"CHASING UP DARWING AND THE UNRESOLVED GEOLOGICAL MISTERIES OF COASTAL PATAGONIA"

PROGETTO ATENO 2007
University of Pisa
Department of Earth Science

"Reconstruction of sea-level changes and climate during the last and present interglacials over Patagonian coast (Argentina). An essay of evaluation for futures climatic scenarios".
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Abstract of the "Progetto Ateneo 2007"

The Patagonia is the only continental landmass emerging along the mid to low-latitudes in the Southern Hemisphere, and this make it a unique region of the world. This represents a key area for understanding the role of the southern hemisphere in regulating climate during the last hundredth of thousand years. From the Andes to Atlantic coast Patagonia preserves and impressive geological record of the glacial events and sea-level oscillations. The Quaternary coastal deposits, often organised in spectacular successions of raised-beaches-ridges deposits contain an almost unexplored archives of past climate. These natural archives can offer precious information on local relative sea-level changes, tectonic and glacial isostasy component, and fundamental information on past surface ocean conditions and, through the study of the continental deposit related to beach-ridge systems, information also on terrestrial climate. This project intends to explore these paleoclimate archives through a multidisciplinary approach as detailed stratigraphy, morphological, paleontological and geochemical analyses of a target area. The target area, the northern part of Gulf S. Jorge (Chubut, Argentina) has been selected collecting and collating remote sensing and literature data and has recently been a subject of a preliminary field work. Concisely, the main aims of the project are: i) to construct a local relative-sea level curve; useful for estimating local deviation to the eustatic component due to glacial isostasy and tectonic activity; ii) to reconstruct local sea surface condition through geochemical studies; iii) evaluate the biological changes associated to different sets of beach-ridges through the paleobiological studies of fossil shells; iv) to study the general evolution of coastal area in relation of evolution of continental deposit related to the beach ridges; v) in a more restricted area, selected on the basis of previous points, sea level rise due to the progressive global warming will be modelled the using IPCC current predictions, in order to produce scenarios for understanding the potential changes occurring in the area during the current climatic change.
This project will provide to the international community new data for understand climate system in this strategically located region of the world. The expected results are important since the patagonian coast is an environment of high natural values (however, it is threatened by oil exploitation, mining and increasing tourism) and represent a natural heritage that need to be preserved for future generations as reserve of marine and terrestrial biodiversity. This project intends to produce and disseminate data also for supporting form of tourism based on care and responsibility and selecting some area to be further preserved as "geosites". All the data will be organised in a Geographical Information System, which will be available, under request, to all the national and international institutions.
This is an ambitious project, which will project an Italian team in one of the "hot" areas for the study on past climate and where the sign of current climatic warming are clear. It also represents the opportunity for developing international scientific collaborations, in a first instance between two countries (Italy and Argentina) linked by strong cultural and scientific relationships.

Abstract of the activity 2008-2009

The project is following its marching list and the main targets of the project for the first year seems to be achieved. They can be summarised: i) educational targets have been obtained with two PhD students now involved within the project; ii) The first field work campaign was very positive and a significant number of samples were collected; iii) Laboratory analyses are mostly in progress but a significant number of data are scheduled for the end of this summer; iv) Preliminary geochemical data seems to confirm the potentiality of the selected natural archives for disentangling the oceanographic and paleoclimatic evolution of Patagonian coast (this was not obvious); v) An area

of particular interest have been selected for specifically addressing a preliminary project for selecting it as geosite; vi) Two entirely new project have been submitted to national institution for further funding and contact with other national/international are in progress for other way of funding and national/international collaboration. Thanks to this intense first year of activity we are ready to prepare the second field campaign now scheduled for February 2009. Slower are the institutional contact with the scientific and academic institution in Argentina for preparing a possible agreement beween institution to be submitted to our University next year for possible funding of exchange project. General economical situation, burocracy and distance make complex to properly fuel this part of the project.

Introduction

The Patagonia is the only continental landmass emerging along the mid to low-latitudes in the Southern Hemisphere, and this make Patagonia a unique region of the world. This represent a key area for understanding the role of the southern hemisphere in regulating climate during the last hundredth of thousand years. From the Andes to Atlantic coast Patagonia preserves and impressive geological record of the glacial events and sea-level oscillations. The Quaternary coastal deposits, often organised in spectacular successions of raised-beaches contain an almost unexplored archives of past climate. These natural archives can offer precious information on local relative sea-level changes, tectonic and glacial isostasy component, and fundamental information on past surface ocean conditions and, through the study of the continental deposit related to beach-ridge systems, information also on terrestrial climate.

