and geochemical records.

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Evolution of small carbonate platforms (Calcare Massiccio and Corniola Formations) in the Umbria-Marche Apennines using strontium isotope stratigraphy: Implications for early Jurassic crustal structure

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The lower Jurassic stratigraphy of the Umbria-Marche Apennines comprises two distinct successions. Small, high-relief carbonate platforms of the Calcare Massiccio Formation are overlain by a thin, "condensed" sequence. In the intervening basins are thick, "complete" sequences of deeper water carbonates and clays. The mechanisms and timing of the development, growth, and ultimate drowning of these small carbonate platforms are critical for understanding regional structural framework.

While the Calcare Massiccio Fm. platform carbonates are extensively exposed, less impressive exposure of the critical intervals at the base of the stratigraphic sections, the Burano and lower Corniola Formations, make direct observation of the relationship between platform and basin facies difficult. Many reconstructions of the lower Jurassic stratigraphy infer late, large-offset normal faults bounding the platform and basin sections.

Strontium isotope stratigraphy provides a high-resolution correlation tool for the region. Because $^{87}Sr/^{86}Sr$ values steadily decrease in the Hettangian-Pliensbachian of the early Jurassic, this is an excellent tool to examine relationships in various carbonate facies. This is particularly so where physical and/or biostratigraphic correlation is difficult, such as those found in the Umbria-Marche Apennines. In the lower Jurassic, older layers correspond with higher $^{87}Sr/^{86}Sr$ values. The values decrease from about 0.707773 at the Triassic/Jurassic boundary to a value of approximately 0.707072 at the Pliensbachian/Toarcian boundary. This corresponds to a decline of approximately 0.000032/My.

Significant interpretations stem from analysis of strontium isotope stratigraphy in the region.

- The small Umbria-Marche platforms drowned synchronously in the late Sinemurian based on identical, within error, $^{87}Sr/^{86}Sr$ values for the Calcare Massiccio Fm./Bugarone Fm. contact of 0.707466 on several platforms.
- After differentiation of the region into condensed and complete sequences, shallow-water carbonate platform sedimentation continued for several million years. Measured stratigraphic sections in the Burano and Bosso Gorges indicate that at least 100m of Corniola Formation was deposited while the adjacent platforms continued to grow.
- The presence of significant deposits of platform-derived material intercalated with deep-water carbonates (megabreccia blocks and Marmarone beds), coupled with limited platform margin foreslope deposits indicate the platform margins were predominately bypass-erosional in character.
- Based from inferred differential accumulation rates for the platform and basinal sequences of approximately 125m/My, the observed relief of the platform escarpments could be generated in less than 7 million years, a time period consistent with the observed stratigraphy in the region.
- These stratigraphic relationships indicate that differentiation into shallow and deep water facies occurred early in the development of the margin, in the latest Triassic/earliest Jurassic. Large offset normal faults are not necessary to create the observed topography and stratigraphic relationships found in the Umbria-Marche Apennines.

Meteorite flux in the Late Cretaceous

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In upper Cretaceous limestones exposed in the Bottaccione gorge near Gubbio (Italy), there are three intervals with elevated concentrations of extraterrestrial ^{3}He [1]. The oldest interval is in the mid Turonian around 91 Ma. The interval is characterized by sharp peaks of up to a factor of 4 increase in the extraterrestrial ^{3}He compared to background level. By dissolving large samples of limestone in acids, the residual material can be scanned for highly refractory, relict meteoritic spinel grains. The element and isotope compositions of the grains give information about the meteorite type that they resided in. The objective in this study is to learn what types of meteorites fell before and during this time interval, and consequently brought the solar-wind induced ^{3}He to the sea floor.

Ten samples of ~100 kg and two samples of ~25 kg were collected from different beds within and below the ^{3}He interval. The samples cover strata from ca. 0 m to 32 m above the reference level (Bonarelli Level). The ^{3}He excursion begins around 15 m above the reference level. Samples were dissolved in HCl and HF acids. The residue was sieved and separated into size fractions 32-63 and 63-355 µm. Opaque chrome-rich spinel and transparent/translucent Mg-Al spinel grains were picked and mounted in epoxy resin, polished with diamond paste and analyzed for chemical composition using SEM-EDS technique. Oxygen isotope analyses of the grains are in progress together with researchers at the Chicago Field Museum and Madison University. Based on chemistry, grains were identified as either EC (equilibrated ordinary chondritic extraterrestrial chrome-spinel), Outlier EC (one or two oxides deviating significantly from ordinary chondritic values), OC (other chromium-rich spinel), OC-V (OC grains with $V_2O_3 \geq 0.45$ wt%) or "Mg-Al" (magnesium-aluminum spinel). The EC grains follow the definitions by [2] with TiO_2 range from [3]. As shown in [4] the EC grains can further be categorized as H, L, and LL groups according to their TiO_2 quantities; H: ≤2.5 wt%, L: 2.51-3.39 wt%, and LL: ≥3.40 wt% A total of 567 spinel grains were found. They are preliminarily categorized as follows: 106 EC (excluding 11 outlier grains), 32 OC-V, 265 OC, and 153 MgAl-spinels (the majority found in one sample). Samples before the ^{3}He interval contain fractions of H, L, and LL chondritic grains comparable to today (47%, 42%, 11% resp.). Within the ^{3}He interval H-chondritic grains dominate with 68%. The overall trend in all samples is an increase of H-chondritic grains relative to L, likely following a disturbance in the asteroid belt. However, a conundrum is that there is no increase in the number of EC grains. This could possibly reflect a difference in sedimentation rate within the ^{3}He anomaly. The conspicuous Mg-Al spinels in one layer within the ^{3}He anomaly need further analysis to either confirm or dismiss an extraterrestrial origin.

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Tectonically induced base-level change in the Quaternary revealed by alluvial fan shifts and rivers re-organization. A case study in the Northern Apennines of Italy

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In active continental extensional basins, subsidence induced by normal faults activity at their hanging-wall is the main factor in the creation of an accommodation space where rivers deliver their sediments. The sediments ages, lithology and geometry provide the timing and rate of faults activity. The migration of active extensional tectonics through time produces a correspondent shift in the position of the active depocenter. This process produces features like wind gaps, abandoned valleys, streams captures and drainage inversions which provide hints on timing and rate of active tectonics migration.

In this work, we address the issue of how the investigation of the recent geological history of a fossil alluvial fan can provide new insights on the spatial migration of active tectonics through time and the consequent re-organization of the rivers network. We investigate a fossil alluvial fan originally deposited into a lower Pleistocence depocenter, which has been uplifted about 200 m at a normal fault foot-wall above the present-day alluvial plain. The area, comprised between Perugia and Spoleto in central Italy, is presently active as indicated by both GPS measures, historical and present-day seismicity.

Based on detailed mapping of the Quaternary deposits, information on the age of the mapped deposits, paleo-currents indicators, geomorphological investigations, and high resolution seismic reflection profiles we reconstruct a peculiar geological history of the area: the eastern part of a lower Pleistocene depocenter in which an alluvial fan was deposited underwent a sudden increase in the activity of a NE-dipping normal fault system. Consequently, the alluvial fan was cut and the western part of the depocenter was de-activated, undergoing incision. On the other hand the increase of subsidence in the eastern part of the basin promoted the deposition of a thick sequence of alluvials and headward erosion of the rivers, which suddenly enlarged their drainage areas producing rivers captures and inversions. This process occurred in the last 0.8 Myr.

By analyzing the present-day alluvial fans areas vs their contributing areas we discuss the variability of the data distribution in the reconstructed geological history of the study area. We stress that a widely multidisciplinary investigation of rivers anomalies and basins subsidence distribution can provide extremely useful hints in the understanding of the steadiness/unsteadiness of faults behavior.

A Late Cretaceous true polar wander oscillation

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Debate has surrounded the existence of rapid Late Cretaceous true polar wander (TPW) ca. 84 million years ago (Ma). Classic paleomagnetic data from the Scaglia Rossa limestone of Gubbio and Moria, Italy, in the Umbrian Apennines, are the primary argument against the existence of Late Cretaceous TPW. A new high-resolution paleomagnetic record confirmed at two overlapping stratigraphic sections in Apiro and Furlo provide evidence for a ~10° TPW oscillation from 86-79 Ma. Representing the most recent large-scale TPW event to be documented, the Late Cretaceous TPW oscillation may have been excited by the "last gasp" of plate reorganization associated with the breakup of supercontinent Pangea or the rise of the Deccan Traps mantle plume in particular.

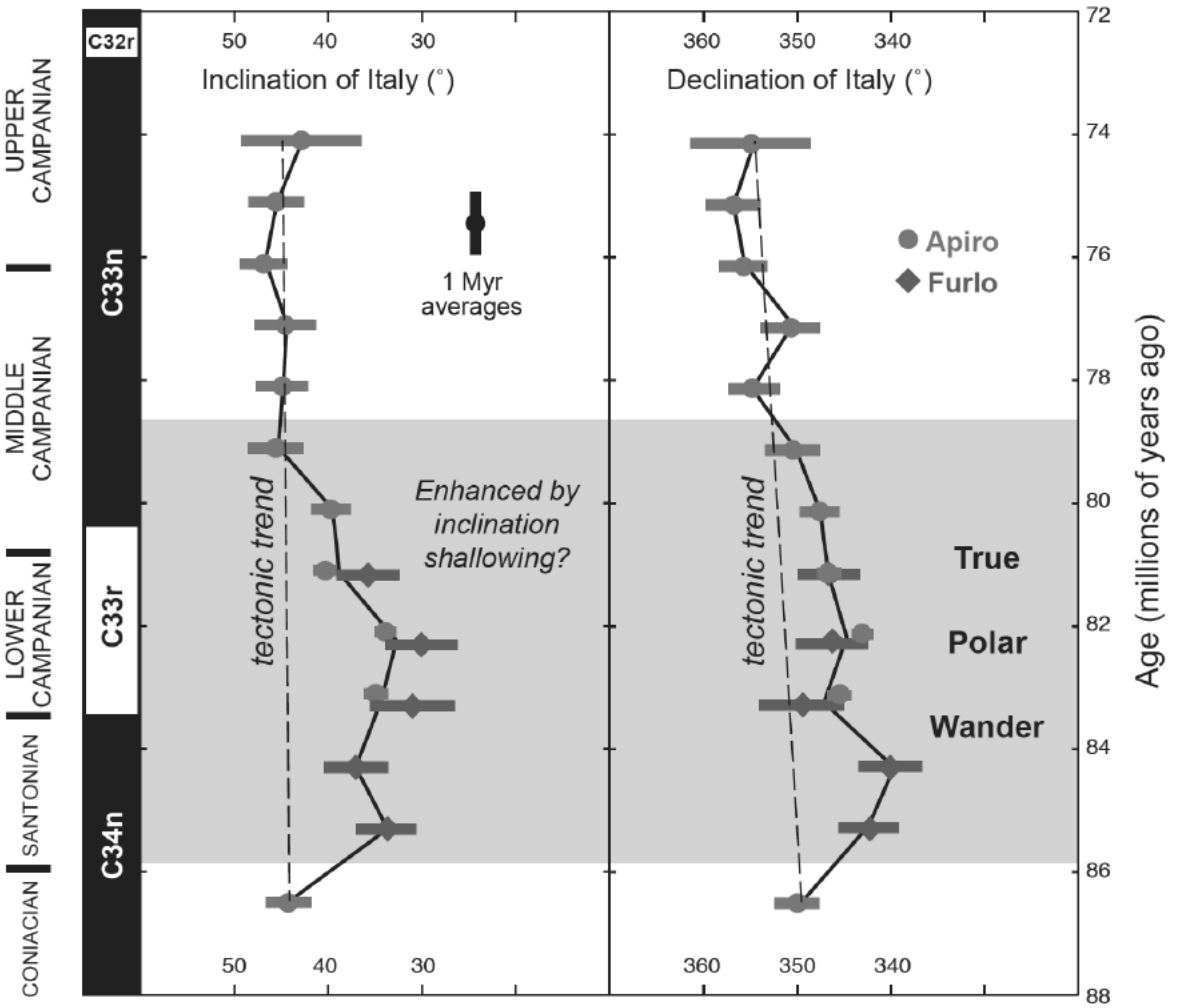

Fig. 1 Late Cretaceous paleomagnetic inclination and declination of Italy. The rapid ~3˚ Myr^{-1} (~33 cm yr^{-1}) excursion of Italy to lower latitude in C33r is interpreted as a ~10˚ TPW oscillation. Dashed linear regressions fit to pre- and post-TPW data, where the gray data are omitted from the fits. Slow (~0.2˚ Myr^{-1}) northward motion and counterclockwise rotation of Italy are interpreted as steady components of background plate tectonic drift on which the TPW oscillation signal is imposed. Global polarity time scale is shown on the left with magnetochrons labeled. TPW is the wholesale rotation of the solid Earth (mantle and crust) around the liquid outer core in order to reinstate rotational stability when mass is redistributed in the mantle due to rising plumes and/or sinking slabs.

Pelagosite revisited: The origin and significance of a laminated aragonitic encrustation on Mediterranean supratidal rocks

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Two centuries ago, with the following words (translated from Italian), Scipione Breislack (1816) describes, for the first time, a strange substance, which today we refer to as pelagosite: "[At the Grotta dell'Arco in the Island of Capri, near Naples] …*one can see attached to the calcareous rock a substance, in most places black in color, smooth and shiny, which, at first sight, seems like a sort of bitumen, and which, after analytical examination, did not yield other products than an empyreumatic oil, an ammoniacal matter, and a carbonaceous residue. This substance is found forming protuberances on the surface of calcareous rocks, sometimes mamillary, some others elongated and slightly compressed as if they had a certain degree of fluidity, flowing like a paste. It is strongly attached to the rock so much that a hammer is needed to detach it. However, the rock on the surface of which it formed, once broken into pieces, does not show any visible trace of it inside. When it has a smooth and shiny appearance, it is constantly black, and it has the true aspect of bitumen. Some other times, however, the surface of these protuberances is scabrous forming small globules similar to cauliflowers; in these cases, its color is dark gray tending to a reddish tinge, and from the irregularities of the surface a few hair emerge similar to down…*". Breislack concludes his description proposing that this strange substance was formed after decomposition and sublimation of some animal matter (alluding to goat dung).

Similar black encrustations with a vitreous luster resembling tar, which cover, in irregular patches, the supralittoral dolomitic rocks of the remote southern Adriatic island of Palagruža, were reported by Marchesetti (1876); one year later, Stossich (1877) christened it "pelagosite" (from *Pelagosa*, the Latin name of Palagruža). The reports by Marchesetti and Stossich were followed by 50 years of investigations by a number of European researchers about the nature and origin of this intriguing mineral. Among them, Biasoletto (1879) proposed that pelagosite is the product of a slow bituminization process of microscopic algae, which were deposited onto the supratidal zone by sea waves. Bellini (1921) came to the conclusion that the formation of pelagosite, which he calls *capreite*, in the lower supratidal zone at Capri, is due to marine microalgae, and that the presence of these encrustations at a certain height above the spray zone was due to tectonic uplifting. Finally, Onorato (1926) published a comprehensive paper on the morphological, mineralogical, physical, chemical, and microbiological characteristics of pelagosite samples from the Tremiti Islands, which are located some 75 km southwest of Palagruža, off the coast of Apulia (southeastern Italy). Pelagosite turned out to be pisolitic aragonite. It consists of pisolitic or mamillary objects with a concentric ring internal structure "*similar to tree rings*", made of a pure, acicular aragonite with a radial orientation within the pisolites, and solidly attached to the rocky substratum. According to Onorato (1926), pelagosite is produced by *"blue-green algae*" (i.e., cyanobacteria) of the genera *Chroococcus* and *Scytonema*, which grow where the supralittoral rock is frequently wetted by sea spry. Airoldi (1936) discusses the role of a new genus of

calcareous alga, christened *Sclerothamnium nitens*, associated with coralline alga *Melobesia*. sp. in the formation of aragonitic pelagosite from the limestone islet of Bergeggi near Savona, and a diabase rock at Fremura, near La Spezia, both located in the littoral Liguria region of northwestern Italy. No relevant contributions about a possible biogenic origin of pelagosite were published following Onorato (1926) and Airoldi (1936), and their documentation of cyanobacterial or microalgal cells contained in pelagosite seems to have fallen into almost total oblivion during the rest of the 20th century.

Today pelagosite and coniatolites encrustations alike are referred to as diagenetic structures forming in shallow back-reef environments along the western Persian Gulf and elsewhere, as well as in equivalent ancient environments represented by carbonate platform limestone formations (Mazzullo and Cys, 1982). Breton (1993) considers aragonitic pelagosite a synonym of evaporitic coniatolite, and reports it from the splash zone along the Mediterranean coasts of Spain, France, and Corsica. In more recent years, Crnjaković et al. (2005) report pelagosite from the supralittoral volcanic andesite of the islet of Brusnik, in the western off shore of the Croatian island of Vis. Duane (2005), referring to microlaminar pelagosite structures found on Quaternary calcareous sandstones exposed along the tidal zone of the Moroccan Atlantic coast, argues that they are formed by physico-chemical precipitation from seawater. Nevertheless, Macalady et al. (2008) report extracting cyanobacterial cells belonging to the genus *Xenococcus* from pelagosite samples collected in the Croatian island of Hvar, suggesting that this bacterium may have a role in nucleating and precipitating aragonite laminae on supralittoral rocks frequently wetted by sea spray, thus essentially confirming the early observations and interpretations by Onorato (1926) and Airoldi (1936).

In this paper, we present a thorough reanalysis of pelagosite from the type locality of Palagruža, and the southern coast of the island of Hvar, paying particular attention to the geomporphological characteristics of its growing environment, its general morphology and intimate structure, mineralogical and geochemical composition, the nature of its microbial content, the rhythmic arrangements of its aragonitic microlaminae probably resulting from local short-term cyclic climate changes, and its potential as a radioisotopic geochronometer.

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Caverns and Sanctuaries

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Italy is filled with caverns. These are the recesses, which, since the dawn of time, have served a multitude of purposes for man: shelter, sustenance, and sanctuaries. One of the most mysterious cult caverns is the Grotta di Scaloria in Manfredonia. Found in 1932, the cavern was filled with carefully painted vases, which were used to capture the drip water of the stalactites. Just how such cave waters may have been used in deep antiquity comes into sharp focus during the Etruscan and Roman periods, when the cloudy, mineral-laden liquid issuing forth from the mammiform stalactites was collected for use as an emollient to ensure nursing mothers produced ample breast milk. Such caverns came to be known as milk caves (*lattaie)* with the slightly supersaturated waters they produced called mountain milk (*latte di monte*) or moonmilk (*latte di luna*). The term moonmilk is a reference to an early notion that the substance was produced when the Moon's rays flowed through rock. Among the best-known of these caves the Grotta Sant'Angelo at Palombaro in Abruzzo, dating to the Roman period. It was a sanctuary dedicated to a fertility goddess with four cisterns cut into the rock beneath large stalactites to collect drip water, her breast milk. This strong association of caves with breast milk is underscored by Rome's founding myth of the royal twins Romulus and Remus, who were suckled in a cave by a she-wolf.

So what might account for the purported healing properties of moonmilk? The secret lies in the presence of *Macromonas bipunctata*, a microbe composed largely of calcium carboxylate ($CaCO_3$), which plays a key role in metabolizing organic acids along with a host of cyanobacteria, fungi, green algae and actinomycetes. The latter is a group of Gram-positive bacteria that are a naturally occurring antibiotic. Collectively, these agents are known to promote healing.

The idea of a cavern as a dark and mysterious place suitable for religious rituals continued from antiquity to the Middle Ages, a time characterized by fear of nature and satanic forces. On the vanguard of a change in perspective toward the natural world was St. Francis of Assisi who is now associated with the environmental movement. He set forth the revolutionary philosophy that the Earth and all living creatures should be respected as creations of the Almighty. He lived in Umbria, a region which is still today, green, fertile and infused with a palpable spirituality. His own cell and bed were carved out of rock. The grotto of the monastery at La Verna was the place at which he received the stigmata of Christ in 1224. The Franciscans continued to promote mountains as being vital in the sacred ritual, promulgating the idea that they would provide a nearness to God and a source of divine inspiration. Indeed, the clefts in the mountain were evocative of the wounds in St. Francis' hands and caused a wave of the faithful to make a pilgrimage to the grotto at La Verna to view the sacred recesses.

St. Francis' affinity for Earthly elements influenced many of the artists of the time such as Giotto, who included rocky landscapes, mountains and forests in his frescoes as a way of presenting the newly popular idea of natural philosophy.

Correlations among the ages of flood-basalt eruptions, extraterrestrial impacts, mass extinctions and times of ocean anoxia of the past 260 Myr

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Oral Presentation

The stratigraphic succession in the Central Italian region has provided evidence for impact/extinction events (e.g., the K-Pg boundary and Late Eocene events, and possibly the J-K boundary), and for ocean-anoxic intervals (e.g., the Bonarelli and Selli Events) probably related to the effects of flood-basalt volcanism. There should be additional evidence for other cataclysmic events in Central Apennine sections, but where should we look? There are 13 documented extinction events over the last 260 Myr, and we find that the ages of 12 coincide, within errors, with the ages of flood-basalt eruptions (8 events) and large impacts (6 events) (Figure 1). The null hypothesis that this could occur by chance can be rejected with high confidence.

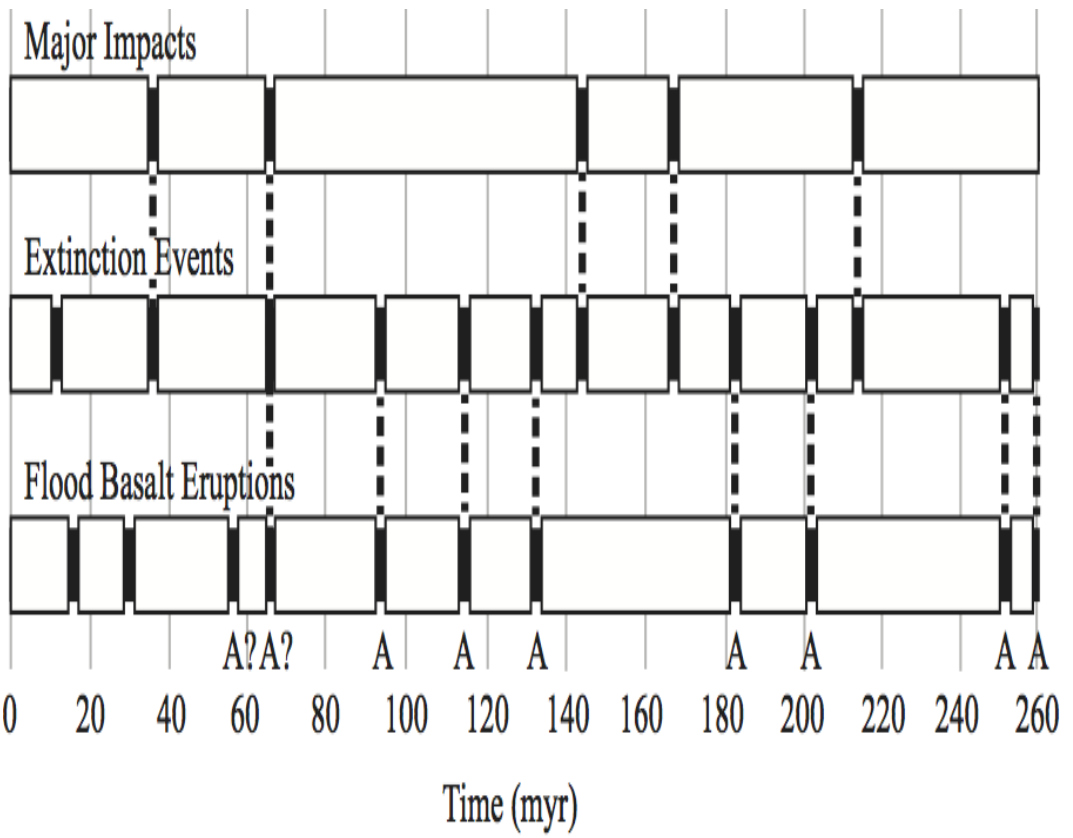

Figure 1. Correlation of the ages of documented extinction events (Raup and Sepkoski, 1986); major impacts (craters > 70 km in diameter); and flood-basalt eruptions of the last 260 Myr. Anoxic events are indicated by A. There are 2 large impacts at 36 Myr ago. In only one case, the end-Cretaceous (66 Myr ago) is there a joint occurrence of a large impact crater (Chicxulub) and a flood-basalt eruption (the Deccan Traps).

The ages of large impacts (craters >70 km in diameter) coincide with extinction events at 36 (two impacts), 66, 145, 168(?) and 215 Myr ago (Figure 1). The ages of flood basalts coincide with extinctions at 66, 94, ~118, 133(?), 183, 201, 252, and 259 Myr ago (Figure 1). The K-Pg boundary at 66 Myr ago correlates with both a very large impact and the Deccan flood-basalt province, perhaps explaining the severity of that extinction event. The time of the eruption of the North Atlantic Volcanic Province Basalts (56 Myr ago), while not marked by a mass extinction event, coincides with the PETM climatic episode.

Furthermore, the ages of at least 7 intervals with evidence of anoxia in the oceans in the last 260 Myr coincide with the ages of flood-basalt eruptions (with high confidence), and are also coeval with extinction events, suggesting a causal connection (Figure 1). These statistical relationships argue that most mass extinction events are related to environmental catastrophes produced by large-volume flood-basalt eruptions and large asteroid or comet impacts. These events should be recorded in the sedimentological, paleobiological and geochemical archives in the well-exposed sections of the Central Italian region.

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A 26 Myr cycle in the ages of impact craters and mass extinctions of life?

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#Deceased

Records of the ages of terrestrial impact craters and mass extinctions of life have been proposed to show a common ~26 Myr cycle, with a similar phase. Models involving periodic comet showers from the outer Solar System suggest that some craters should occur in periodic clusters, which seems to be the case (Figure 1). Previous studies have all used very similar crater and extinction age data, so in order to provide a new perspective, we employ a new method of cross-wavelet transform analysis to the records of impacts and extinctions, which allows these two data sets to be compared directly for cyclic components.

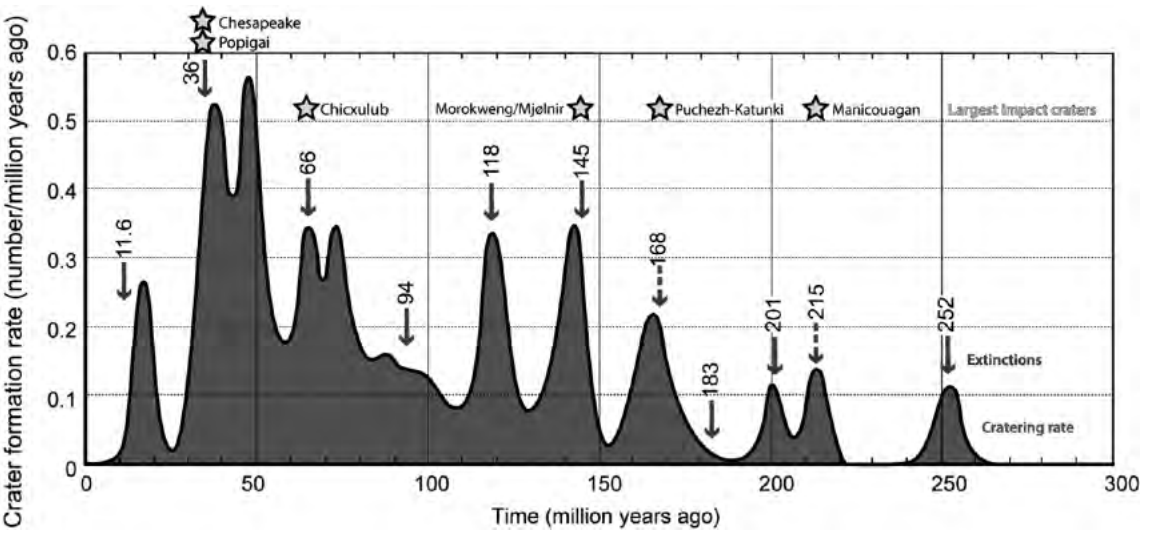

Figure 1. Crater formation rate (number/Myr) for 37 craters, compared with times of extinction (arrows) and the 6 largest impacts (stars) of the last 260 Myr.

The scalogram of the cross-wavelet transform of impact-crater ages against extinction events reveals that almost all cross-variability of these two data sets is strongly concentrated at the 26 Myr wavelength (Figure 2). The phase lag between impacts and extinction events is close to zero. The most recent expression of the cycle, t_0 = ~13 Myr ago.

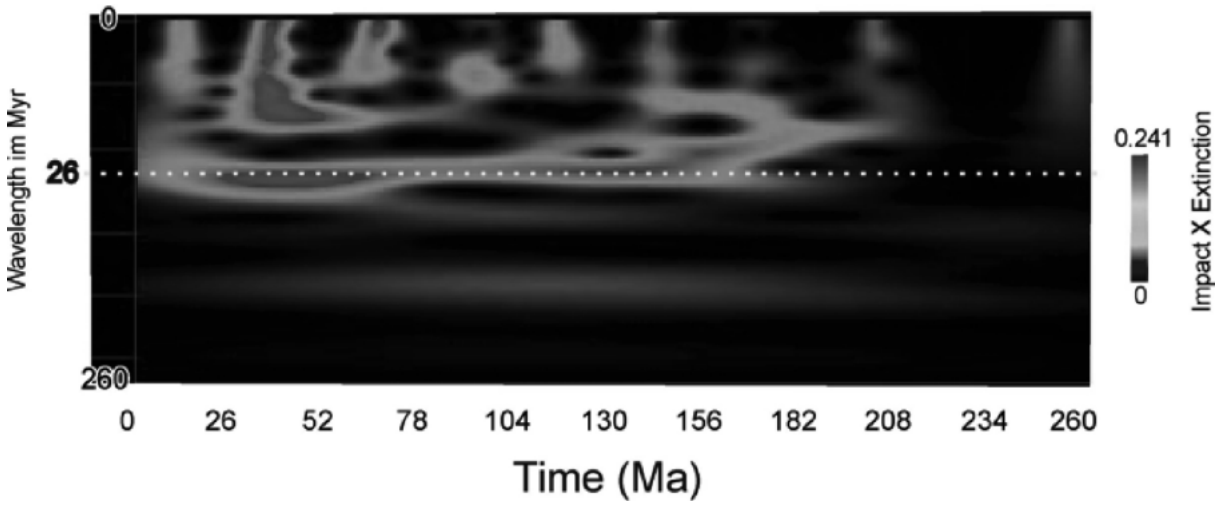

Figure 2. Cross-wavelet transform scalogram of impact-crater (37 events) and extinction (12 events) data over the last 260 Myr, showing the cross-amplitude (Impact x Extinction), and instantaneous time lag (i.e., phase shift) between the two data sets. Note the concentration of power at ~26 Myr (this suggests high significance), where t_0 (the most recent expression of the cycle) = ~ 13 Myr ago.

One 26-Myr cycle seems to be missing (Figure 2), which would be equivalent to ~227 to 230 Myr ago, close to the Carnian/Norian boundary and a minor extinction event (~228.4 Myr ago). We note that two newly re-dated craters, Lake Saint Martin (227.8±1.1 Myr ago, 40 km diameter), and Paasselka (231±2.2 Myr ago, 10 km diameter) have ages that overlap with that extinction event. Our analyses suggest that some impact craters tend occur in periodic clusters, with a cycle of ~26 Myr, which correlates with a similar cycle seen in extinction events, and supports a connection between periodic large-body impacts and some mass extinctions of life.

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High-resolution multiproxy cyclostratigraphic analysis of environmental and climatic events across the Cretaceous-Paleogene boundary in the classic pelagic succession of Gubbio (Italy)

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We studied a high-resolution multiproxy data set, including magnetic susceptibility (MS), $CaCO_3$ content, and stable isotopes ($\delta^{18}O$ and $\delta^{13}C$), from the stratigraphic interval covering the uppermost Maastrichtian and the lower Danian, represented by the pelagic limestones of the Scaglia Rossa Formation continuously exposed in the classic sections of the Bottaccione Gorge and the Contessa Highway near Gubbio, Italy. Variations in all the proxy series are periodic and reflect astronomically forced climate changes (i.e., Milankovitch cycles). In particular, the MS proxy reflects variations in the terrigenous dust input in this pelagic, deep-marine environment. We speculate that the dust is mainly eolian in origin and that the availability and transport of dust are influenced by variations in the vegetation cover on the Maastrichtian-Paleocene African or Asian zone, which were respectively located at tropical to subtropical latitudes to the south or far to the east of the western Tethyan Umbria-Marche Basin, and were characterized by monsoonal circulation. The dynamics of monsoonal circulation are known to be strongly dependent on precession-driven and obliquity- driven changes in insolation. We propose that a threshold mechanism in the vegetation coverage may explain eccentricity-related periodicities in the terrigenous eolian dust input. Other mechanisms, both oceanic and terrestrial, that depend on the precession amplitude modulated by eccentricity, can be evoked together with the variation of dust influx in the western Tethys to explain the detected eccentricity periodicity in the $\delta^{13}C$ record. Our interpretations of the $\delta^{18}O$ and MS records suggest a warming event ~400 k.y. prior to the Cretaceous-Paleogene (K-Pg) boundary, and a period of climatic and environmental instability in the earliest Danian. Based on these multiproxy phase relationships, we propose an astronomical tuning for these sections; this leads us to an estimate of the timing and duration of several late Maastrichtian and Danian biostratigraphic and magnetostratigraphic events.

Applying and evaluating the use of portable X-ray fluorescence (pXRF) measurements on pelagic carbonates: Maastrichtian strata from the Bottaccione Gorge, Gubbio, Italy

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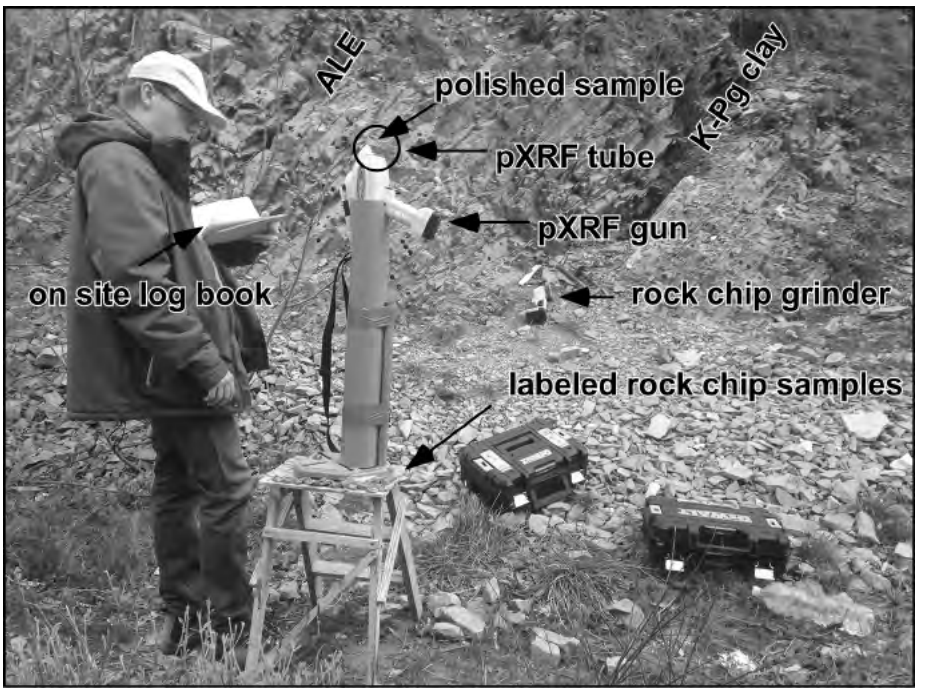
Portable X-ray fluorescence (pXRF) devices are increasingly used for acquiring elemental data for multi-proxy studies. Pelagic carbonate sections are a commonly studied archive for paleoclimatological and stratigraphical research. Therefore this study applies and evaluates the use of pXRF measurements on pelagic carbonates from the well-studied terminal Maastrichtian section of the Bottaccione Gorge near Gubbio, Italy. A calibration with carbonate reference materials is set up to acquire absolute elemental concentrations, and allows for comparison with previous geochemical studies. Furthermore the potential for cyclostratigraphical (Fe) and chemostratigraphical (Mn and Sr) applications is demonstrated. Moreover, we indicate a diagenetic imprint on at least the bulk $\delta^{18}O$, Sr-concentrations and Sr-isotope signals of this section. Overall, it can be concluded that with proper measurement strategies and careful calibration, pXRF measurements can be a reliable, relatively easy, non-destructive, less expensive, and relatively fast method to acquire multi-elemental concentration data (Ca, Fe, Mn, Sr). These data are valuable additions to classical proxies as magnetic susceptibility and calcium carbonate content to multi-proxy studies of pelagic carbonates.



pXRF in action at the K-Pg interval in the Contessa Highway section of Gubbio. Time needed for a team of two operators for one sample data acquisition is 90 seconds including: collection of a 2 cm^2 rock chip, polishing with a battery stone grinder, labeling in a sample bag, duplicated pXRF measurements, entering the data in an electronic file and in a log book.

Factors controlling tectonic inversion

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Many regions show both extensional and contractional events, with structures reactivating or overprinting each other during tectonic inversion (e.g. Butler et al., 2006). Positive inversion is the change from extension to contraction (e.g. Williams et al., 1989), while negative inversion is the change from contraction to extension (e.g. Lake and Karner, 1987). Tectonic inversion involves the reactivation, in the opposite sense, of individual normal or reverse faults, or of zones of extension or contraction. Inversion is typically developed variably across a region, and we suggest that locations in which inversion occurs are controlled by proximity to the main zone of deformation (e.g. mountain belts), and therefore stress magnitudes, and by crustal strength. Factors that can control crustal strength include lithology, crustal thickness and temperature, relative orientations of stress axes and structures, friction on faults and the occurrence of overpressure. For example, the softer, overpressured sediments in a warm basin above thinned crust are more likely to be inverted than surrounding basement highs. Examples from Europe are used to illustrate the patchy development and likely causes of inversion structures.

Inversion implies a stress evolution in which there is interchange between σ_3 being vertical to cause vertical thickening, and σ_1 being vertical to cause vertical thinning (Peacock et al., 2017). This interchange will typically involve a phase in which σ_2 is vertical, promoting strike-slip faulting. We link the changes in the magnitudes of stress axes with related changes in fluid pressures (P_f) to understand a common phase of strike-slip deformation between periods of regional extension and regional contraction. This behaviour, illustrated using examples of structures in southern England, is described because the area was affected by Alpine contraction but did not experience significant crustal shortening and thickening, so the inversion structures are well-preserved. Examples from the Apennines of Italy are presented to show that these phases of strike-slip faulting can be recognised not only in the foreland-thrust belt transition zones, but also within more severely deformed orogenic interiors.

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The Strontium isotope record of paleohydrological change in the Turkana Basin at the termination of the African Humid Period

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One of the most significant features of Holocene climate change in East Africa is the African Humid Period (AHP), which terminated at ~ 5 ka. Many lakes in the East African Rift System (EARS) were strongly affected by the AHP, generally exhibiting strong lake level response to the alternating wet and dry conditions. One of the larger lakes in the EARS, is Lake Turkana which was filled to overflow level for much of the early Holocene and experienced a dramatic ~70 meter lake level drop at the endtermination of the AHP, turning it into the terminal lake system that it still is today.

The climatological drivers of Lake Turkana hydrology are potentially complex, because it is situated under the influence of two large atmospheric convection systems; the Intertropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB). Shifting of these atmospheric systems at the end of the AHP dramatically re-organised spatial rainfall patterns over the Turkana Basincatchment, causing a shift in runoff contributions from the different sub-catchments of the Turkana Basin.