Importance of Patagonia paleoclimate studies - Ice-core data show that they were anti-phase between the hemispheres (i.e. a cool North Atlantic coincided with a warm Souther Ocean, and *vice versa*) and that North Atlantic consistently lagged Antartic climate by ca 1000 to 3000 years (Bluinier & Brook, 2001, Caillon et al 2003; Bianchi & Gerdsonde, 2004). Brocker (1998) proposed that this apparent anti-phasing was due to a seesaw-like switching of deep-ocean ventilation (the so-called “bipolar seesaw”). For instance, at the end of the last glacial period (i.e. Termination I: ca 20-10 ka), the Southern Ocean seems to warm before the North Atlantic (Turney et al 2003; Lamy et al 2004; Vandergoes et al 2005). Paleoclimate modelling suggests this warming may have re-ignited North Atlantic thermohaline circulation, leading to strengthening of the North Atlantic Current and the collapse of Northern Hemisphere ice sheets (Knorr & Lohomann 2003). A similar scenario has been proposed for the previous glacial termination (ca 140-125 ka) (Knorr & Lohomann 2003). Therefore, Patagonia location is ideal for testing alternative hypotheses about the mechanisms of climate change based on synchrony or asynchrony between the hemispheres (eg Sudgen et al 2005).
In addition, the Patagonia in one of the most important region of the southern Hemisphere for producing aeolian dust. Aeolian dust effect climate, both directly by altering the radiation budget of the atmosphere and indirectly by influencing the biological uptake of CO_2 by ocean and then regulating atmospheric partial pressure of carbon dioxide. For instance, the phytoplankton growth in the Southern Ocean has been shown to be limited by iron supply (Coale et al 2004), and aeolian dust is a substantial source of iron, and then iron-limited ocean region are particularly sensitive to change in dust input. The in-phase changes between climate and dust flux has been observed in Equatorial Pacific (Winckler et al 2008) and Antartica (EPICA community member 2004). For instance EPICA ice core (EPICA community member 2004) provides evidence that glacial dust deposition at high latitude was as much as a factor 25 higher than during interglacial periods. Thus, dust may have been an important player in climate change in the past and is potentially one for the future.

The importance of Patagonian area for the reconstruction of climatic changes is witnessed by the interest of international scientific community with, for instance the ICDP project "PASADO" in the maar lake Potrok Aike (southernmost Patagonia), for the constant interest on Patagonia as a subject for studying the record of glacier fluctuations (eg Singer et al 2004; Rabassa, 2008). Under current climatic warming, Patagonia Icefield are rapidly tinning and their contribution to progressive sea-level rising appears globally significant indicating a very high glacial dynamic (Rignot et al 2003). Indeed, during the Last Glacial Maximum (ca 20-25 ka) Patagonian ice fields expanded to form a continuous ice field from approximately 35°S to 56°S. Patagonia, therefore, provides an ideal location to study southern hemisphere mid-latitude environmental changes during the waning of that ice field, to compare, for instance with northern Hemisphere location like North Europe and North America. Overall, the collection of climatic data from Patagonian on land and on coastal deposits is of paramount importance for a complete understating of climatic system. This is further highlighted by the fact that Patagonia not only offer a uniquely southern location, but the area spans the southern westerlies, the dynamic component of the atmospheric circulation of the southern hemisphere. As such it holds the promise of linking climatic processes in mid-latitudes with those of the Antarctic domain, and, already mentioned to test hypotheses focused on the synchrony of the climatic events.

The coastal archives - The Patagonia coast extending from ca 40°S to 52°S preserves an unique succession of raised beach deposit for which recent investigation suggest to be discontinuously constructed from Holocene to stage isotopic 9/11 (Schellmann & Radtke 2000; Rostami et al 2000; Isla & Bujalesky 2008), and probably older (our preliminary analyses). These exceptional archives is localised in a semi-arid area, where chemical weathering is extremely reduced and past landforms and deposits appears extremely well preserved. Most of these marine landforms are locally dissected by rivers forming complex system of continental and marine terraces creating a natural condition for investigating the evolution and relation between continental and marine deposits and their climatic significance. Most of the coast of Patagonia is an area characterised by high natural values and with significant natural reserves (e.g. Valdez Peninsula). This environment is, however, in fragile equilibrium under human pressure (increasing tourism, offshore oil exploitation) and future climatic changers could produce a significant lost of marine biodiversity and of ecological niches. To understand how this environment formed and how it evolved under the sea-level oscillations and climatic changes represent a priority for preserving this natural heritage.