Here, I present a Holocene Turkana lake water Sr-isotope reconstruction based on the analysis of well-dated lacustrine ostracods and shells, which reveals consistently high Sr isotope values for the early Holocene, followed by a significant, but gradual drop in Sr isotope ratios across the AHP termination. Since lacustrine Sr isotope ratios are a runoff provenance indicator in this setting, such dramatic lacustrine Sr isotope change points towards a significant (climate-driven) reorganisation of runoff contributions from different sub-catchments to Lake Turkana.

Mass extinctions and biodiversity: a view from 2017

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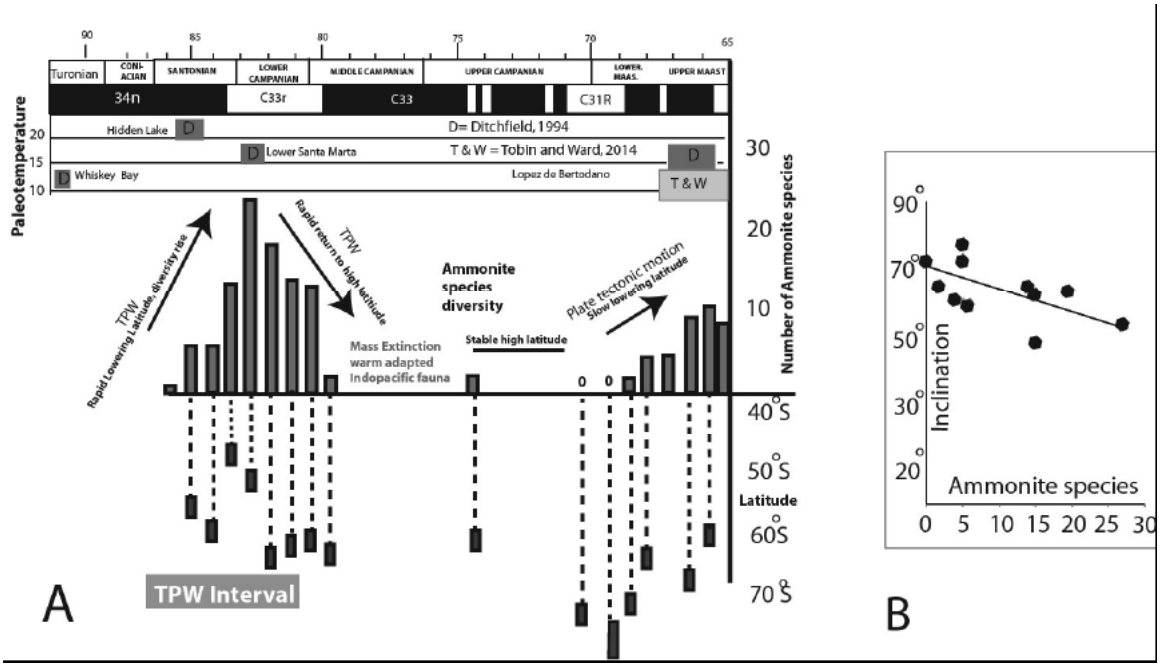
The paradigm changing discovery by Alvarez et al (1980) totally upended our understanding of mass extinctions and how quickly biodiversity can change due to extraterrestrial causes. Since that time the science caused by this monumental discovery has shown that terrestrial changes caused by rapid increases in greenhouse gases from flood basalts have also caused major extinctions: these are now termed "Greenhouse Mass Extinctions". Also, the idea that there was a "Big Five" is totally outdated as events prior to the evolution of animals led Ward and Kirschvink to propose a "Big Ten". But here we consider how biodiversity certainly has been affected by two new areas of research: the effects of True Polar Wander, and the rapid evolution caused by Heritable Epigenetics. We will present new, unpublished information and data from the late Cretaceous of Antarctica, from the Devonian of Western Australia, and the late Triassic of the Queen Charlotte Islands (caused by the Manicouagan Impact Event) to provide a new look at 21st century extinction and evolutionary events in deep time.



Data from Upper Cretaceous of James Ross Island area, Antarctica, showing how True Polar Wander was involved in major diversity change in ammonite diversity. Composite figure bringing together diversity, paleolatitude, and paleotemperature. Paleotemperatures from Ditchfield et al, and Tobin and Ward, 2014. B. Relationship between ammonite diversity and paleolatitude as shown by paleomagnetic inclinations. The correlations coefficient shows this relationship to be highly significant.

Unifying several decades of GNSS/GPS measurements to study Adriatic microplate motion and neotectonics in the Southern Alps and northern Dinarides, Slovenia and surroundings

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This presentation will introduce and review our work to unify data from several decades of GNSS/GPS experiments to measure and study the motion of the Adria microplate and active deformation in and around Slovenia near the NE corner of the microplate. We are working to determine a unified velocity field using data from a combination of cGPS and eGPS sites that were collected over variable time periods, and processed in different ITRF reference frames, and processed at both the Universities of Ljubljana and Miami, using both GIPSY and Bernese software.

The presence of an Adriatic microplate clashes with the interpretation that Neogene geologic features in this region indicate that active Nubia-Eurasia convergence is taken up across the Apennines and Alps. This neotectonics–geological mismatch likely reflects the very recent birth of the Adria microplate, termination of the Nubia–Eurasia Alpine collision, and recent Adria slab break-off beneath the Apennines.

We studied the motion of the Adriatic microplate using Eurasian-plate-referenced, GPS-derived velocities from Istria Peninsula (Slovenia, Croatia) and Po Plain (Italy) sites and compared this to an independent result that we derived using earthquake slip vectors around the edges of the microplate. Our best-fitting GPS Adria–Eurasia angular velocity vector (Euler pole) comes from 7 Istria Peninsula (Slovenia, Croatia) and 10 Po Plain (Italy) sites; it locates at 45.03°N, 6.52°E, with a 0.297±0.116°/Myr counterclockwise rotation rate. This GPS-derived pole overlaps with our earthquake slip-vector-derived pole. We also present new, on-going work and review additional historic and recent determinations of Adriatic microplate motion.

Active deformation in and around Slovenia and centered on the Southern Alps-Dinarides junction is likely caused by contraction along the NE corner of the rotating Adriatic microplate, rather than by Africa (Nubia)-Eurasia collision, which has likely ended. To quantify and study active deformation in this region, we are working to unify a data set from >60 episodic GPS sites in northern Croatia and Slovenia, >50 permanent GPS regional reference stations. Our preliminary results indicate a significant and sharp (~2.5 mm/yr) transpressive gradient in the velocity field across the Sava Fault (Periadriatic zone) and through central Slovenia, likely the zone of highest seismic hazard in Slovenia and marking a zone of active lateral extrusion in the southern Alps and Dinarides driven by Adria-Eurasia convergence.

Poster Presentations

Paleoclimate implications of Pliocene tree rings from the Dunarobba Fossil Forest (Umbria, Italy)

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The main periodic climatic oscillationsm in the present world are ENSO (El Nino Southern Oscillation) and PDO (Pacific Decadal Oscillation) in the Pacific realm, and NAO (North Atlantic Oscillation) and AMO (Atlantic Multidecadal Oscillation) in the Atlantic realm. These annual to decadal scale oscillations exert significant controls on regional climate and also influence the mean temperature of the planet. The persistence of these oscillations in a much warmer world is an important, largely unresolved question. Some authors have suggested that ENSO oscillations may cease operation in a warmer climate, while others have suggested that they persist even in warmer climates; little is known about the persistence of NAO into the past. If either (ENSO or NAO) of these climatic phenomena ceased to operate in the near future, it would have significant implications for humans. One way to address this question of the persistence of these oscillations is to look for annually-resolved climate proxy records from recent warm climatic periods. If these proxy records show the same kind of high-frequency climatic variability that characterizes the modern versions of phenomena like ENSO and NAO, we then have evidence in support of the persistence of these oscillations in warmer climates. Annually-resolved climate records from the distant past are difficult to find, but one important source is fossil trees, whose annual rings can yield useful information on climate variability over decadal to centennial time scales. In this paper, we present an analysis of tree rings from the Late Pliocene (i.e., 2.5 million years old) fossil forest near the village of Dunarobba, in the southern Umbrian Apennines of Italy. This fossil forest is a *unicum* inasmuch it consists of a set of more than 70 large tree trunks of an extinct species of sequoia or cypress, standing routed in place, and with original cellulose still preserved. Spectral analysis of tree ring series (325 and 448 years in duration), combined with oxygen isotope analyses of the cellulose, provide a glimpse into the mean annual temperature and the inter-annual climate variability that characterized this region at the end of the Pliocene, when the concentration of atmospheric CO_2 was about 400 ppm. The high-frequency variability of the ring width time series shows significant spectral components that are consistent with the influence from the North Atlantic Oscillation, and to a lesser extent, the solar cycles and the El Nino – Southern Oscillation. The mean annual temperature estimate of about 19°C, based on a model that combines ring widths and oxygen isotope values, is a full 6°C warmer than the present day value for this region. These elevated temperatures are consistent with estimates from pollen analyses and with estimates from higher latitudes.

Structural and Kinematic Analysis of the Conero Riviera from Ancona to Portonovo, Italy

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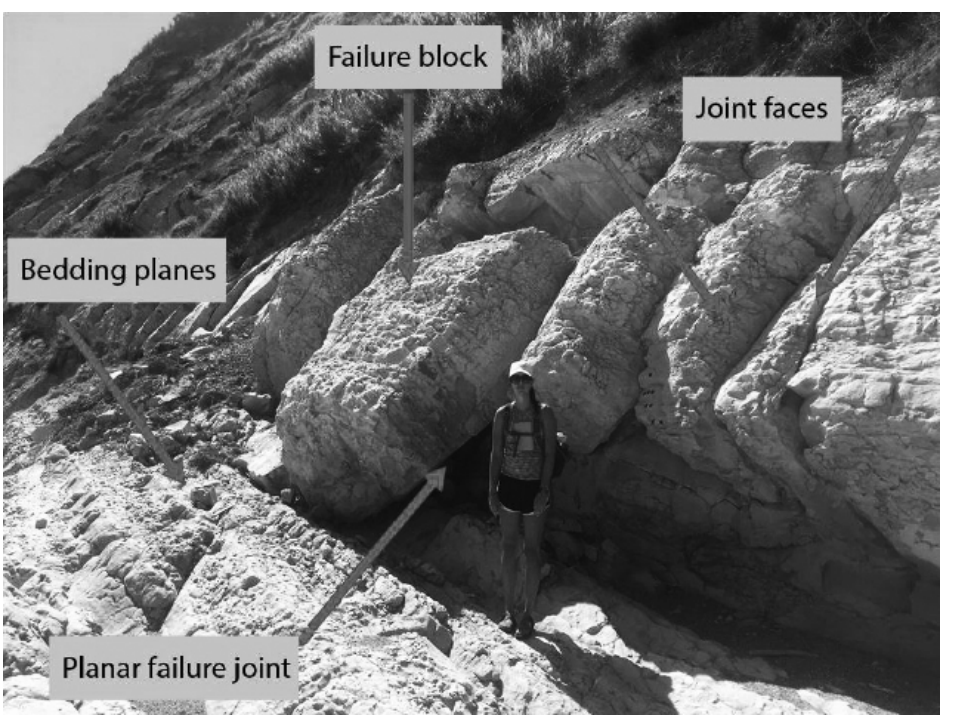
The cliffs above the public beaches of the Conero Riviera between Ancona and Portonovo, Italy, are comprised of carbonate rocks and are subject to copious rainfall and occasional earthquakes. The area has experienced large-scale landslide events, from Portonovo's 14th century landslide to Ancona's more recent 1982 landslide. Though these events have been studied at length, there are no studies on this region's risk of future landslides. Based on the historical and geological evidence, it is important that the Ancona coastline be assessed for landslide risk. This study aimed to determine the role of geologic structures in the area near these two historic landslides using kinematic analysis as well as structural and stratigraphic field data collected between the Ancona shipyard and the southernmost accessible beach of Monte Conero. We collected data from within several different rock units and observed distinct patterns of jointing, faulting, and bedding along the coast. Some of these structures show risk of planar and wedge failure. There is evidence of recent rockfalls and landslides, all of which were smaller than the two historical slides. We conclude that the Conero Riviera coastline is at risk for future landsliding and rockfall, making it dangerous for beachgoers and resort infrastructures.



Planar failure along a joint plane of a block of Bisciaro limestone near the Ancona shipyard.

Chromite grains distribution in the ^{3}He anomaly of the Tortonian stage at the Monte dei Corvi Beach section

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The Miocene Epoch was a time when the northern Apennines accretionary wedge was built up and the present day ocean-climate system configuration took shape (Montanari et al. 2017). The Messinian (Late Miocene) recorded a salinity crisis, and during the late Tortonian there was another exceptional event that might have affected the global climate and ecology system: a collisional disruption of the >150 km diameter asteroid that created the Veritas family 8.3 ± 0.5 Myr ago in the asteroid belt. This event increased the flux of interplanetary dust particles rich in ^{3}He to the Earth (Farley et al. 2006). The Late Miocene ^{3}He anomaly has been registered in deep sea sediments from ODP site 926 (Atlantic ocean), ODP site 757 (Indian Ocean) and in the late Tortonian-early Messinian Monte dei Corvi section near Ancona, Italy (Montanari et al. 2017).
Here we report the results of the study performed in Monte dei Corvi section aimed to recover extraterrestrial chromite grains connected with the ^{3}He anomaly, similarly to results obtained for the late Eocene ^{3}He anomaly in the nearby Massignano section (Boschi et al., 2017). The Late Eocene ^{3}He anomaly is similar in duration and magnitude to that in the Late Miocene. In this study three ~100 kg samples have been collected: two within the ^{3}He peak and one outside the anomaly as a background reference sample. In total 1151 chrome spinel grains have been recovered in the Monte dei Corvi section but none of the grains has an extraterrestrial origin. The results supports the hypothesis that the event that formed the Veritas family has not produced an asteroid shower to the Earth. Another evidence is the absence of a crater of this age on Earth (Farley et al. 2006). The terrestrial grains recovered have been classified and the composition showed that all the grains have an ophiolitic origin with no substantial compositional change and distribution through the section. The terrestrial grains genesis area was probably the Alps massif. From the Late Eocene the Umbro-Marche basin received via run off terrigenous material from the Alps, and the pelagic succession shows a general increase in the siliciclastic component from an average of ~20-30% in the Late Eocene Scaglia Variegata to ~40-50% in the mid Miocene Schlier formation. This mechanism might explain why the terrestrial grains are more common in Monte dei Corvi than in Massignano.

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Tectono-Stratigraphic Setting of Cenozoic Intermontane Lake Basins: A Comparison Between Selected Systems of the Rocky Mountains, USA and Central Italy - Implications for Studying Gale Crater Mars

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Lake deposits record a sensitive balance between hydrology, sedimentation, and tectonics (Eugster, 1982). Because the relative volume of water in lakes is low compared to marine systems, lakes are poorly buffered against changes in these factors and respond quickly to fluctuating conditions. Thus, the geo-biologic record preserved in the sedimentary strata of lacustrine basins is more sensitive on a finer time scale to environmental changes than most marine settings. For this reason, lake sediments and lacustrine strata are a robust data set to study local climatic conditions and climate change; response of sedimentary systems to changes in base level, rates of sediment supply, and accommodation; and response of biologic communities to forcing events and conditions (Carroll and Bohacs, 1999). Lake deposits are important economically as well. High organic productivity under favorable conditions coupled with proximal siliciclastic and carbonate reservoirs yield rich petroleum systems that account for around 5% of global oil reserves, ca. 60+ billion barrels and approximately 10% of the world's current production, ca. 8+ million barrels of oil per day (Sladen, 2012).

The study of lacustrine systems has experienced a significant renaissance in recent years for two main reasons. 1) The economic importance of microbial lacustrine carbonate hydrocarbon reservoirs in the recent discoveries in the Lower Cretaceous, offshore Brazil (Bosence *et al*., 2015). And, 2) the recognition that the most likely depositional environments within which to find indications of life on Mars are within ancient lakes and associated strata (Grotzinger *et al*., 2014). In both instances, deep-water offshore Brazil and Mars, directly interpreting the geology is difficult as either outcrops don't exist (Brazil) or are incredibly remote (Mars). Because of this, locating and identifying analogs is of critical importance.

We are interested in better understanding a range of lacustrine systems and the driving conditions for microbes to have a significant influence on the deposition or modification of lacustrine sediments, to understand the distribution of microbial facies within the three-dimensional architecture of lacustrine strata, and to better understand the physical characteristics of these deposits (Eby *et al*., this conference). Toward this end, we are cataloging the tectono-stratigraphic setting of a wide range of Cenozoic intermontane basins in the Rocky Mountain West (Montana, Idaho, Wyoming, and Utah). Three overlapping tectonic settings in both time and space are responsible for these lake basins. Oldest to youngest: foreland basins associated with Laramide compression and crustal loading by basement involved uplifts (Paleocene and Eocene), intra-arc basins resulting from extension associated with inboard migration of the arc due to flat-slab subduction (Eocene and Oligocene), and Basin and Range extensional basins (Miocene through Recent). These lake basins vary in size, geometry, and tectonic setting and the tectono-stratigraphic architecture of these basins provides a framework within which the sedimentology of various lacustrine systems can be evaluated (see Eby *et al*., this conference). Additionally, this study includes a comparison with Late Tertiary through Recent lake basins in central Italy that result from intra-arc extension. These basins are similar in tectonic origin to lake basins in eastern Idaho and western Montana, but developed under very different climatic conditions. The goal is to

better understand the intricacies of lacustrine systems both as strata of economic importance and to better recognize and predict key facies on Earth and potentially on Mars.

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Scanning magnetic microscopy of spherule-bearing K-Pg boundary clay: a new technique for magnetostratigraphic constraint of the age of impact spherule alteration

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The globally-distributed impact spherules of Cretaceous-Paleogene (K-Pg) boundary layers are one of the most readily apparent features of such deposits in the field. They formed as condensates of the vapor plume of the Chicxulub impact event and, due to plume dynamics and chemical heterogeneity, were deposited as several mineralogically distinct compositions. In the Umbria-Marche K-Pg sections the original compositions were subsequently altered to spherules dominated by 1) goethite, 2) potassium feldspar, or 3) glauconite. While the conditions that promote the alteration observed have been previously reported, the timing (and potentially the duration of such seafloor conditions) has not been constrained. The presence of highly magnetic goethite (and variably magnetic glauconite) spherules and the magnetic reversal at the base of C29n only 300 kA following the K-Pg boundary could provide such constraint. However, conventional paleomagnetic techniques are hampered by the presence of additional magnetic phases in the surrounding clay.

This study proposes the application of scanning magnetic microscopy (SMM) to resolve the polarity of the goethite spherules independently of the clay matrix. Scanning magnetic microscopy is a developing technique that creates a spatial map of the magnetic field measured in a horizontal plane above polished rock surfaces or petrologic thin sections, analogous to an aeromagnetic survey at a sub-millimetre scale. At such a spatial resolution, SMM can identify the contribution of individual mineral grains and calculate the paleomagnetic magnetic vector of discrete particles.

For analysis using SMM, four polished thin sections from the well-described Petriccio section were prepared using techniques that minimize the application of magnetic fields. The polished samples contain visible spherules of varying compositions at the surface. SMM of the surface will yield field maps that contain both background signal from the clay matrix and discrete signals from the goethite spherules. Treating the spherule signal as a dipole source allows the full paleomagnetic vector to be calculated, and compared to that of the background. This analysis will reveal if the alteration of the goethite spherules from their olivine precursor was sufficiently rapid to occur during a single magnetochron, and if so, if that chron is normal or reversed. While diagenesis cannot be ruled out as a factor in goethite formation, the measured paleomagnetic direction is a possible line of evidence constraining the onset of oxidizing conditions on the Umbria-Marche basin seafloor to greater or less than 300 kA following the K-Pg boundary event.