Although, these beach-ridges have been partially studied mainly with the intent to reconstruct relative sea-level changes (Schellmann & Radtke 2000) and/or isostasy and tectonic component (Codignotto et al 1992; Rostami et al 2000) are practically unexplored as climate archives (Isla & Bujalesky 2008).

Geographical and geological framework - The Cenozoic geodynamic evolution of the Patagonia resulted mainly from the convergence of the Nazca and Antarctic Plates beneath the South American Plate and from the transcurrent movements along the boundary between the Scotia and South American Plates. Plate subduction led to the collision of segments of the Chile Ridge with the Chile Trench. This ridge-trench collision process began west of Tierra del Fuego at about 14 Ma (Cande & Leslie 1986) with the development of the triple junction between the South American,Nazca and Antarctic Plates migrating northward to its present position (~46.5° S; Cande & Leslie1986; Forsythe et al 1986).

The complex plate boundary configuration resulted in the presence of distinct tectonic provinces in the area. The easternmost part of the continent forms the relatively undeformed Magallanes foreland, west of that is the Cretaceous–Tertiary Magallanes fold-thrust belt, and further west is the Mesozoic to Recent magmatic arc. Extensive plateau basaltic lavas were erupted in southern Patagonia during the Neogene in a backarc position onto the thick sequence of siliciclastic and pelitic sediments which represents the filling of the Austral Patagonian rift, the southernmost of a series of NW–SE continental rifts that developed since Late Triassic time due to extensional

tectonism linked to the Gondwana break-up (Urien et al 1995; Corbella et al 1996). The youngest deposits of these basins are Late Miocene–Holocene fluvial sediments with intercalated pyroclastic materials and glacial sediments (Mercer 1976;Clapperton 1983). Progressive uplift of the chain since the Late Miocene is responsible of the beginning of the Patagonia glaciations and the development of the Patagonia climate (eg Ramos & Ghiglione 2008; Rabassa 2008 and refs therein). Ice fields and smaller ice caps exist on the higher massifs in the Andes, with particular centres in the Cordillera Darwin (55°S) and the North and South Patagonian Icefields between latitudes 46–47.5°and 48–51°, respectively. The climate of the area varies from subantarctic in the far south to warm temperate in the north with mean annual temperatures varying from 5°C in latitude 55°S to about 11°C in latitude 40°S. Precipitation is dominated by the westerlies and the rain shadow effect of the Andes. Annual precipitation exceeds 7000 mm/yr on the west coast in the core of the westerlies at latitude 50°S and falls away to 2500–3000 mm/y to the north and south. In southern latitudes precipitation levels decline sharply in the lee of the mountains and may be less than 300 mm/yr only tens of kilometres from the mountain front.

The Quaternary Marine successions - The Patagonian littoral deposits (the so-called "marine terraces" in local literature), were studied discontinuously since the 19th century (eg Darwing, 1846). The first systematic studies, still relevant for the area, was the contribution of the Italian geologist E. Feruglio (eg 1950). However, only since the 1980 there were the first, radiometrically supported, modern works (eg Codignotto et al 1992). Of fundamental importance, especially for the chronological dating and stratigraphy are, among others, the work of Rostami et al (2000) and the superb contributions of Schellmann (Schellmann 1998; Schellmann & Radtke 2000, 2003). Most of the "marine terraces" in this area are composed by successions of regressive coarse beach-ridges mainly related to intermittent storm activity.

These beach ridges and/or marine terraces are usually interpreted as formed during phases of global marine high stand. Most contain highly fossiliferous marine strata, with abundant and excellently preserved shell concentrations. Modern studies on these association are mainly due to M. Aguirre (e.g. Aguirre 2003; Aguirre et al 2005). However, paleobiological and taphonomich aspects are still poorly known. The study of these deposits poses several different type of challenges, which require a team with different attitudes, a fact which has lacked in the most of previous studies (eg many studies with significant chronological information lacked the contribution of sedimentologist and palaeontologist, or many very good morphological and stratigraphical works lacked a strong chronological support).