Paleoenvironmental signature of the Selandian-Thanetian Transition Event (STTE) and Early Late Paleocene Event (ELPE) in the Western Neo-Tethys

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Poster Presentation

Sedimentary records of the early Cenozoic indicate a series of events with climatic and carbon cycle variability known as hyperthermals. A ~200 kyr long event of environmental disruption during the Paleocene, not described before and here named Selandian–Thanetian Transition Event (STTE), has been recognized and well constrained in the Western Tethys Contessa Road section (Gubbio, Italy) trough high-resolution biostratigraphic, geochemical, and rock-magnetic property data. The STTE exhibits peculiar stressed ecological responses among calcareous nannofossils and foraminifera, which highlight marked environmental perturbation affecting the geobiosphere. The environmental instability is not confined within the photic zone but extends to the seafloor leading to more trophic conditions of the sea surface waters with an enhanced, but of short measure, nutrient availability on the seafloor under almost unchanged warm-water conditions and marked rise of lysocline. Distinct magnetic properties of sediments that record the STTE at Contessa, as low susceptibility and decrease in total ferromagnetic mineral content are consistent with reductive dissolution. However, we also document two components in the isothermal remanent magnetization (IRM) and First-Order Reversal Curves (FORC) diagrams that suggest the occurrence of magnetofossils throughout the STTE, indicating that the occurrence of bacterial magnetite is not due to a preservation effect. Systematic variations in bio-geochemical and magnetic parameters are consistent with increased primary productivity at times of increased terrigenous input and, therefore, increased nutrient supply. Noteworthy, the uppermost part of the STTE includes the suspected hyperthermal, short-lived Early Late Paleocene Event (ELPE). The ELPE event shows an episode of increase in magnetic properties of the sediments, including an increase in magnetofossil concentration, as indicated by IRM components and FORC diagrams. The comparison of our biotic and abiotic records throughout the Selandian-Thanetian transition with available data across the ELPE and related remarks from former investigated ocean and land-based sites provides lines of evidence that this event is part of a more complex scenario than hitherto supposed.

Comparative Sedimentology of Rocky Mountain and Central Italian Intermontane Lakes: Potential Implications for Lacustrine Sediments in Gale Crater, Mars

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Terrestrial analogs for fluvio-lacustrine sediments can constrain and enrich the interpretation of rocks interrogated by the Mars Science Laboratory (MSL) Curiosity within Gale crater that were deposited under non-marine ("continental") subaqueous environments (Grotzinger et al., 2014, 2015). At least three lake levels within Gale crater have been identified based on geomorphic evidence (Palucis et al., 2016). Sedimentary rocks observed along Curiosity's traverse may represent several fluvio-lacustrine environments including fluvial conglomerates and barforms, proximal-deltaic deposits, thickly laminated deeper water deposits, and heterolithic low-stand deposits with candidate desiccation cracks that suggest oscillating lake levels (e.g., Williams et al., 2013; Grotzinger et al., 2015; Edgar et al., 2017; Schieber et al., 2017; Stein et al., 2017). Linking the sedimentological record to the lacustrine reconstruction remains a critical knowledge gap. In this poster, we highlight key features of the lacustrine record in western USA and central Italy, that may lead to more detailed geologic reconstruction of martian lake processes in Gale crater including identifying the dynamic threshold controls within the lake system.

Understanding the climate and structural links to sedimentology of lacustrine basin fills can benefit from comparison of well-studied Cenozoic and modern lakes of the western USA. Our ongoing work in the Green River Formation (Eocene Lake Uinta) of the Uinta Basin and its modern analog, Great Salt Lake (GSL) (both in Utah), provide book ends for studying mixed chemical and siliciclastic lacustrine deposits (Chidsey et al., 2015; Eby et al., in review). Superb outcrops and a continuous core have allowed us to document much of the 14 my development of the Green River Formation through numerous cycles of Lake Uinta's history. The origins and tectonic setting of the Uinta Basin and GSL are examples of a complete spectrum of Cenozoic intermontane lacustrine deposits being catalogued in the Rocky Mountain West (mostly in Montana and Utah; see accompanying abstract for this meeting by Bowen et al., this conference). Enriching these studies with data from intermontane continental basins of central Italy (deposited under a different climatic setting than Great Salt Lake and Lake Uinta) will make this catalogue of lacustrine deposits robust for understanding a substantial part of the Gale crater section as the MSL Curiosity rover continues its scientific exploration up the flanks of Mt. Sharp.

The abundance of late Tertiary and modern lakes in central Italy provide a natural laboratory for documenting the size, geometry and tectonic controls on sedimentation and basin fill by transported siliciclastic and volcanogenic sediments versus chemical sediments (carbonates and silicified deposits) controlled by lake waters and (travertine) springs. Current focus is on the Plio-Pleistocene Fucino Basin (Cavinato et al., 2002; Giaccio et al., 2015) where fault scarps and some core results have indicated a stratigraphic framework of lacustrine units from marginal to open-lake facies. Data already published from Fucino Basin are being analyzed in a Lake-Basin-Type (LBT, sensu Bohacs, 2003, 2016) framework for constructing a record of lake processes to compare with observations on the LBT's of other terrestrial lacustrine sites, as well as Mars.

Documentation of habitable environments and possible deposits with biosignatures has remained an important task of the ongoing MSL mission as well as informing future martian landing sites in lacustrine settings (e.g., Schon et al., 2012; Grotzinger et al., 2015). Terrestrial microbialite biosignatures, such as those found in the Green River Formation and Great Salt Lake, and their

association with adjacent lake facies, can help researchers better understand the probability of finding similar deposits on Mars. Drone surveys and extensive field work in and around GSL have helped explain facies relationships and the origin of many grain types, microbialite morphologies, microtextures and early diagenetic cementation processes (Vanden Berg et al., 2016a & b). In addition, groundwater and micro-seeps may contribute to the formation of microbialite "giants", while microbialite growth patterns are often controlled by large-scale desiccation polygons.

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Mineralogy of the Terrigenous Component of the Cretaceous-Paleocene Umbria-Marche Succession

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The pelagic limestones of the UM succession contain some minor component of terrigenous siliciclastic material. There have been a couple of studies on the mineralogical composition of this terrigenous component, but no comprehensive studies have yet been completed on these siliciclastic. Arthur and Fischer (1977) reported the general mineralogy of the Marne a Fucoidi (Scisti a Fucoidi), Scaglia Bianca, and Scaglia Rossa to be primarily biogenic calcite derived from coccoliths and foraminifera, and the remaining fraction of terrigenous clay and silt proposed to be wind-blown. The mineralogy of Fucoid marls was reported as 20-70% $CaCO_3$, and the rest quartz, illite mica, pyrite, chlorite, and montmorillonite. The mineralogy of the Scaglia Bianca was reported to be similar to that of the Marne a Fucoidi. The mineralogy of the Scaglia Rossa was reported to be greater than 50% calcium carbonate, and the rest quartz, illite mica, and montmorillonite with some pyrite in the lower parts of the formation. The mineralogy of the Cretaceous-Paleogene (K-Pg) boundary clay was reported semi-quantitatively as 61% mixed-layer illite-smecite, 21% illite, and 18% kaolinite by Johnsson and Reynolds (1986). Goethite and hematite were reported as the non-clay phases present in the K-Pg boundary clay. In addition to the minerals found within the clay, up to 3% chlorite and an unspecified amount of quartz were reported for several limestone and marl levels in the Scaglia Rossa.

There are mineralogical data for several of levels within the Scaglia Rossa (Johnsson and Reynolds, 1986), and qualitative data on what the mineralogy is within the Marne a Fucoidi, Scaglia Bianca, and Scaglia Rossa (Arthur and Fischer, 1977). However, comprehensive data throughout the section does not yet exist on the mineralogy. To fill this gap, samples would be collected throughout the Gubbio sections at regular intervals. The terrigenous component would be extracted and analyzed using X-ray diffraction. Data would be analyzed on software such as Bruker's DIFFRAC.EVA and TOPAS to obtain quantitative mineralogy.

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Implications for central Italy paleoclimate from 95,000 yr B.P. until the Early Holocene as evident from Frasassi Cave speleothems

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In this study we present a composite $\delta^{18}O$ and $\delta^{13}C$ record obtained from four speleothems from the Grotta Grande del Vento cave, located within the Frasassi karst system, central Italy. The ages were determined by U-series analysis, employing thermal ionization mass spectrometry (TIMS), and cover most of the time period from ~95,000 yr B.P. until ~10,000 yr B.P. including the last part of stage 5, most of the last glacial and the early Holocene period, with a hiatus lasting from ~ 65,000 to ~ 55,000 yr B.P. Comparison with the $\delta^{18}O$-$\delta^{13}C$ record of speleothems from the Soreq Cave, Israel, located in the Eastern Mediterranean (EM) region, shows that the stable isotopic profiles of Frasassi speleothems, a cave located in the north central Mediterranean region, have similar trends excluding the period from ~85,000 yr B.P. and 80,000 yr B.P. time interval known as sapropel S3 in the EM. This is the only period in which the $\delta^{18}O$ profile of Soreq speleothems shows opposite trend relative to Frasassi speleothems, reflecting the influence of the sapropel events mainly on the hydrological system in the EM region. A major pronounced isotopic event during the last glacial in central Italy and Israel is observed between ~54,500 and 52,500 yr B.P., most probably reflecting a major wet and warm event in the region. $\delta^{18}O$ values of Frasassi speleothems are usually more depleted compared with Soreq by ~2-4‰, reflecting the difference in temperature and the isotopic composition of rainfall between the two sides of the Mediterranean basin. $\delta^{13}C$ values of Frasassi speleothems are usually enriched by more than 3.0‰, reflecting different vegetation, probably higher proportion of C4 vegetation overlying the Frasassi cave system compared to that of the Soreq Cave area.

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An integrated stratigraphic analysis of the "problem" of the Oligocene-Miocene boundary at Monte Conero, Italy

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An integrated stratigraphic analysis of the Bisciaro and Scaglia Cinerea Formations at Monte Conero in central-eastern Italy offers a detailed, nearly continuous record of pelagic deposition influenced by orbitally controlled climate cycles spanning the Oligocene-Miocene boundary. Previous attempts to precisely determine the location and age of the boundary have been complicated by syndepositional tectonism and marine regression in the Mediterranean. The present study examines a section that was located farther from Alpine and Apennine orogeny than previous sites and was therefore presumably undisturbed by tectonic activity. Petrographic and geochemical analyses of a volcanic ash layer from the Monte Conero "BiCiCore" indicate its correlation with the regional bentonite marker bed known as the Livello Raffaello. A biostratigraphic analysis places the FO of *Paragloborotalia kugleri* at 19.95 m, which informs the placement of normal polarity chron C6Cn.2n at 21.2 m. Both datums are used to locate the Oligocene-Miocene boundary, which is more commonly placed at the base of C6Cn.2n. The section appears to include a 1.2 Ma depositional hiatus in the late Oligocene, perhaps resulting from regional marine regression, but the paleomagnetic record indicates the boundary is preserved intact in the core. A cyclostratigraphic analysis of magnetic susceptibility throughout the core yields a record of eccentricity cycles, which may be compared to the eccentricity solution of Laskar et al. (2011) to determine an astrochronological age for the boundary. While the Raffaello layer within the BiCiCore yielded no zircons for radiometric dating, a U-Pb zircon analysis of a sample of the same Raffaello bentonite from the Contessa section near Gubbio dates the volcanic ash at 22.38 ± 0.23 Ma. This radiometric age supports the astrochronological dating, which places the Rafaello at approximately 22.2 Ma, comfortably within the uncertainty of U-Pb. Defining the boundary as the base of normal polarity chron C6Cn.2n, the age of the boundary is 23.7 Ma. This is nearly 0.7 Ma older than the currently accepted age of the boundary but well within the range of debated dates. The robust micropaleontological, paleomagnetic, and paleoclimatic data retrieved from the core, as well as its correlation with radiometrically dated bentonite layers within the section, makes Monte Conero an excellent locality for defining the location and age of Oligocene-Miocene boundary.

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Tectonic and sedimentary evolution of the Umbria-Marche basin during the Mesozoic

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Tectonic activity in the Tethys realm during the Mesozoic is well documented from the Apulia Platform to the Central Apennines, as well as in the Dinarides and Southern Alps. Since the Triassic, continental rifting with a prevalent transtensional tectonic stress field has been responsible for the different phases of basin evolution, from rifting to drifting. The Mesozoic tectonic structures affecting the Umbria-Marche basin can be defined in terms of their geometry and kinematics by analyzing the synsedimentary deformation affecting the stratigraphic succession. In this region, a system of NW-SE and N-S normal faults shaped the pelagic carbonate platforms during the Middle and Upper Jurassic and drove the basin's subsidence with different thickness and facies variations since the Late Cretaceous.

The Jurassic stratigraphic succession records this setting with huge lateral and vertical facies variations as well as with synsedimentary deformation. Slopes characterised by sedimentary wedges, neptunian dikes, slumps and detritic facies connect the shallow water carbonate platform facies with deep-water pelagic carbonate-siliceous sediments of the basin area.

Lower Cretaceous synsedimentary deformation, possibly linked to the tectonic activity, is widespread from the internal sectors of the Gubbio area through Mt. Conero and to the Adriatic off-shore. These structures include hiatus with stratigraphic thinning and thickening, and involve a different part of the Cretaceous stratigraphic succession, between the Hauterivian-Lower Aptian Maiolica Formation and the Aptian Marne a Fucoidi Formation. In many outcrops, it is possible to observe detachment extensional structures, imbricated slides, slumps and chaotic layers distributed vertically and longitudinally.

Several internal trigger mechanisms induced by external regional tectonic events such as earthquakes can be invoked. The significant increase in the total organic carbon in the Hauterivian/Aptian layer of the Maiolica and Marne a Fucoidi Formations suggests the possibility that the limestone layer, sandwiched and sealed in between clays of the organic-rich black shales, could have favored a pore pressure increase approaching lithostatic stress. With a thin overburden, lithostatic stress is more easily reached at low hydrostatic pressure. A subvertical system of calcite veins crossing the limestone layers represents the primary pathway for fluid driven breaching of joint seals.

Upper Cretaceous synsedimentary deformation, involving both limestone and marly-limestone layers of the pelagic Scaglia Formation, has already been documented by many authors in different outcrops in the Umbria-Marche Apennines. Detachment extensional features, imbricated slides, slumps, and calcareous turbidites represent the main observable structures.

The restoration and rotation of the geometries and kinematics of these synsedimentary deformation features to their original paleomagnetic orientations has shown that a lot of the tectonic activity corresponds to the main trend of the extensional lineaments and is linked to the transform faults of the westernmost Tethys rifting systems.

250 Millions Years of Earth History in Central Italy: the last year 2016 AD

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A significant sequence of earthquakes occurred in the Sibillini Mountains in Central Italy from August to October 2016. On August 24th, Mw 6.1 earthquake struck the area between the town of Amatrice (Rieti Province) and Arquata del Tronto (Ascoli Piceno Province). Several ground ruptures along different strands of SW dipping extensional faults occured over a distance of more than 20 km, throughout the morphologically complex landscape of the Sibillini Mountain chain and the Laga massif. The October 26th Mw 6.0 earthquake was centred in the Visso area (Macerata Province), approximately 30 km northwest of the previous event. On October 30th, an Mw 6.5 event occurred near Norcia (Perugia Province), in an area located between the epicentres of the former earthquakes. This event reactivated existing ground ruptures and produced further rupturing over a larger area.

A detailed field mapping of spatial geometries of the surface coseismic ruptures of active faults is the basis for the identification of seismogenic structures and represents an important step towards assessing the recurrence intervals and magnitudes of earthquakes. Data of fracture distributions, fault offsets, and links between geometries along the fault strands are the essential tools for extrapolating and constraining the depth of the fault plane from a kinematic point of view. Kinematic fault analysis integrated with geophysical data allows to constrain any seismotectonic model. Integration of geological and seismological data remains one of the main objectives when identifying active faults and assessing their potential hazard.

A hihgly detailed map of the coseismic surface ruptures was created by integrating a direct and a classical structural field survey with low altitude aerial photos and remote sensing data interpretation. The digital images were processed using Structure from Motion algorithms obtaining 3D clouds of more than $3*10^7$ points for each area. These point clouds, permitted to generate a fully rendered 3D geological model making the extraction of the fracture geometries possible. Digital surface models and orthophoto mosaics allowed to detect displacements of several centimetres n areas where the faults and fractures can be easily traced. The attitude of these discontinuities, expressed by offset, dip direction and dip, was measured using a combination of GIS tools, integrated and verified with the digital field survey checks, and subsequently processed via the traditional geometrical spatial methods using structural statistical tools. The along-strike displacement versus distance of the fault planes and ground ruptures was analysed along several cross sections orthogonal to the fault strikes. Generally, the surface ruptures cross known normal faults. They have a continuous extent of ~25 km and consist of open cracks and vertical dislocations or warps (2 m maximum throw) orientated NW-SE. The cross sections highlight slip accommodation through linkage, which shows to be a common fault growth mechanism.

These structures are an exceptional example of the complex geological evolution of a region, where at least three tectonic phases are overprinted. The last active extensional phase affecting Central Italy, highlighted by the recent seismic activity and the development of coseismic surface ruptures, permits us to bear witness to the geological evolution of the region.

Integrated stratigraphy and correlation of slack water deposits from the Caverna del Carbone and Sala della Sabbia in the Frasassi cave complex (Marche, Italy)

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The Caverna del Carbone (CDC) is a small horizontal cave with a 3 m high entrance vault that perforates, for about 30 m, the southeastern side of the Frasassi gorge at about 232 m of elevation, which is about 32 m above present thalweg of the Sentino River flowing at the bottom of the gorge. Sala della Sabbia (SDS), instead, is a room in the giant Grotta Grande del Vento, which, along with the Grotta del Fiume and the Buco Cattivo caves (and a number of other smaller caves), is part of the ca. 30-km-long Frasassi hypogenic karst maze (see Montanari, this volume). The SDS is found at about 29 m above thalweg, some 300 m straight south from the entrance of CDC. At present, there is no accessible communication between the two caves because the inner termination of CDC is clogged by a deposit of alluvional slackwater sandy lime. On the other hand, at SDS there is a ca. 2 m thick deposit of well sorted and very fine fluvial sand, which contains well preserved ostracod shells (some paired) and pollen, evidently transported in suspension by flooding river water slowly flowing at an estimated velocity of 1-2 cm/sec. OSL dating on plagioclase from the upper layer of the sand deposit yielded a mean age of 115 ± 14 ka (see Fiebig et al., this volume), which indicates that the flooding occurred during the Eemian interglacial period. Our working hypothesis is that the flooding river alluvionated the cave from the CDC entrance, which implies that the CDC sill was close to thalweg at that time (see model proposed by Montanari, this volume), and no other cave entrances are known on the southern side of the gorge at that elevation. It is so that we have engaged in a detailed sedimentological and stratigraphic analysis of Room-C, the inner room of CDC where limey slackwater sediment obstructs the probable passage to the Grotta Grande del Vento. Here we used a manual auger to drill a borehole through 2.5 m of sediment down to bedrock, retrieving samples at 15 cm advancements. Sedimentologic (grain size, petrographic, micropaleontologic) analyses of these samples allowed to reconstruct a stratigraphy of this slack water deposit, which seems to have recorded a series of alluvional and erosional events, with a possible unconformity at about 1 m depth. At about 20-40 cm depth, in a 60 cm deep pit we dug around the borehole site, we found a 5-cm-long chert blade embedded in the fine lime, which is consistent with a mid-Late Paleotithic artifact. But in a little niche 120 cm above the floor of Room-C, we found the remnant of a fluvial gravel deposit, indicating that once upon a time the cave was filled up by a thick bed of coarse fluvial sediment, which, eventually, was eroded away. It is plausible that this gravel was rushed into the cave by the flooding river during a time of aggradation, i.e., during the Last Glacial Maximum. All these sedimentological evidences point to a complex history of alluvionation, further complicated by the OSL age of 200 ± 17 ka from detrital plagioclase at the bottom of borehole PIT-3, and an age of 173 ± 15 ka from the top of the borehole (Fiebig et al., this volume), where the mid-Late Paleotithic chert blade was found. Possibly, the CDC cave started to be alluvionated some 200 kyr ago from a higher entrance (i.e., Sala del Fuoco, see Montanari et al., this volume), before the CDC entrance was incised by the river, but then during the Eemian and the following Würm glaciation, the CDC cave entrance was incised, and the flooding river could have reworked the old slackwater sediment, and re-alluvionated the whole cave until clogging the passage to the Grotta Grande del Vento.