One of the main problem encountered so far by researches is the definition of clear markers of past position of sea level. Indeed, the storm dominated macro-and mesotidal Patagonian coast poses a significant challenge for the accurate determination of past sea level.

The aims of the project - The main aim of the project is focused on basic sciences and consist in a study of the effect of sea-level and climatic changes on the coastal environment through palaegeographic, palaeoecological and paleoenvironment reconstructions over a selected sector of Argentinean coast using geomorphological, stratigraphic, paleontological and geochemical methods. In particular, during this project particular attention will be paid to correlate raised marine deposit to the transitional-continental-related deposits in order to appreciate the relation between sea-level variation and the changes and impact on coastal and continental depositional systems.

This represent an important effort in studying coastal areas of southernmost south America substantially poorly known. In particular it is important to disentangle the different role of eustatic component (i.e. variation of general ocean volume due to glaciation-degalciation periods), local tectonic and effect of the glaioeustatic component being Southern Patagonia interested by the presence of thick ice-cap during glacial periods. This, therefore, want be a multidisciplinary study of the area to understand how environment can change in function of climatic and sea-level changes in areas of low human impact. As secondary (but not less important) aim this project want to be a

first tessera for creating a more comprehensive view of areas potentially single out as geosites for future preservation and potentially development of sustainable resource like compatible tourism.

The selected area -The area of study was selected on the basis of preliminary analysis of satellite images and collection and collation of previous studies within the financially supported pilot project "Ateneo 2007" (funded by University of Pisa, Leader G. Zanchetta). The criteria for the selection of the area were: i) Occurrence of several order of terraces, for which we can suppose the presence of at least Holocene, MIS5, MIS7, MIS 9 and MIS 11 successions (MIS: Marine isotope stage; ii) Availability of stratigraphic and morphological preliminary data; iii) The possibility to have different morphological setting including wave cut abrasion platform and inner terrace cliff erosion to be correlated with dated deposits (this prevents an expensive field works and allow the test different approaches for estimating past sea level changes); iv) the availability of a basic set of radiometrically dated units (this reduces the cost of dating for some selected stratigraphic units); v) The abundance of continental deposits for which a relation with "marine terraces" can be determined and that can be useful to infer condition at time of sea level changes (i.e. during both falling and rising of sea level); vi) select an area for which a large influence of freshwater input can be neglected. This makes it possible to select samples, which give real information on sea conditions and not complicated by mixing processes; vii) the availability of local geodetic station to anchor elevation data and that can offer the opportuinity to implement local topography thanks to GPS systems.
The preliminary work has allowed us to selected the northern part of Golfo S. Jorge (Provincia del Chubut) between Bahia Solano and Capo Raso (Fig. 1), which include all the required criteria listed above (and in particular the presence of older terraces not identified by previous authors make for this area extremely probable the presence of MIS 11 or even MIS 13). Preliminary analyses of beach-ridges fossil parautochtonous assemblages indicated the main marine character of the fossil faunas (Aguirre, 2003). In fact, currently the littoral area is characterised by open marine conditions in subantarctic cold-temperate waters, salinity is c. 34-34.5 ‰ and temperatures reach 3-11°C in winter and 5.5-14.5°C in summer. The modern littoral zone at Golfo San Jorge (45-47° S) belongs to the southwestern Atlantic sector of the Magellanean Zoogeographic Province. This marine biogeographic area extends from Golfo Nuevo (Chubut, c. 43° S) southwards to Cabo Hornos (55° S) and is dominated by the cool Falkland (Malvinas) Current, a northward-running branch of the subantarctic Cabo de Hornos Current. The Malvinas Current moves northwards up to about latitude 28° S (Santa Catarina, Brazil) in winter or to Rio de La Plata in summer. Its mean temperature ranges yearly from 4 to 11° C and salinity ranges yearly from 33.8 to 34.4 ‰. Further north of the area of study, from Golfo Nuevo to 28 °S extends the Argentine Zoogeographic Province, a transitional area influenced by the cool Falkland Current and the warm Brazilian current. The latter is a branch of the South Equatorial current and moves from north to south (mainly subtropical shallow water masses of 34.5-38.85‰ and 18-24 °C) (Bastida et al 1992). There are paleontological evidence that this current shifted significantly southward during the Middle Holocene, ca 8-6 ka (Aguirre & Whatley 1995).

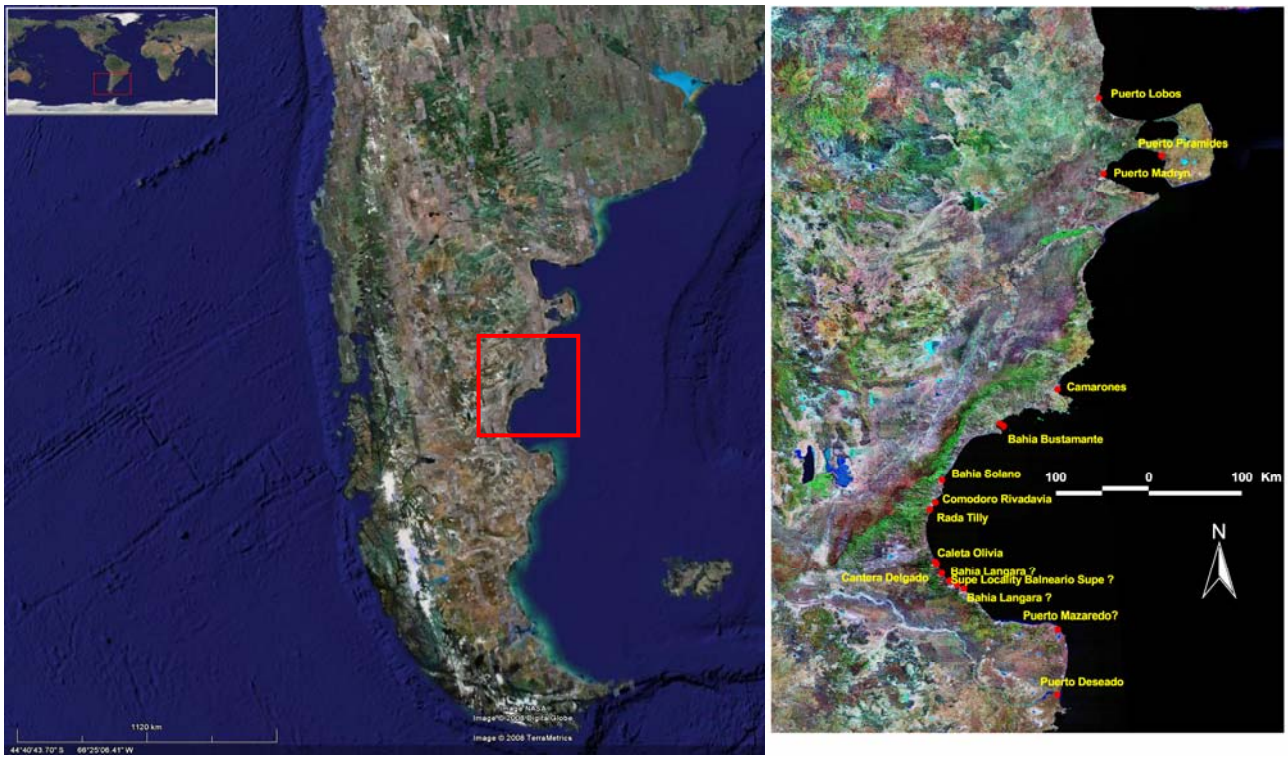

Fig. 1- **Schematic map for the study area.**

For the area there is a basic geological map at 1:250000 (Sciutto et al 2000) and more detailed data are also available for some beach-ridge successions. No significant studies seems to exist for continental deposits in this area (Martinez & Coronato 2008), and this represents an important gap that we want to fill by this project. Review of the beach ridges geology of this area are available in Schellmann & Radke, (2003), Aguirre (2003) and Isla & Bujalesky (2008). Chronological data suggest the presence "Marine terraces" as older as MIS 9 (also dubitatively attribute to MIS11), however, our preliminary investigation indicate an unrecognised (or possibly two) set of beach-ridges lying at higher altitudes respect to the older terrace reported by Schellmann & Radke (2000, 2003). Recently published remotes sensing data indicate a very intriguing development of large (for the area) mass movements of different ages, which show a complex relation with continental and marine deposits (Gonzalez Diaz 2004), which are worth of attention also for the possible hazard these mass movement can pose, but more in general for the processes affecting this sector of Patagonia.

The Malvinas (Falkland) curren

The Malvinas (Falkland) Current is a branch of the Circumpolar Current and flows northward along the continental shelf of Argentina (Fig. 2) until it reaches the Brazil Current offshore the Rio de la Plata estuary (Legeckis and Gordon 1982, Garzoli 1993, Vivier and Provost 1999a). Legeckis and Gordon (1982) examined satellite infrared images and described the Malvinas Current as a 100-km wide band of cold water over the continental slope.