A probable Paleolithic sanctuary in the Room of Fire of the Grotta del Fiume at Frasassi (Marche, Italy)

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In 1986, while exploring the Grotta del Fiume cave in the Frasassi gorge (Marche region, northeastern Apennines of Italy) a team of speleologists from the GSM-CAI of Ancona discovered a new room, here christened "Sala del Fuoco" (room of fire). In this remote and difficult-to-reach large, flat-bottomed room beautifully decorated by shiny, crystalline speleothems, the speleologists found a skull of a male mountain goat or steinbock (*Capra ibex*) set on the tip of a short stalagmite. Unfortunately the skull was accidently destroyed and disposed of before the speleologists dutifully intended to deliver it to the Archeological National Museum in Ancona (see Fig. 1 and Parco Naturale Regionale della Gola della Rossa e di Frasassi, 2000). On the floor of the room, the speleologists also found four chert blades, which were delivered to the Archeological Museum in Ancona, and the charcoal remains of a fire pit. A tunnel at the western end of the room was filled by a fine polygenic breccia with plant roots sticking out of it, indicating that the tunnel was leading to a close entrance of the cave now obstructed by landslide debris. These finds suggested to the speleologists that the Sala del Fuoco room represented a Late Paleolithic dwelling, which was suddenly abandoned when a landslide blocked the entrance of the cave (Forestalp, 1986). Despite its importance, this discovery was never publicized much, nor further scientific investigations were made in this fascinating site. Not until when, twenty years later, a team of speleo-geologists from GS CAI of Fabriano and the GSM-CAI of Ancona lead by Alessandro Montanari from OGC, revisited this room sampling and studying alluvional slackwater sediments (sand and clay) underlying the speleothemic pavement of the cave, which today rests some 65 m above the Frasassi gorge thalweg (see Montanari, this volume). While there, a sample of charcoal from the fire pit was collected and eventually dated with 14C AMS at 16345 ± 300 yr cal BP (Montanari 2007, unpublished). In further expeditions, the speleologists carefully surveyed this cave using modern laser mapping techniques, checking out each single corner of it. In doing so, they discovered a mound of broken bones of a steinbock, including a half mandibular bone with teeth still in place, which yielded a 14C age of 16718 ± 119 yr cal BP, thus consistent with the age of the fire pit charcoal. But the strangest thing was found not far from the fire pit, on the western side of the room. It was a mound of speleothem crust slabs, which were broken and eradicated from the floor pavement and piled up on the side. The slabs are now re-cemented with centimeter-thick new speleothemic calcite. Samples of the speleothem cement and of the pavement crust itself are currently being U-Th dated at M.I.T by David McGee. But the big question the speleo-geologists asked to themselves is for what reason a troglodyte man of the Epigravettian culture should have ruined that beautiful, ceramic-like speleothem floor piling up the broken slabs on a side? The most reasonable answer is that he wanted to free the surface of the lose sandy slackwater deposit underlying the hard crust, so to easily dig a hole, a pit, or perhaps a grave… Preliminary subsurface georadar imaging of the whole floor of Sala del Fuoco is showing, in fact, that in that 2 m^2 spot there is an anomaly probably caused by the lose sediment of the dug up hole contrasting

with the more compacted surrounding sediment, or perhaps there is a low density object (or a body?) buried there. While waiting for a necessary by-law authorization from the Superintender of the Archeological Heritage of the Marche Region to organize a scientific archeological dig, the archeometric data and the archeological evidences gathered so far in this cave, such as a few chert tools, one fire pit, one deposit of broken steinbock bones, and a steinbock skull placed on a stalagmite like it would represent a totem, let alone a possible grave, strongly suggest that this site was not a residential dwelling frequented by a human community for a long period of time, but rather a solitary site frequented for a short time (i.e., until the entrance was sealed by a landslide some 16.5 thousand years ago) by one or a few people who, perhaps, were using this fabulous underground space for spiritual purposes. In any case, these finds represent the oldest dated evidence of *Homo sapiens* in the Frasassi and Rossa gorges, and one of the few dated sites in Italy of the first part of the Pleniglacial period, between 20,000 and 14,500 years ago.

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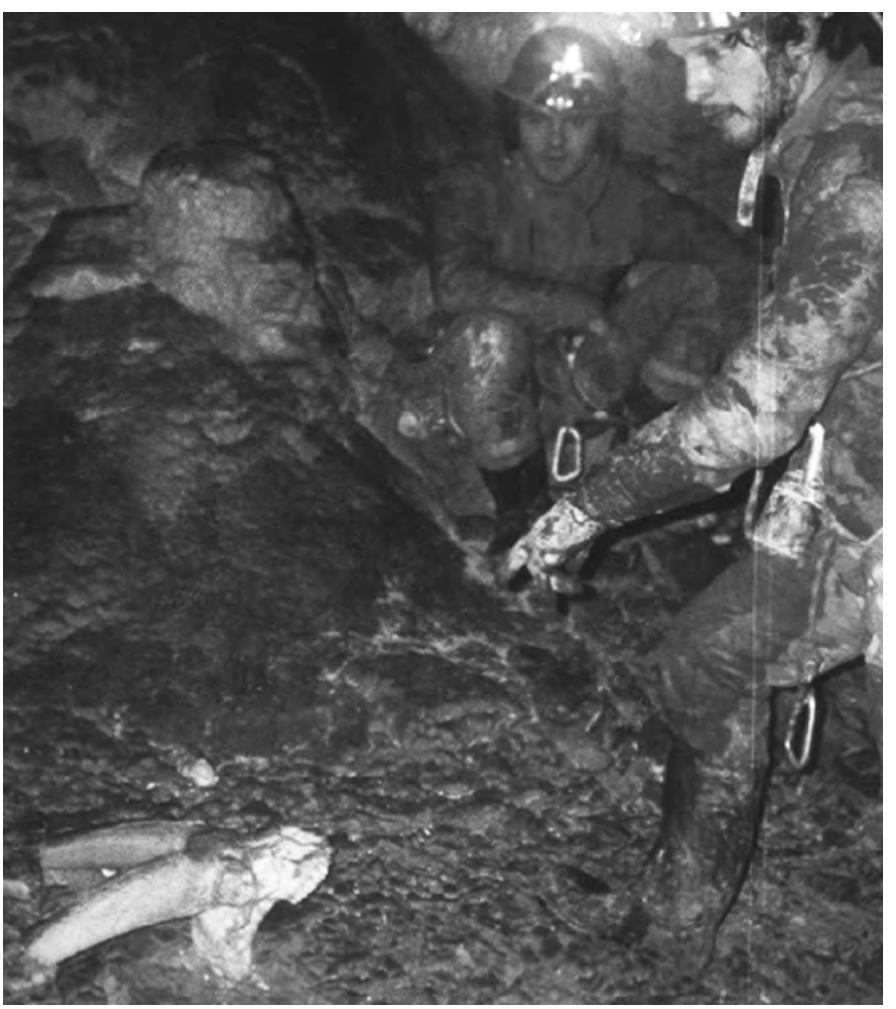

Fig. 1 – The discovery of Sala del Fuoco in 1986. Photograph taken from Parco Naturale Regionale della Gola della Rossa e di Frasassi (2000). I quaderni del Parco: Il Mondo Sotterraneo, Edited by Gruppo Speleologico CAI-Fabriano, p.81.

Late Bronze Age, seismically-induced megalandslide in the Esino River valley near San Cristoforo (Province of Ancona, Italy) and consequent formation of a large ephemeral lake

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Near the village of San Cristoforo, mid way between the town of Borgo Tufico and the Frasassi gorge in the narrow Esino River valley along highway n. SS-76, we report about a large landslide body with a volume of about 1 million cubic meters, which detached from the limestone cliffs of the western slope of Monte Scoccione, blocked the river with a ca. 40 m high "dam" (which eventually was re-incised by the river), and formed a lake up valley with a surface of about 4 million m^2, which flooded the Esino River and its tributary Torrente Giano valleys up to contour line 250 m asl. By surveying the landslide body filling the valley, we assessed that it is a coarse breccia with boulders exclusively made of limestone from the Calcare Massicio Formation. This is the massive lower Jurassic limestone, which makes up the cliffs and crags of the western rim of Monte Scoccione, some 500 m above Esino thalweg. The opposite San Cristoforo-side of the valley is instead made up exclusively of lower Cretaceous to Paleogene pelagic limestone formations. The large detachment scar of the landslide is still visible just below the western rim of Monte Scoccione. The landslide breccia rests on top of a gravel deposit pertaining to the last glacial fluvial terrace Qt4. Some 2 km up valley from the landslide barrage, at the locality of Trocchetti, the Esino River incises a whole section of the Qt4 fluvial terrace (actually a gravel strath terrace on Eocene-Oligocene Scaglia Variegata and Scaglia Cinerea marly limestone formations). In this revealing exposure, the fluvial gravel reaches 3.5 m above thalweg, and is overlain by a 1 m thick graded deposit of fine sandy lime. The contact between these two sedimentary units is marked by a dark horizon suggesting a reducing event on the floor of what we interpret as a lake. AMS 14C dating of charcoal fragments and gastropod shells contained in this lacustrine deposit yielded ages of 3774 ± 82 yr cal BP and 3655 ± 70 yr cal BP, respectively. This suggests that the landslide occurred in the late Bronze Age and that the gravel deposit underlying the lacustrine sediment actually represents a Qt7 fluvial terrace (Wegmann and Pazzaglia, 2008).

In the outcrop at Trocchetti, the contact between the fluvial gravel and the overlying lacustrine lime, along with the redox horizon, is cut by a small fault with a normal offset of about 30 cm, a ca. NE-SW strike and a 60° SE dip. The fault is capped by the lacustrine deposit, which does not appear to be offset. This suggests that the faulting occurred at the time of the landslide, and thus that the landslide may have been triggered by a strong earthquake.

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Amphora in amphora: the Vodeni Rat anchialine cave in the Pakleni archipelago (Hvar, Croatia)

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In the tiny island of Sveti Klement in the Pakleni Archipelago, on the southeastern offshore of the island of Hvar (Croatia), there is a small anchialine cave, with a narrow entrance (ca. 40 x 60 cm) located some 13 m above sea level, and about 30 m inland from the rocky littoral of Vodeni Rat (literally Cape Water). Anchialine caves, with salty water at the bottom and fresh or brackish water at the top, which normally reaches sea level, are common if not the rule among the many known caves along the littorals of the Dalmatian karst. What makes of Vodeni Rat cave an *unicum*, is that at about 20 m below sea level, thus some 10 m above the bottom of the cave, Croatian speleoscuba-archeologists found, laying intact on a rock ledge submerged in the bottom zone of salt water, five ceramic amphora, some of Roman epoch (ca. I century AD), others of Byzantine epoch (ca. VI century AD) (Mesić, 2006). This find testifies that until the VI century AD the cave was not anchialine, the freshwater level was way down to 20 m below sea level, and the precious drinking water was lifted up from down there to the surface probably by farmers of the nearby Roman villas of Momici and Soline (Mesić, 2006). This practically means that, until then, the cave had no communication with the nearby sea, probably because fractures and joints in the surrounding limestone were sealed by speleothemic calcite, and/or the internal walls of the cave were waterproofed by speleothems and flowstones, as reported by Mesić (2006), which implies that the freshwater filling the cavity was supplied exclusively by rain. We do not know what caused the seals to break after the VI century, letting seawater infiltrate into the cave. Perhaps an earthquake may have cracked those calcite-filled joints and fractures, or a change in chemistry of the freshwater may have caused dissolution of the fracture-sealing calcite. The matter of fact is that a U-Th date of the calcite filling these joints yielded and age of 305.2 ± 6.3 ka, suggesting that the cave became a sort of waterproof vase, like an amphora in fact, sometimes in the Middle Pleistocene.

In recent years, researchers and students of the Osservatorio Geologico di Coldigioco (OGC) have revisited the Vodeni Rat water hole, carrying out preliminary sampling of the water column at different depths (top, middle, and bottom) for basic pH and conductivity analyses (Fig. 1), and also sampling with a 33 □m plankton net, the top meter of the freshwater zone for a biologic assessment. It turned out that the freshwater zone is populated by a diversity of stygobitic crustaceans, including at least two species of amphipods (*Salentinella* cf. *balkanica* and *Niphargus* cf. *hereberi*), one species of thermosbaenaceans (*Tethysbaena* cf. *halophila*), one cyclopoid copepod (*Halicyclops* sp.), and one cryptic species of ostracod (*Pseudolimnocythere* sp.). These animals, which are currently under specialized study for precise taxonomic determinations (also including DNA sequencing), are known to exist in karstic anchialine and freshwater caves on both sides of the Adriatic Sea. But given the geochronology of the cave, i.e. the 305.2 ± 6.3 ka U-Th age of the sealing

calcite, and the age of the Byzantine and Roman amphora, we are coming up with the hypothesis that these crustaceans may represent organisms that entered in the cave sometimes in the Middle Pleistocene, and since then they were trapped in this natural amphora vase until Present. Eventual genomic analysis may give information on the evolutionary history of these animals trapped and isolated from the surrounding world for more than 300 thousand years. One more aspect of this ancient environment that is worth mentioning, is that all around the Vodeni Rat water hole, where the limestone is criss-crossed by a pervasive grid of calcite-filled fractures and gouges (apparently a fault zone), grow a number of juncacean bushes, which typically prosper in wet, marsh areas, and certainly not on an arid limestone littoral. We have seen from a boat during a periplus cruise around the Pakleni islands just a couple more of these *juncus* bushes only in another spot on Sveti Klement: could it be that there is another freshwater karstic reservoir below the surface over there? More exploration of the littorals of the Pakleni will have to be done, along with accurate sampling of the water column of the Vodeni Rat cave, both for physical-chemical analyses and for biologic (and microbiologic) analyses in order to characterize this ancient environment with a datable history. A team of researchers and students of OGC are heading back to Hvar, with tools and instruments, departing three days after the end of this Penrose conference. We'll let you know how it went.

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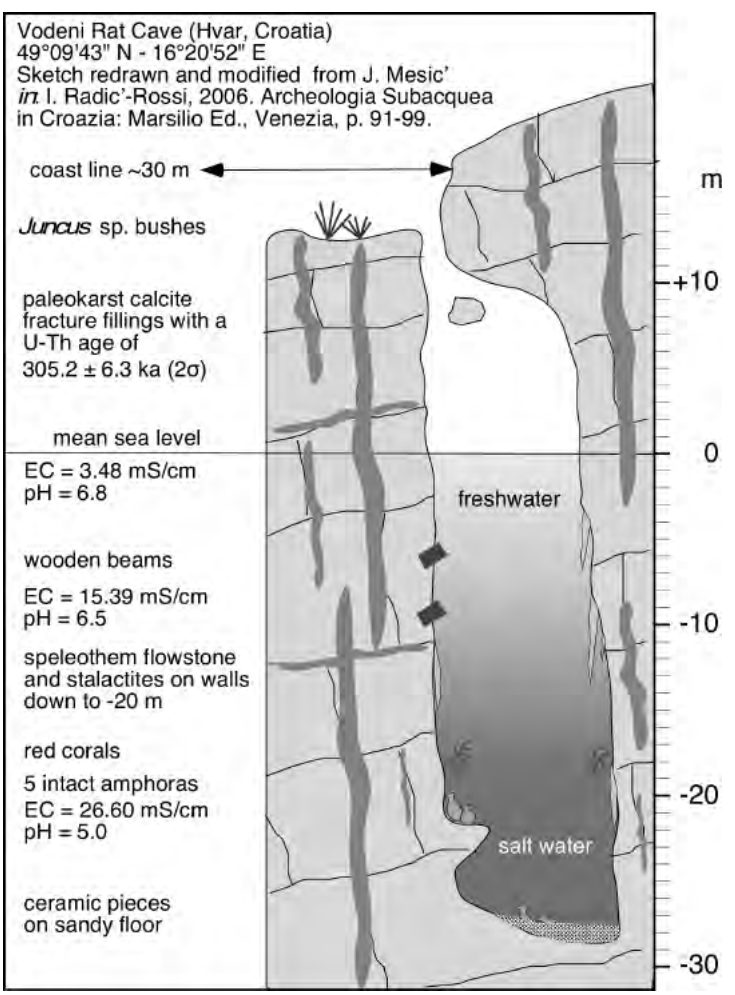

Fig. 1 – Synoptic figure of the Vodeni Rat anchialine cave.

Last Glacial Maximum giant sand dunes on the island of Vis, Croatia

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The Island of Vis (Croatia) is the westernmost great island of the central Dalmatian archipelago situated 45 km from the mainland. The island represents a foreland anticlinal structure (cf. Korbar, 2009 and references therein) made up predominantly of a more than 1500 m thick succession of Jurassic to Cretaceous shallow-water carbonates that was pierced by the Komiža salt diapir in its western part as evidenced by the middle Triassic evaporites accompanied by various sedimentary and volcanic rocks (Belak et al., 2005; Korbar et al., 2012). In its eastern and central parts, there are several karstic depressions filled with Quaternary sands and calcareous debris, and covered with terra rossa. At the sand pit in Veliko Zlo Polje, situated in the eastern part of Vis in a NE-SW elongated valley, at the elevation of around 100 m a.s.l., a 20 meters thick and approximately 140 meters wide outcrop of Quaternary aeolian sands is exposed. The sand body is composed of a sub-horizontally laminated unit partly exposed in the bottom of the investigated section, and a cross-bedded unit up to 9.5 m thick which can be traced along the whole profile. The horizontally laminated sand has a primary dip of 1-5° with a mean direction to the NNW and probably represents a bottomset of an aeolian dune. The cross-bedded unit shows a unimodal foreset dip with a mean direction of 340° i.e. towards the NNW (Pavelić et al., 2014). The sand is very well sorted and fine grained. The grains are sub- to well-rounded and moderately spherical. The sand is composed of carbonate detrital grains (up to 80%), mostly lithic fragments of various limestones. The insoluble residue of the analyzed samples consists of the siliciclastic detritus, mostly of individual well-rounded quartz grains and lithic fragments such as chert, quartz-sericite schist, quartzite, and tuffitic particles. The heavy mineral content (~9%) is represented by opaque minerals (up to 59%) and translucent heavy minerals, among them pyroxenes, mostly hypersthene and diopside, and amphiboles are the most abundant grains. Epidote, garnet, tourmaline, zircon and chromite are represented in a lesser amount. Such mineral composition points to older metamorphic and magmatic rocks as the source of the material.

To establish a chronological framework of the investigated sands, the optically stimulated luminescence (OSL) dating method was applied on quartz grains extracted from 5 samples. The samples were measured using the single aliquot regenerative dose protocol (SAR) of Murray and Wintle (2000, 2003). Optical stimulation (50 s at 125°C) was carried out using blue LEDs (470±30 nm) and luminescence signals were detected using a U340 filter (7.5 mm). All quality tests prior to any measurements appeared appropriate to yield reliable D_e (equivalent dose) values needed for the calculation of ages. The obtained ages ranging from 16.4±1.0 ka (sample ZLO2) to 25.8±1.7 ka (sample ZLO5) can be correlated to the Last Glacial Maximum (OIS2). During the peak of the glaciation, the North Adriatic basin was dry land, a vast plain exposed to aeolian deflation.

The source area of the predominantly carbonate material could be rather local since poorly cemented Oligocene biocalcarenites outcrop on the neighboring island of Biševo that is also covered by patches of similar aeolian sands (Korbar et al., 2012), and were probably exposed during the LGM on outer limbs of the Vis anticline. The source area of the

siliciclastic material had to be lithologically complex and was most probably released by the breakdown of older sedimentary, igneous and metamorphic rocks of the Dinarides, their erosion and grinding during the glaciers within the Dinarides, transportation of the material by the cross-Dinarides main rivers Cetina and Neretva and its deposition on their alluvial plains (Pavelić et al., 2014). As seen from the dating results, during the Last Glacial Maximum (OIS2) this alluvial plain was exposed to aeolian deflation and the material was reworked by wind forming the dune field in the topographic depression on Vis.