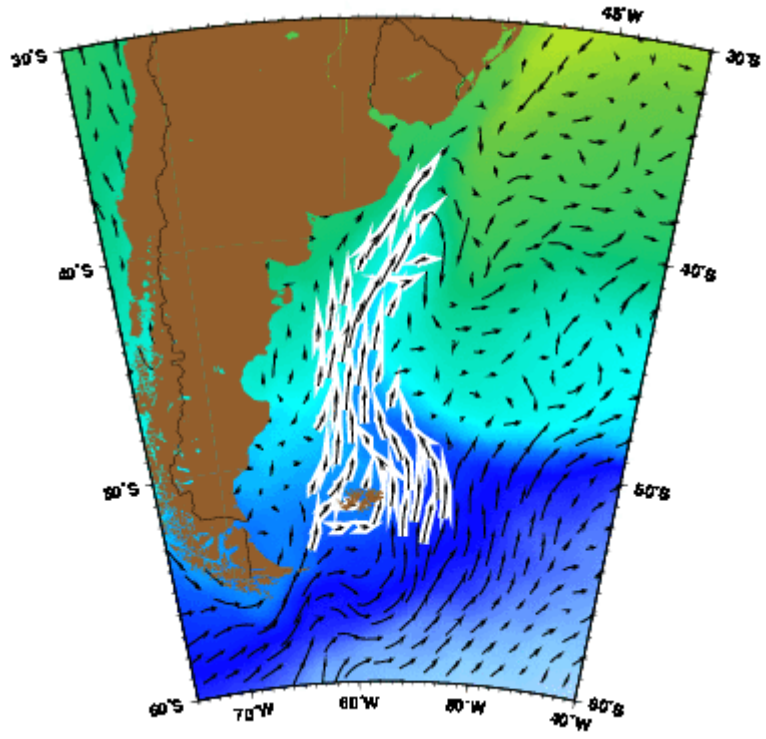

Fig. 2. **The Malvinas current as represented by the Mariano Global Surface Velocity Analysis (MGSVA). It is the northward flow component of the S. Atlantic subpolar gyre. The Malvinas current transports cold water along the coast of S. America and this water mixes with warmer waters of the Brazil current in an region known as the Brazil-Malvinas confluence.**

The western sea surface temperature (SST) boundary of the current was adjacent to continental shelf waters, the northern boundary was marked by the warm Brazil Current, and the eastern boundary lay between the cold Malvinas and the warm water that results from mixing of meanders and warm-core eddies associated with the Brazil Current (Fig. 3). The Malvinas Current is strong, relatively fresh, and cold, with mean SST of 6°C (Brandini et al. 2000). Thus, when it meets the weak, warm, southward-flowing Brazil Current at the Brazil-Malvinas Confluence, a sharp gradient in temperature and salinity can be observed (Goni 1996). Based on hydrographic data, it is believed that the Malvinas Current has a strong barotropic component and that it is well-mixed (Peterson and Stramma 1991, Vivier and Provost 1999a).