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Mid-Pleistocene to Recent ostracod record in slack water deposits of the Frasassi gorge and cave system as a prospective proxy for palaeoenvironmental reconstruction

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To trace environmental changes of the tectonically active Frasassi area in the northeastern Apennines of Italy, the distribution of ostracod valves was studied in a series in slack water deposits collected from both caves and river banks, representing various time windows from lower Middle Pleistocene to Holocene, and allowing comparison with the modern ostracod assemblages in the Sentino River. The studied sediment sequences: BDR (Buco dei Rovi cave, ca. 780 ka), GBV (Grotta della Beata Vergine – ca. 650-450 ka), CDC and SDS (Caverna del Carbone and Sala della Sabbia – ca. 115 ka), and SBH (Sbif House fluvial swamp deposit – ca. 30 ka), as well as TRO (lake and river overbank deposits of the Esino River – 3.7 and 2.0 ka) yielded nearly 800 subfossil valves of ca. 25 ostracod species, of which all but three are known to live today in the Sentino River or Frasassi Cave system. Due to the fragmentary and/or immature nature of recovered valves, their specific determination proved difficult in several samples and resulted in lumping under generic level. Nevertheless the species accumulation curves estimating the total species richness show that not many more taxa would be observed by increasing the number of samples. However, species/taxa richness of individual sediment samples was generally low and varied from 3 (in some samples of BDR and GBV) to 12 (CDC) with a mean ± SD of 5.9 ± 3.0. The most common and abundant taxa in the studied sediment samples were *Candona* spp. ex gr. *neglecta* (33.8% of the analyzed valves, present in 15 out of 16 studied samples), *Potamocypris* spp. (26.8%, 14) and *Ilyocypris* spp. (20.6%, 16), which also constituted the indicator taxa of each of the studied site/age palaeoassemblages. Due to variations in mutual proportions of these taxa, the site/age sequences differed significantly in the taxonomic structure of their ostracod palaeoassemblages (PERMANOVA pMC = 0.011-0.025) and could be successfully discriminated (100% allocation success by Canonical Analysis of Principal Coordinates). For instance the SDS assemblage with valve oxygen isotope composition of $\delta^{18}O$ = -5‰ recovered from sediment OSL dated at 115 ± 17 ka is clearly dominated by *Potamocypris* spp. (69%) and different from the somewhat younger CDC assemblage with $\delta^{18}O$ signature = -3‰ where *C. neglecta* group dominated (34%) whereas *Potamocypris* spp. relative abundance was on average only 15%. Such preliminary associations should, however, be interpreted cautiously and further study is needed (integrating also pollen analysis and more stable oxygen isotope measurements) to prove a cause-and-effect relationship between the recorded differences in ostracod palaeoassemblage successions and major glacial/interglacial environmental and climatic changes. Finally, the structure and species composition of the palaeoassemblages differed also significantly from modern ostracod assemblages from the Sentino R. and sulphidic spring (PERMANOVA pMC = 0.001-0.049). The main disparity has to be attributed to the lack of *Prionocypris zenkeri* in the fossil assemblages, which is a clear dominant today in the Sentino R. As *P. zenkeri* is a relatively large species (compared to *Candona* spp., *Ilyocypris* spp. and *Potamocypris* spp.), this difference may be due to the sorting effect and/or breakage of large valves, which were left unidentified and not analyzed in the fossil material. Additionally, valves of stygobitic species were found in sediment samples recovered from the caves, while these species do not occur today in surface riverine habitats of the Frasassi area.

Archeometry of Late Paleolithic finds in the caves of the Frasassi area (Marche, Italy)

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In the Frasassi Gorge along the Sentino River, and in the adjacent Rossa Gorge along the Esino River, Paleolithic dwellings are found in a few caves and in small rocky shelters. In this paper, I review the archeological finds and archeometric determinations in three sites, which were used for habitative purposes. All of them are dated to the latest phase of the Epigravettian culture, between the warm interstadial of the Allerød period (Late Pleistocene) and the beginning of the interstadial of the Holocene epoch. However, two other cave sites in the Frasassi Gorge, the Grotta della Beata Vergine and the Sala del Fuoco, yielded findings suggesting cultural or religious utilizations, which date back to the Gravettian and the beginning of the Epigravettian cultures. The caves representing habitative dwellings here revisited are the Grotta della Ferrovia and the shelter of Cava Romita, both in the Rossa Gorge, and the Grotta del Prete in the western end of the Frasassi Gorge. The Grotta della Ferrovia consists of an elongated cavity in the limestone bedrock, where unfortunately anthropic deposits have been almost completely destroyed by clandestine digs. Lithic artifacts were found in the upper layers of the deposit in the inner part of the cave (Broglio and Lollini, 1982; Bartolomei and Cattani, 2005). Charcoal found in this anthropic horizon, yielded an age of 11700 ± 200 yr uncal BP, which once recalculated as a calibrated BP age, would be referable to the warm Bølling-Allerød interstadial, confirmed by the micromammal associations. The archaeological sites in the shelters of Cava Romita were irremediably damaged during the works for the construction of tunnels along the state highway SS 76, in the Rossa Gorge, with the exception for the Site 1 (Guerreschi et al., 2005) miraculously preserved in a small rock recess. Animal bones found in the anthropic horizon of this site yielded ages of 10350 ± 60 yr uncal BP and 10020 ± 65 yr uncal BP (Broglio and Lollini, 1982; Bartolomei and Cattani, 2005), which would be recalculated as an age range of about 12250-12000 cal BP, thus referring to the Younger Dryas when a sharp decline in temperature occurred immediatly before the present Holocene epoch. In fact, micro- and macro-mammalian, and malaco-fauna suggest a cold climate in this mountain area. The oldest anthropic horizon n. 6 in the Grotta del Prete yielded dates of 9990 ± 100 yr uncal BP, i.e., about 11500 ± 100 yr cal BP (Broglio and Lollini, 1982; Bartolomei and Cattani, 2005), thus still pertaining to the beginning of the early Holocene epoch (Preboreal stage).

Numerous lithic artifacts in these three sites including narrow chert blades and bladelets. The lithic industries show a progressive (stratigraphic) scarcity of "microgravettes" (which are projectile points made from narrow bladelets characterized by a straight or slightly curved blunted back, which is formed by very abrupt retouches) and a progressive increase of backed and truncated bladelets. In these three sites, ornamental objects were also found, such as atrophic red deer canines with holes for necklace suspension, a perforated chert pebble, and marine bivalve and gastropod shells (Gurioli, 2005a-b). In the Grotta della Ferrovia (Zampetti et al., 2005) also were found a number of limestone pebbles some of which incised with decorations such as simple notches or more elaborated barbwire-like designs. The radiocarbonic datings, the paleobotanic and faunal evidences, and the lithic industries of all these findings put together are chronostratigraphically consistent with the final part of Pleistocene Epoch and the beginning of early Holocene, and culturally with the more recent phase of the Epigravettian cultural period of the final Upper Paleolithic. With respect to climate, these sites are pertaining to the final of Lastglacial period (from the warm Allerød oscillation to the cold Younger Dryas and, finally, to the current, warmer Holocene).

A striking recent find from the Grotta della Beata Vergine was the "Venus of Frasassi", a 8.7 cm tall, 2.7 cm wide, and 3.6 cm thick feetless figurine carved from a stalactite, and portraying a pregnant woman with stretched-out arms (Coltorti et al., 2012), which reminds those rare

(rigorously feetless) statuettes such as the famous Austrian Venus of Willendorf, representing the Gravettian cultural period of the late Paleolithic (between 28 and 20 thousand years ago). Unfortunately the Venus of Frasassi was found by a casual visitor, on the dirt floor of the Beata Vergine cave, out of any archeological or stratigraphic context. This cave is a large cavern that hosts a church built by Pope Leo XII from Genga in 1829, and since then it has been a destination of frequent pilgrimages, religious ceremonies, and even a theatrical live nativity scene every year during the Christmas festivities. A recent study of the archeological record of the Beata Vergine cave by Pignocchi and Montanari (2016), corroborated by detailed sedimentological, stratigraphical and radioisotopic geochronological analyses of cave sediments, lead to the conclusion that no anthropic horizon exists in this cave older than Neolithic culture which confirmed what already emerged from studies carried out in the past 150 years or so by a score of eminent Italian archeologists. Practically human frequentation in the Beata Vergine cave started in the early Neolithic, perhaps some 7,500 years ago at the earliest, and thus the isolated "Gravettian" Venus found here represents a puzzling oddity.

A most important Paleolithic discovery in the Frasassi Gorge was made by a team of speleologists from the GSM-CAI of Ancona in 1986 in the Grotta del Fiume cave complex (Forestalp, 1987), here christened "Sala del Fuoco" (room of fire). In this remote and difficult-to-reach large, flat bottomed room beautifully decorated by crystalline speleothems, the speleologists found a skull of a male mountain goat or steinbock (*Capra ibex*) set on the tip of a short stalagmite (unfortunately the skull was accidently destroyed and disposed of before the speleologists dutifully intended to deliver it to the Archeological National Museum in Ancona). On the floor of the room, the speleologists also found four chert blades (three simple blades and one blade retouched forming a point), and the remains of a fire pit. A tunnel at the western end of the room was filled by a fine polygenic breccia with plant roots sticking out of it, indicating that the tunnel was leading to a close entrance of the cave now obstructed by landslide debris. A charcoal sample from the fire pit yielded a 14C AMS age of 16345 ± 300 yr cal BP (Montanari 2007, unpublished), which represents the oldest dated evidence of *Homo sapiens* in the Frasassi and Rossa gorges, and one of the few dated sites in Italy of the first part of the Lateglacial (in Europe called Pleniglacial, from 20,000 to 14,500 years ago). Recently, speleologists of GSM-CAI and CAI-Fabriano have carefully surveyed this cave with modern laser mapping techniques. In doing so, they discovered a mound of broken bones of a steinbock, which yielded a 14C age of 16718 ± 119 yr cal BP, thus consistent with the age of the fire pit charcoal (Montanari, Mainiero, et al., this volume). While detailed sedimentologic, stratigraphic, speleothemic, and U-Th geochronological analyses are in progress, the archeological evidences found so far in this cave such as a few chert tools, one fire pit, one deposit of broken steinbock bones, and a steinbock skull placed on a stalagmite like it would represent a totem, strongly suggest that this site was not a residential dwelling frequented by a human community for a long period of time, but rather a solitary site frequented for a short time (i.e., until the entrance was sealed by a landslide some 16.5 thousand years ago) by one or a few people who, perhaps, were using this fabulous underground space for spiritual or cultural purposes.

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Multi-proxy Cretaceous-Paleogene boundary event stratigraphy: the Gubbio and other Umbria-Marche basin sections

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The classical sections of Gubbio are well-known from a variety of studies, especially from the pioneering work done in the fields of biostratigraphy, magnetostratigraphy and the Cretaceous-Paleogene boundary (K-Pg B). This study aims to investigate the event stratigraphy related to the K-Pg B transition in the pelagic carbonate sections of the Umbria-Marche basin, including the Gubbio sections. The selected stratigraphical interval contains various events such as the second and third Deccan volcanic phase, the K-Pg B impact, the post mass extinction recovery and the beginning of the occurrence of the Paleogene hyperthermals (Fig. 1). Existing high-resolution (cm-scale) proxy series (magnetic susceptibility, calcium carbonate content, bulk carbonate $\delta^{18}O$ and $\delta^{13}C$) for the Gubbio sections of the Bottaccione Gorge and the Contessa Highway were complemented with elemental data acquired by portable X-ray fluorescence (XRF), $^{87}Sr/^{86}Sr$ and $^{187}Os/^{188}Os$ isotope ratio's. In addition, analogue sections in the Umbria-Marche Basin were selected (mainly "the Morello section") to carry out parallel proxy measurements in order to compare the reproducibility of proxy series inside the basin itself.

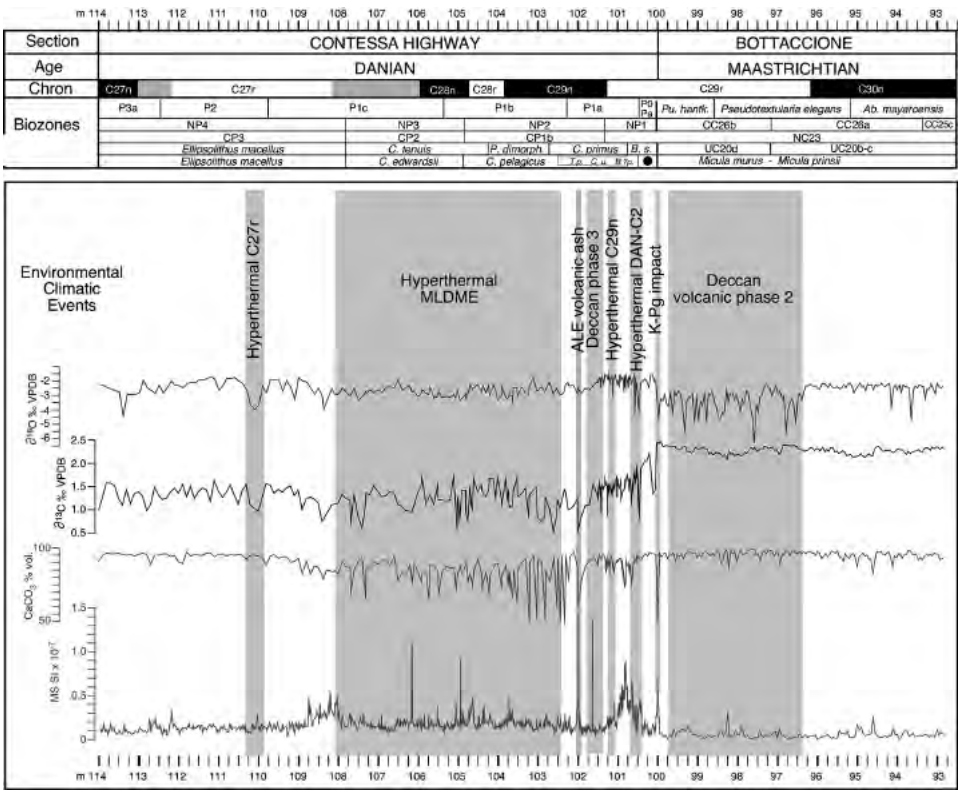

Fig. 1 - Multiproxy series, and environmental and climatic events across the K-Pg boundary in the classic sections of Gubbio (from Sinnesael et al., 2016 – GSA Special Paper 524).

Integrated stratigraphy of cave deposits in the Grotta dei Baffoni at Frasassi (Marche Apennines, Italy)

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The massif of Jurassic limestone making up the core of the Frasassi-Valmontagnana blind thrust anticline, hosts a large hypogenic sulfidic cave complex, which, due to Pleistocene tectonic uplifting, has been incised by the Sentino River forming the deep Frasassi Gorge. Being a hypogenic cave that formed below base level (i.e., below water table), the Frasassi cave complex is organized in seven horizontal hypogean "floors", the youngest presently active at piezometric (river) level, the oldest some 200 m above the Sentino thalweg. Therefore, the Frasassi cave complex records the tectonic uplifting history of this still active Apennine mountain belt (e.g., Cattuto, 1976; Mariani et al., 2007, and references therein). Speleothems and alluvional slack water deposits in near-cave entrance sites may provide radioisotopic ages to date the location of the base level at any given time during the uplifting of this area, thus to obtain data points to estimate a mean uplifting rate. Stalagmites, which grow anywhere and at any time on the dry cave floor, and thus do not indicate the exact position of the water table when they started to grow, would nevertheless provide a minimum age for that particular paleokarstic level via U-Th dating techniques. On the other hand, near-entrance alluvional slack water deposits undoubtedly indicate that the river was flowing at that elevation when was flooding the cave, carrying in and depositing its sedimentary load (gravel, sand, and lime). Siliciclastic material in these slack water sediments such as quartz and feldspar grains, would provide geochronometers, which can be dated with optically stimulated luminescence (OSL) or cosmogenic ^{10}Be-^{26}Al dating techniques. With this principle in mind, we conducted a detailed sedimentologic and stratigraphic analysis of one such limey-siliciclastic slack water deposit in the Grotta dei Baffoni, a large subhorizontal cavern who's entrance is located on the north cliff of the eastern Frasassi Gorge, at about 65 m above present Sentino River thalweg, thus corresponding to the 5th floor of the Frasassi cave complex of Mariani et al. (2007). In fact, the narrow tunnel at the northern end of the cave some 50 m from the entrance, is clogged by this limey deposit that, over the rest of the central part of the cave, is covered by a speleothemic crust, which yielded a U-Th date of 17.2 ± 11.3 ka (see Figure 1). However, both the crust and the underlying alluvional sediment contain terrestrial gastropods and animal bones (rodents, birds, and bats), indicating that the limey siliciclastic alluvional deposit has been reworked from the entrance hall and re-deposited down there in the inner end of the cave at a time when the cave was already dry, well above river level. Nevertheless, this reworked slack water sediment, which would not provide siliciclastic geochronometers suitable for reliable OSL dating, overlaps a colonnade of large speleothems, one of which yielded an U-Th age of 76.9 ± 2.4 ka. Considering that a sandy slack water deposit at 30 m above present thalweg in the Grotta Grande del Vento on the opposite side of the Frasassi Gorge, corresponding to the 3rd level of the Frasassi cave complex, yielded an accurate OSL age of 115 ± 17 ka (Fiebig et al., this volume), the expected age for this 5th floor at 65 m above present thalweg would be more like around 200 ky. Therefore, the 79 ka U-Th age for the speleothem in the Grotta dei Baffoni should be considered as a minimum age for this topographic level. Perhaps collecting a sample in the innermost part of the large speleothem, when technically possible, will yield an a older U-Th age closer to the expected mid Pleistocene age of ca. 200 ky.

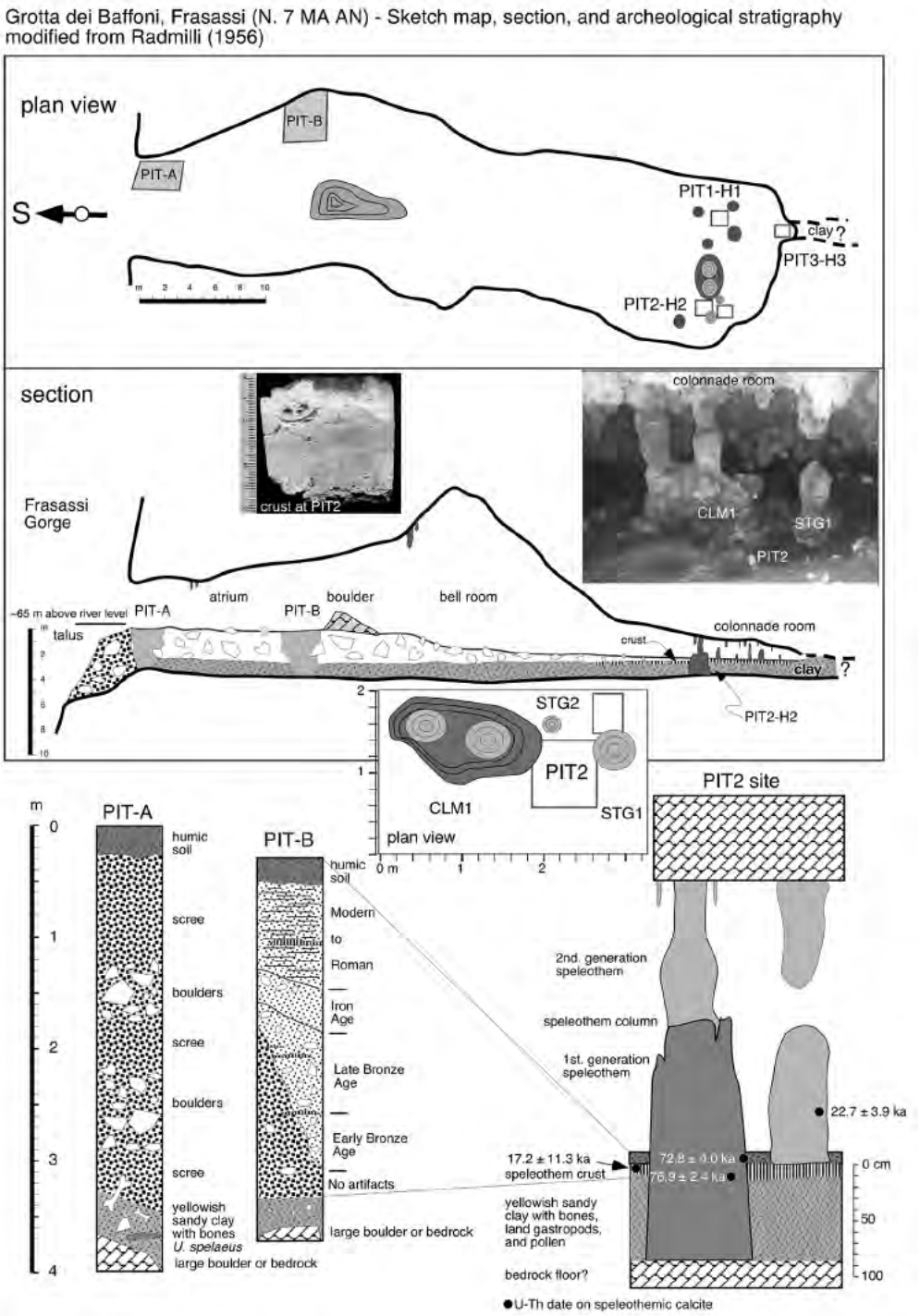

Figure 1 – Synoptic model of the sedimentology, stratigraphy, and U-Th geochronology of the Grotta dei Baffoni cave.

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Syn-sedimentary deformations in K-Pg limestones within a thrust-related anticline of the Umbria-Marche Apennines, Italy

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The geometry of collision mountain belts that were formed at the expenses of passive continental margins is often complex because orogenic structures, such as thrusts and related folds, commonly interfere with pre-orogenic extensional structures, namely normal faults, resulting in composite structural assemblages (Butler et al., 2006). In these settings the analysis of the relationships between depositional and structural features may provide very useful tools to correctly unravel the local sedimentatry and deformation history (e.g. Pace et al., 2017).

A detailed field analysis was carried out in the Umbria-Marche Apennines along an outcrop where pelagic limestones of Upper Cretaceous-Paleogene age are magnificently exposed. The outcrop is located on the eastern face of Monte San Vicino, near the village of Frontale di Apiro (MC), and represents part of the forelimb of a macroscopic thrust related anticline that was formed during the Neogene compressional events that led to the construction of the Apennines (Barchi et al., 1996). Within the section, the exposed pelagic carbonates, that comprise the iridium-rich level at the K-Pg boundary (Alvarez et al., 1980) are affected by slumping and by mesoscopic normal faults. A careful analysis of the relationships between slumps and normal faults makes it possible to correctly unravel the local chronology of events and hence to infer the depositional and deformation history of this part of the Scaglia Formation basin. The results of this investigation make it possible to ascribe the investigated normal faults to events that predate the construction of the Umbria-Marche belt. Therefore, the normal faults at Frontale are distinct from those that overprint the main compressional structures, responsible for the present-day seismicity of central Italy. These results confirm earlier observations (Montanari et al., 1988; Bice et al., 2007) and make it possible to discuss some aspects, in part still problematic, of the evolution of the Apennine mountain range.

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Field trip to Gubbio

Thursday September 28

8:30 - Leave Cingoli from hotel.

We will be travelling southwest, straight across the grains of the Umbria-Marche (U-M) Apennines (Fig. 1), first across the Marche Ridge anticlinorium, up the Esino River valley, and then across the Fabriano plain, which is the synclinorium between the Marche Ridge and the Umbria-Marche Ridge, and eventually across the U-M Ridge passed Fabriano. Then we will swing on a NW direction along the Gubbio plain, which is a half graben, and, passed Gubbio, we will head up along the Contessa valley, which cuts through, on a NE-SW direction, the Gubbio half anticline. There will be lots of road works all along the cruise, with beautiful fresh exposures of most of the units making up the U-M Succession, which Sandro will point out from the bus, with the help of the microphone and theatrical harm waving.

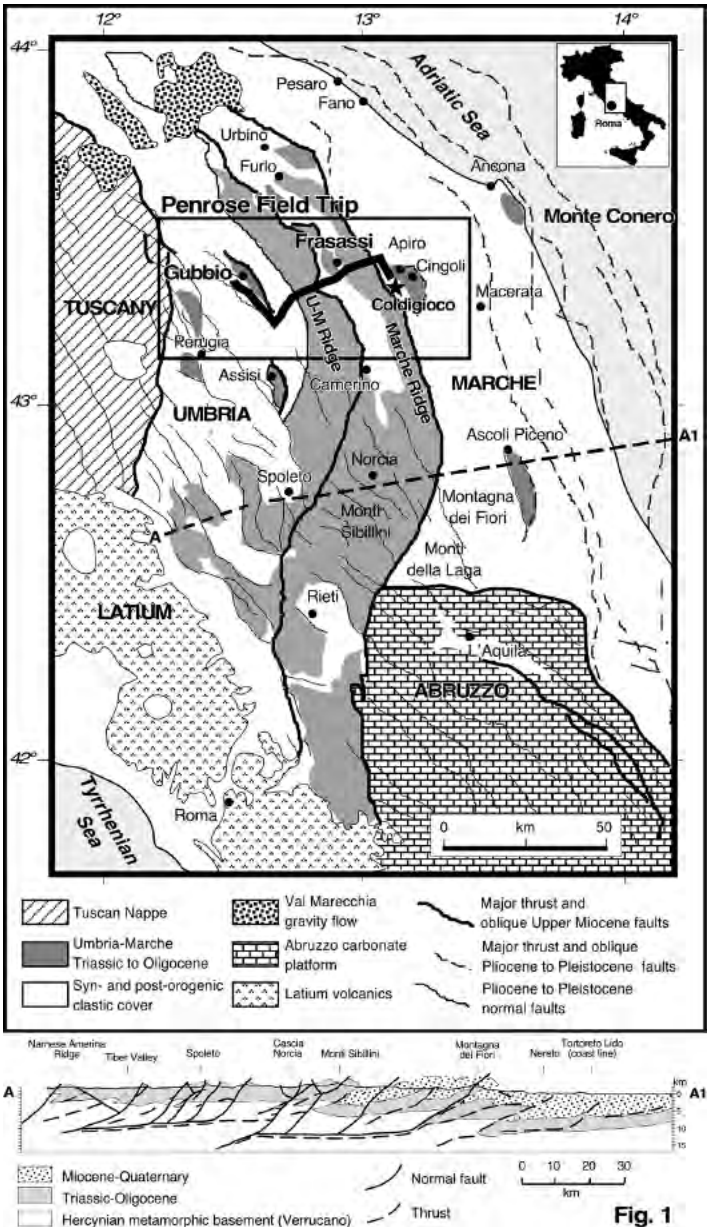

Fig. 1

10:00 - Stop at Cave Barbetti, at the top of Contessa Valley, near Gubbio. Please follow Sandro's stratigraphic explanations, with the help of the Umbria-Marche Stratigraphic model shown in Fig. 2.

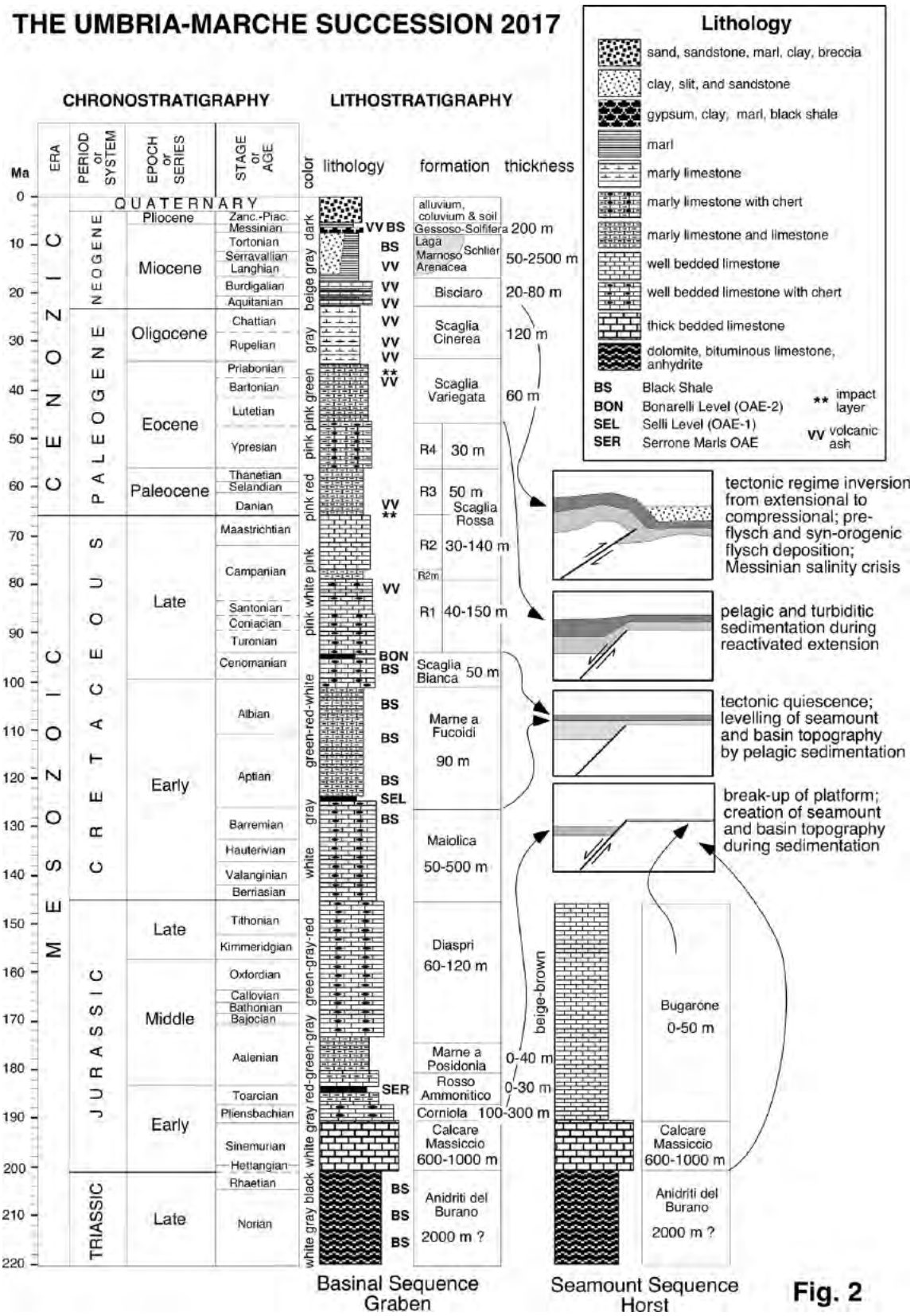

Fig. 2

From this vista point, we can admire a 180° panoramic view of the Barbetti quarries, from the CQ to the east, to the CB quarry to the west. Here, the pelagic marly limestones of the Scaglia Variegata and Scaglia Cinerea formations are quarried for the manufacturing of Portland cement by the Barbetti Company of Gubbio. The CQ quarry, now dismissed and partially refilled, still exhibits a quarry face, which exposes the upper part of the Eocene Scaglia Variegata Fm., and the overlying Olicocene Scaglia Cinerea Fm., all the way up to the lower Miocene Bisciaro Fm. The same sequence of formations, which also includes de whole Bisciaro Fm., the mid Miocene Schlier Fm., and part of the overlying Marnoso-Arenacea Flysch Fm., are spectacularly exposed in the giant, still active CB quarry (see Lowrie et al., 1982, GSA Bulletin, v. 93, p. 414-432; and Coccioni et al., 2008, GSA Bulletin, p. 487-511, and references therein).

11:00 - Stop at Cave Vispi, down at the bottom of the Contessa Valley. The Contessa valley succession starts with the uppermost part of the Tithonian Diaspri Fm. in stratigraphic contact with the overlying Berriasian Maiolica Fm. This contact, thus, roughly corresponds to the Jurassic-Cretaceous boundary, dated at some 145.5 Ma, which is exposed along the creek at the southwestern end of the Contessa valley. The rest of the Maiolica is spectacularly exposed on the Vispi quarry face, in stratigraphic continuity with the overlying Aptian-Albian Marne a Fucoidi Fm., the Cenomanian Scaglia Bianca Fm., and the Turonian-Coniacian part of the R1 member of the Scaglia Rossa Fm. These limestones are quarried by the Vispi Company to produce aggregate for the manufacture of concrete. From our vista point, we can admire some 50 million years of Earth history (see Fig. 3) as recorded, layer by layer, by these well-bedded pelagic carbonates. Practically, in this rhythmic alternations of limestone, chert, shale, or marl, each lithologic couplet represent a Milankovich precessional cycle.

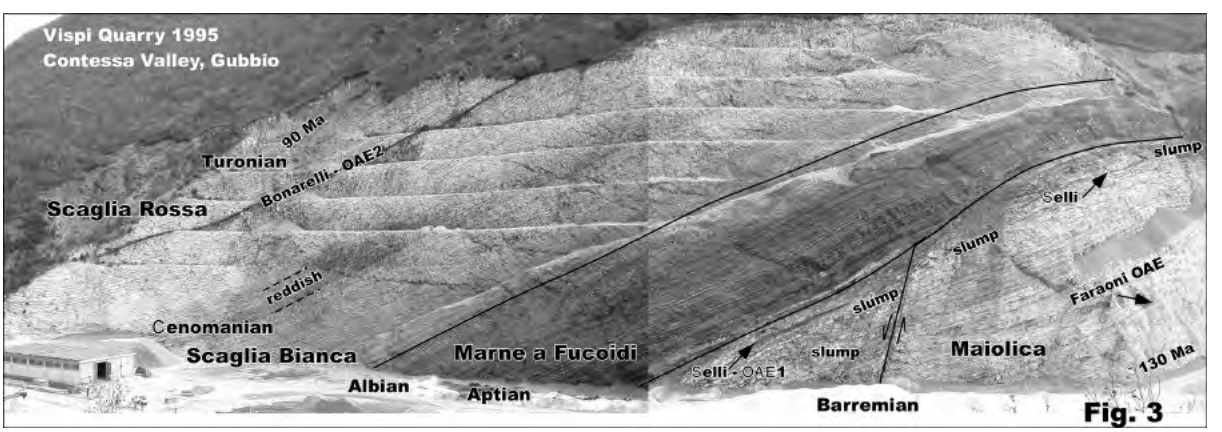

Fig. 3

11:45 - Stop and park at Trattoria del Bottaccione restaurant (near Gubbio, on the Gubbio-Scheggia road): 20 minute walk from the Bonarelli to the historical K-Pg boundary outcrop.

In this walk, we will stop here and there to check and talk a bit about some important events as they are recorded in these pelagic limestones, such as the Bonarelli OAE-2, the mid-Turonian event with its extraterrestrial ^{3}He anomaly K1, the Early Campanian Event (ECE), with its ET ^{3}He anomaly K3, the lower Maastrichtian mysterious Inoceramids extinction event, and, finally, the much celebrated K-Pg boundary interval, with its environmental and climatic events preceding and following the Chicxulub impact (see Fig. 4).

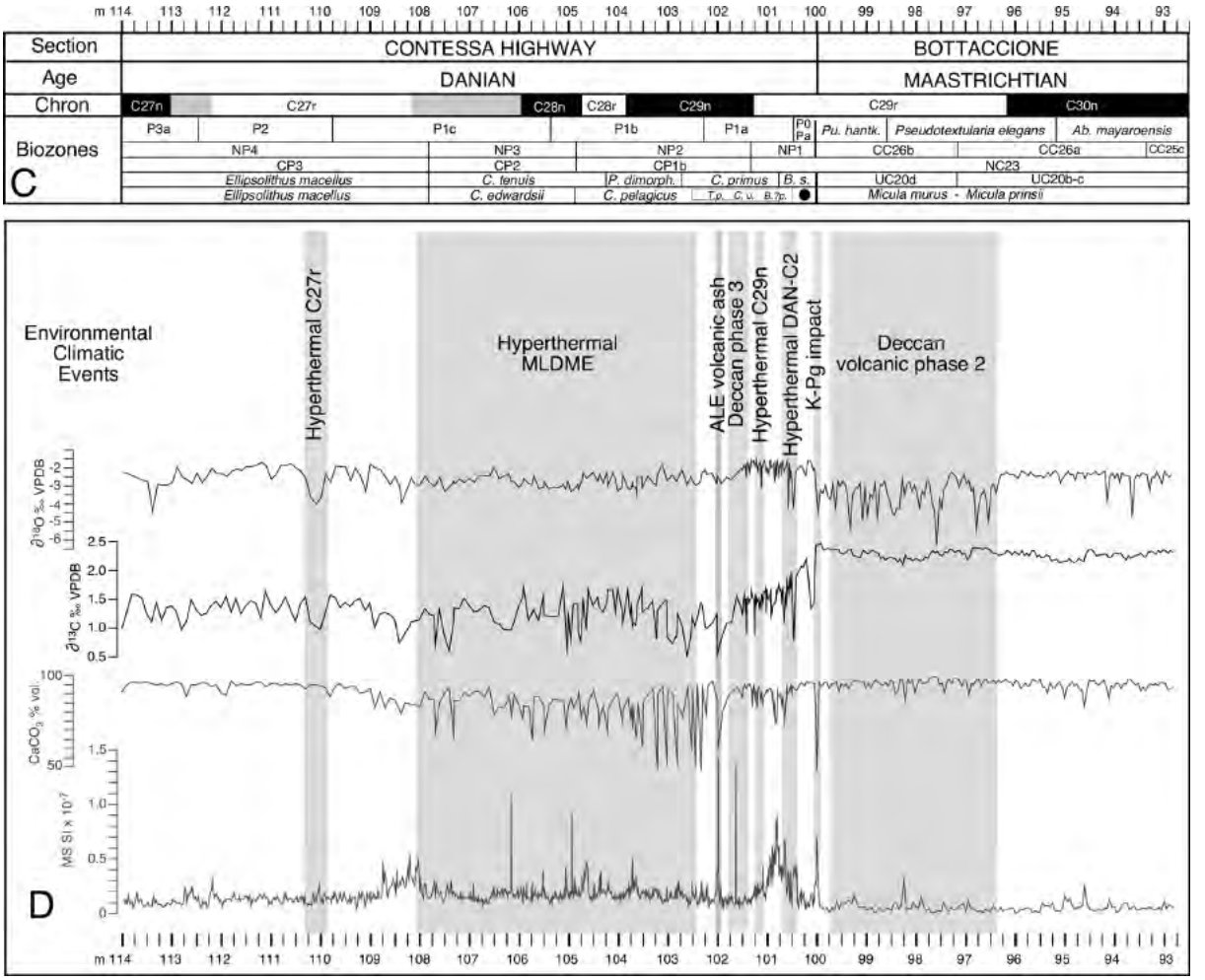

Fig. 4 – Integrated stratigraphy of the K-Pg transition at Gubbio (from Sinnesael et al., 2016, GSA SP 524).

Once we get in front of the famous K-Pg boundary, Sandro will briefly explain the sedimentological characteristics of the Scaglia Rossa Fm. across the R2 and R3 members (i.e., the K-Pg transition – see Fig. 5), but then Matthias Sinnesael will explain the details of the chemostratigraphic record of this interval, as illustrated in Fig. 6. We hope that this would encourage questions and discussion among the participants of this Penrose Conference.

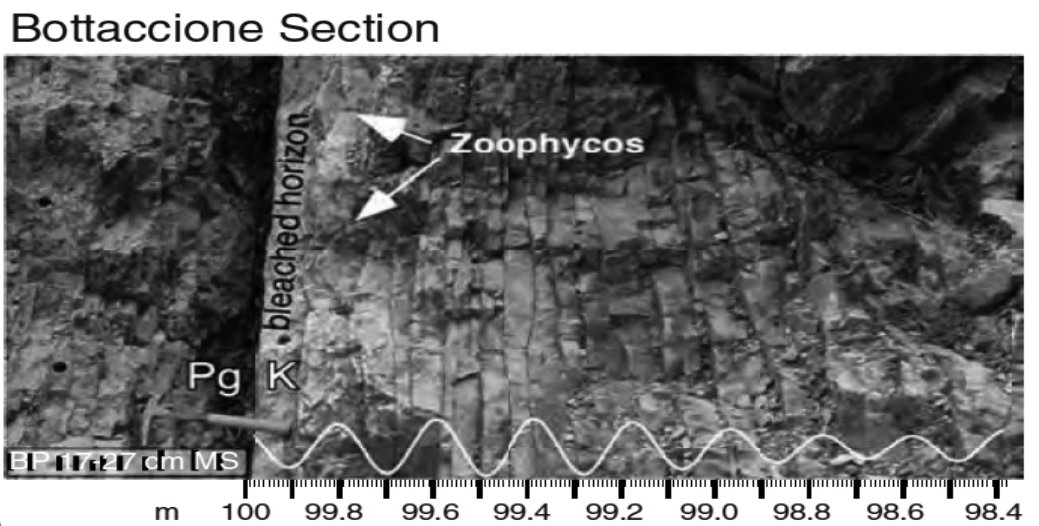

Fig. 5 – The K-Pg boundary outcrop of the Bottaccione Gorge (from Sinnesael et al., 2016, GSA SP 457).

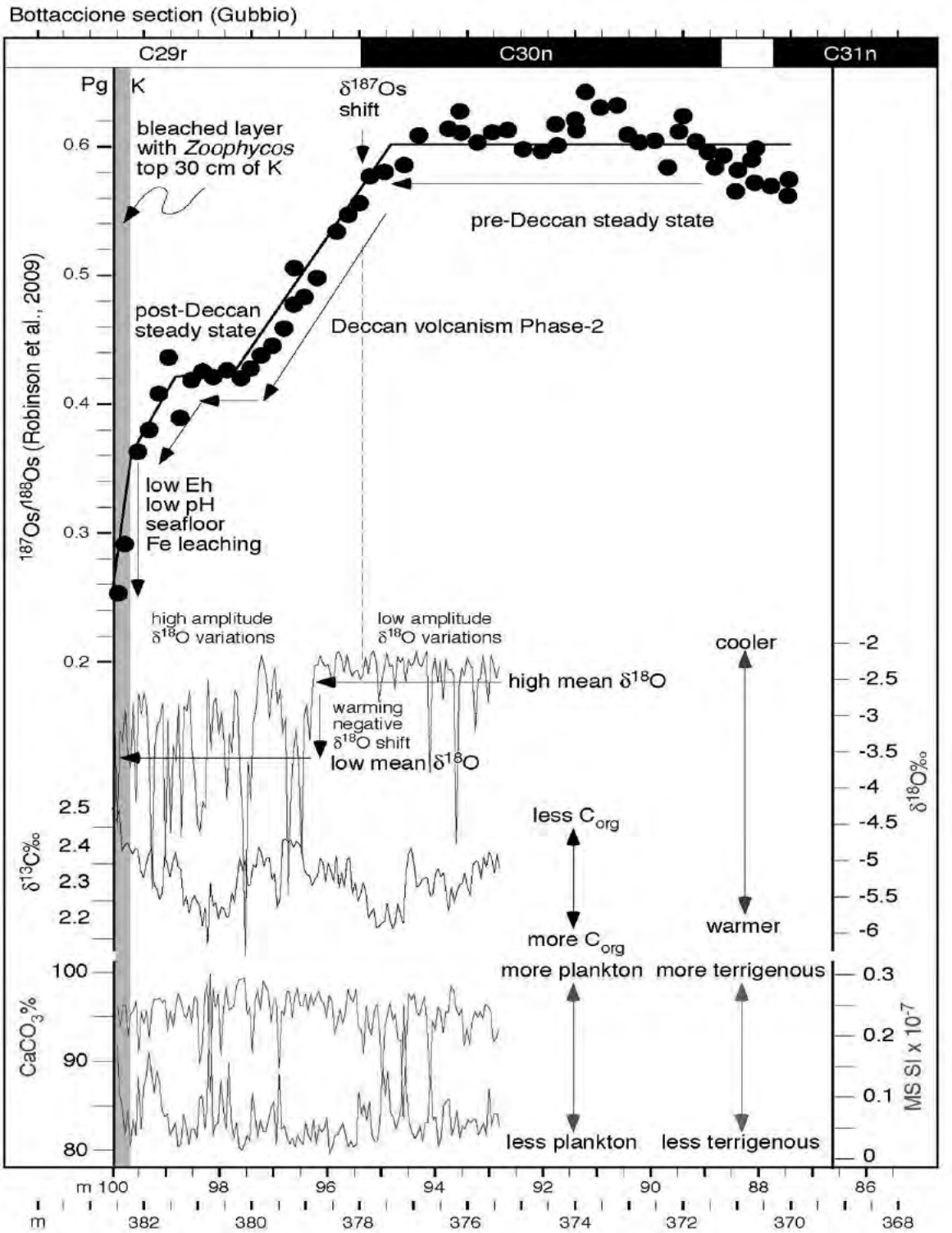

Fig. 5 – Chemostratigraphy of the terminal Maastrichtian in the Bottaccione section (from Sinnesael et al., 2016, GSA SP 457).

1:00 p.m. - Walk back to the restaurant for lunch. Buon appetito!

3:00 p.m. - Drive to Gubbio bus parking for a 2 hour tourist visit of the town.
5:00 p.m. - Drive back to Apiro-Cingoli. We'll be there at around 6:30 p.m.

Field trip to Frasassi

Friday September 29

8:30 - Leave Cingoli from hotel.

9:15 – Take a 800 m walk into the Frasassi Gorge, with Sandro explaining the geologic history we can see written on the cliffs of this spectacular canyon.
10:15 – We start a tour in the Frasassi show cave, with Sandro explaining the geologic history written in the guts of the Frasassi-Valmontagnana anticline.
12:00 – Return to Apiro for lunch at Biroccio Restaurant. Buon appetito! See you at the megaparty in Coldigioco at 6:00 p.m.

Strolling in between stones

INFRA SAXA, the Latin name of the Frasassi Gorge, literally means "in between stones". Across the U-M Apennines, there are many picturesque gorges carved by little rivers in between stones, which flow straight to the NE in an anti-Apenninic direction to reach the nearby Adriatic Sea. These hundreds-meter-deep canyons are the result of a Pliocene-to-Pleistocene antecedent folding and regional tectonic uplifting coupled with the incision of these rivers, which want to maintain their profile along their valleys, a process that is still going on today. After all, these rivers have shaped their valleys the minute the Apennine orogen emerged from the sea, and once the path of their thalweg was first traced, they had no place to go other than keep flowing, stubbornly, along that path. And so uplifting coupled with forced incision is what characterizes the neotectonic history of this part of the Apennines. And yet, Frasassi is a very special gorge, unique in the context of the U-M superimposed river valleys cutting across the structural grains of this NW-SE trending fold-and-thrust mountain belt. This is because the Sentino River cuts through a blind thrust-anticline, the hanging wall of which brought the late Triassic anhydrites of the Burano Fm. up close to the surface (see simplified geologic map and cross section in Fig. 1.). Because of that, deep waters in the reducing subterranean environment of the Burano Fm,, which is mostly made up of calcium sulfate ($CaSO_4$, aka anhydrite), get enriched in hydrogen sulfide (H_2S), and eventually reach the surface up to piezometric level (i.e., the level of the river's thalweg), via the fractured massive, pure limestone of the overlying Jurassic Calcare Massiccio Fm. But when this sulfidic water encounters the oxygenated water of the phreatic aquifer, the H_2S oxidizes forming a most aggressive sulfuric acid (H_2SO_4), which brutally dissolves the limestone creating large cavities inside the mountain, This is how we observe and measure the Frasassi hypogenic cave complex forming at present. And yet, the Frasassi caves have a past history, which is linked to the afore-mentioned process of tectonic uplifting coupled with river incision. Moreover, this coupled process is punctuated by alternating episodes of river aggradation and erosion, which result from alternating glacial and interglacial periods. This causes periodic variations of the piezometric level, and the result of all this, is a giant cave complex organized in seven horizontal floors (see cave map and section in Fig. 2). Speleothems that formed in these cavities, or the remnants of alluvional sedimentary deposits found at different elevations, have thus recorded the complex tectonic and environmental history of this part of the world for the past million years or so (see kinematic model in Fig. 3). And here is the chance for Sandro to narrate to you this amazing Little Big History, strolling with you in between the stones.

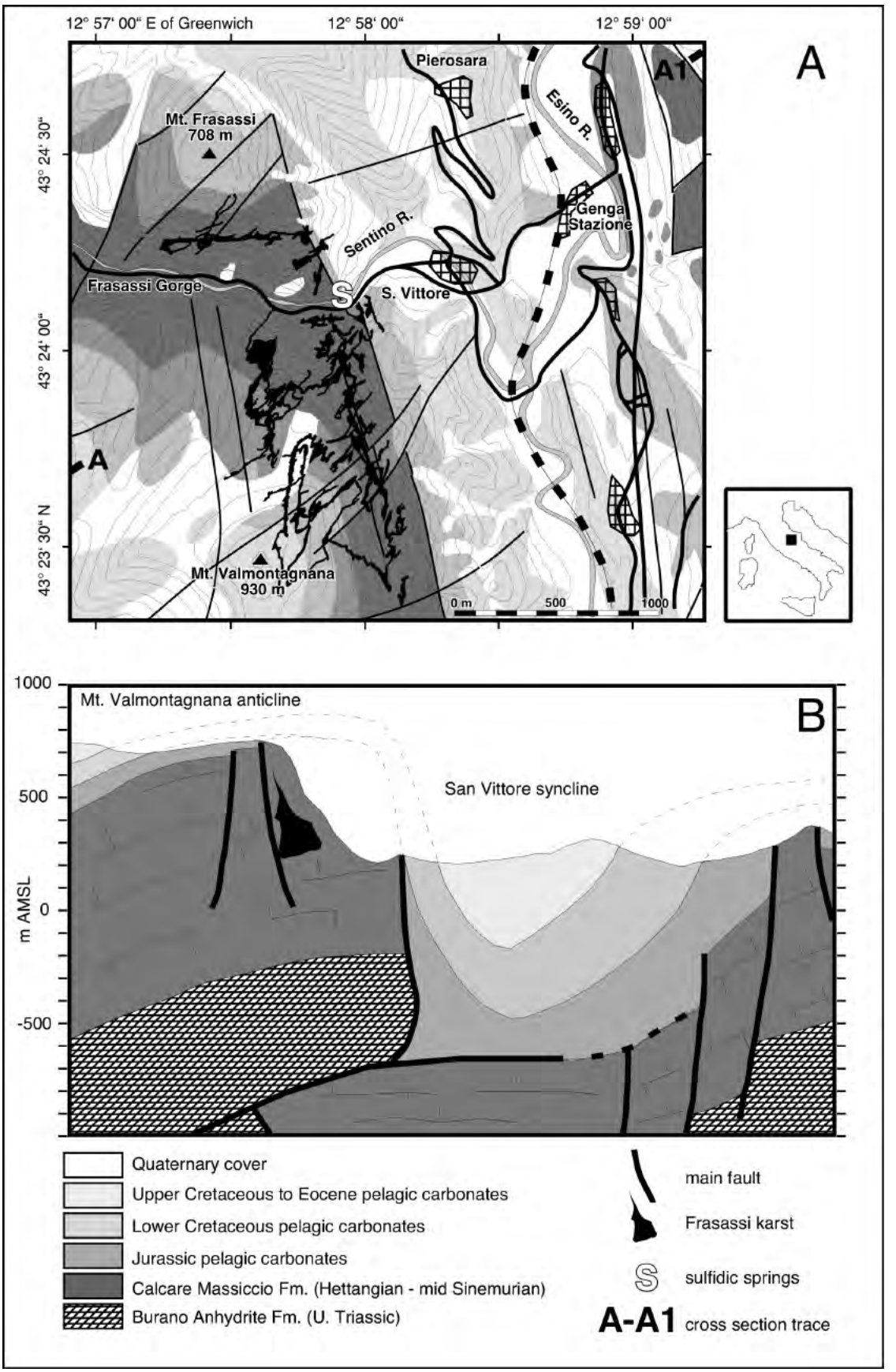

Fig. 1 – Simplified geologic map and cross section of the Frasassi blind thrust-anticline (from Mariani et al., 2007, EPSL v. 257, p. 313-328).

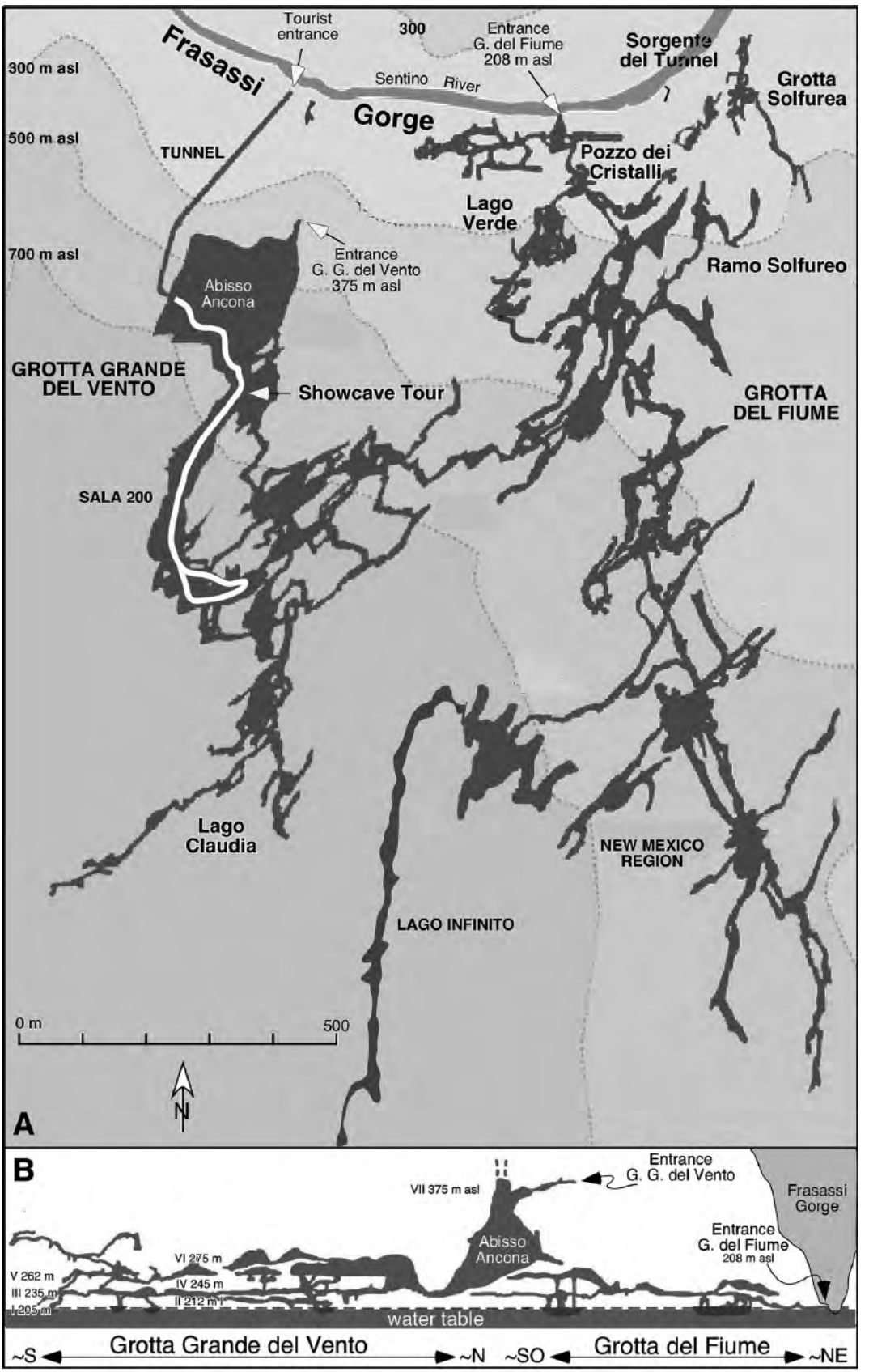

Fig. 2 – Simplified map of the 3rd floor, and cross section of the Frasassi hypogenic cave complex (from Mariani et al., 2007, EPSL v. 257, p. 313-328).

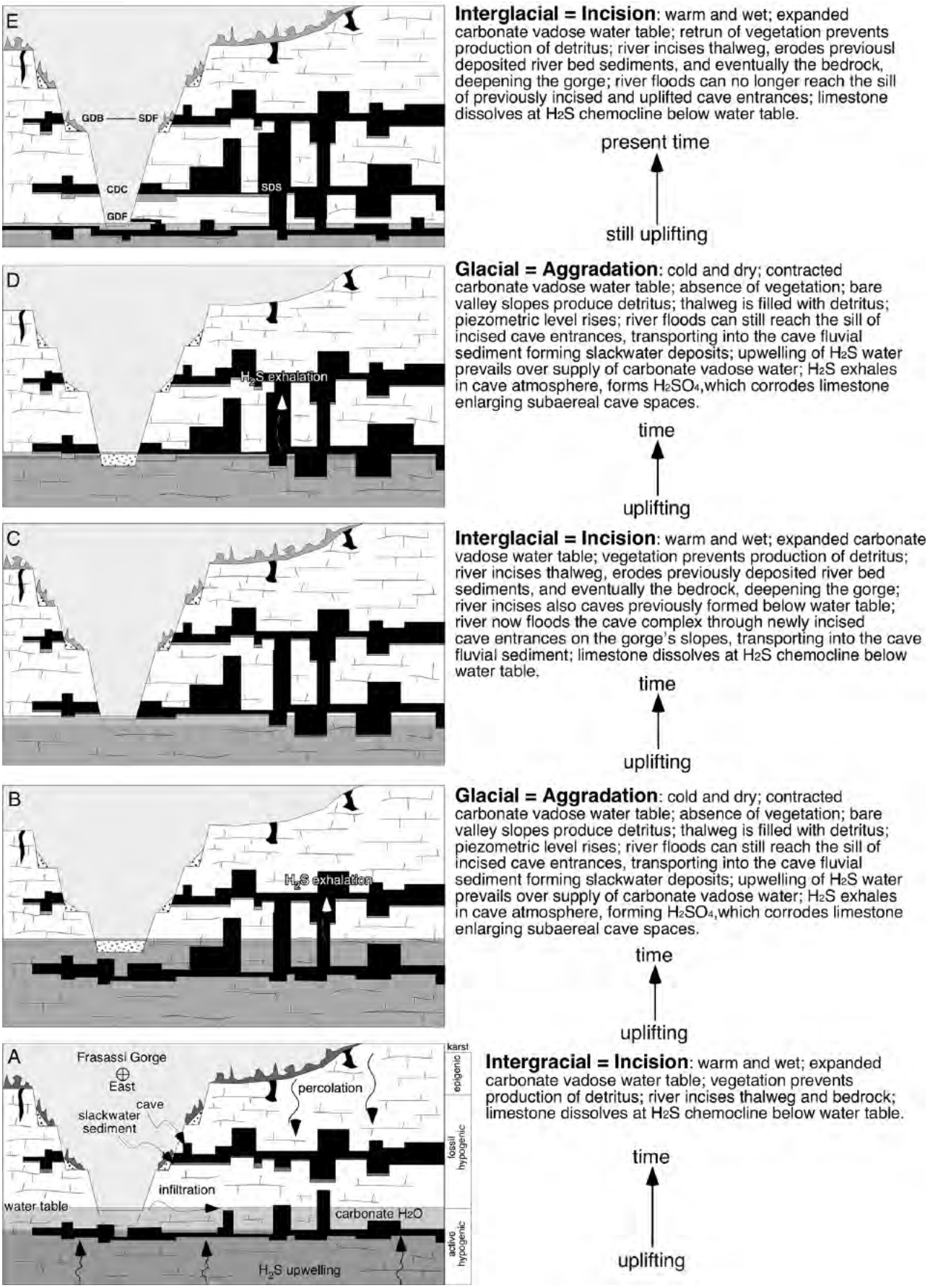

Fig. 3 – Kinematic model of the Frasassi hypogenic cave system (from Montanari, this volume).

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