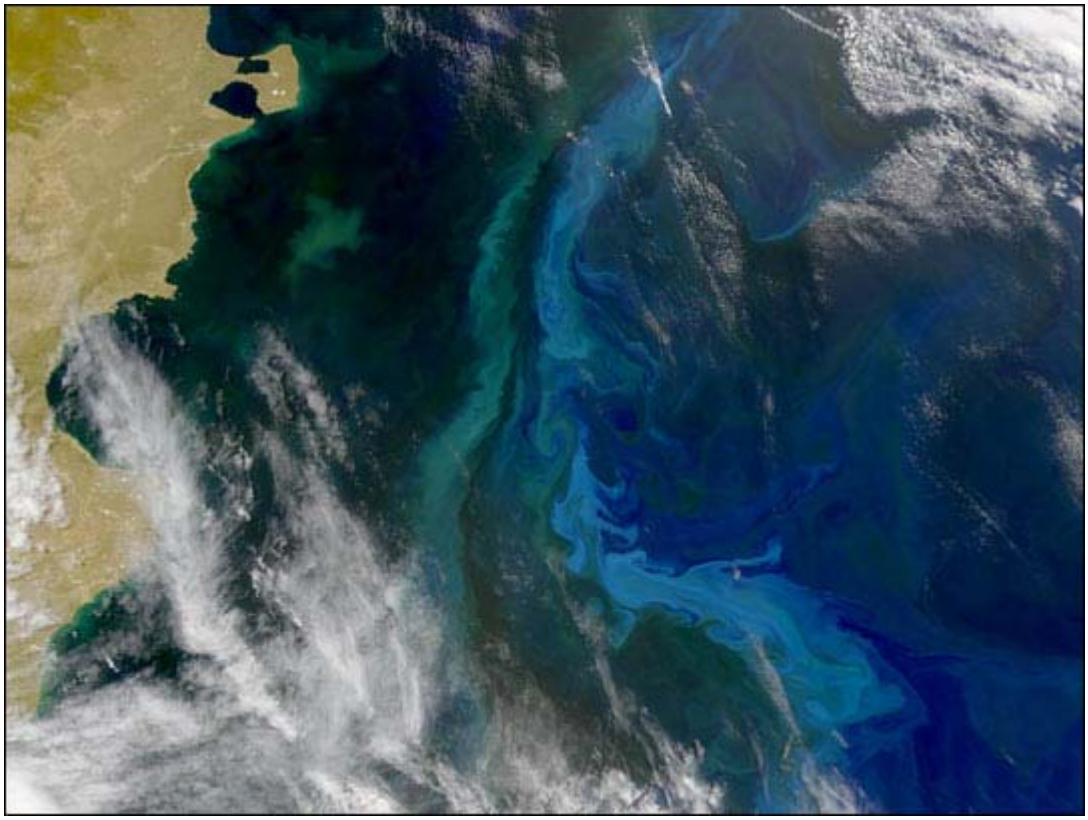

Fig. 3. **The bright waters off the east coast of Argentina mark the convergence of the Malvinas and Brazil Currents. The interaction of the two currents brings nutrients from the dark ocean depths to the sunlit surface, resulting in dense blooms of phytoplankton, especially in the spring and early summer.The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) imaged the area on November 29, 2001.**

It is also thought that the current has significant non-zero bottom velocities, a claim that was directly verified by Harkema and Weatherly (1989, as cited in Garzoli 1993). Their bottom current meters measured velocities of up to 10 cm s^{-1} (Garzoli 1993). Both of these factors must be taken into account when calculating values of transport by using a reference level of no motion. Estimates of the volume transport of the Malvinas Current vary widely in the literature, depending on the reference level that is chosen (Garzoli 1993). For example, using a reference level of 1000 m at 38°S, Garzoli (1993) obtained a transport of about 24 Sv. Using a reference level of 1400 m at 42°S and 46°S, Gordon and Greengrove (1986) obtained values of 10 Sv at both locations, although they believed that this value represented the lower limit of the real flow. Piola and Bianchi (1990 as cited in Garzoli 1993), using 1000 m as the reference, found 10-12 Sv. With a reference level of 3000 m at 42°S, Peterson (1992) found 60 Sv in the first 2000 m and 75 Sv in total, while at 46°S he found 70 Sv in the first 2000 m and 88 Sv in total. Choosing the bottom as their reference level at 45°S, Saunders and King (1995) calculated 50 Sv in the thermocline and 60 Sv in total (Maamaatuaiahutapu et al. 1998). Vigan et al. (2000) noticed that the transport values decreased from south to north. In particular, observations between 40°S and 38°S plummeted from about 20 ±5 Sv to zero. They attribute this to the fact that the Malvinas Current returns to the south at these latitudes. Thus, the location of the observations, relative to the location and orientation of both the high-velocity core of the Malvinas Current and its return flow, may also account for some of the variability in transport estimates. Direct measurements of the velocity of the Malvinas Current are scarce. According to Peterson (1992), surface drifters in the Malvinas Current travel at about 40 cm

s^{-1}. Garzoli (1993) found geostrophic velocity values of 102 cm s^{-1} at 36.5°S and -61 to -62 cm s^{-1} at 36.6°S that were associated with the northward-flowing Malvinas Current and the southward return flow, respectively. The along-shelf flow of the Malvinas Current is highly variable from year to year, and it does not appear to have an annual or even a semi-annual cycle. However, there is a suggestion of significant energy at periods of about 135 days (Vivier and Provost 1999a, 1999b). On the other hand, the cross-shelf flow (perpendicular to the coast) clearly shows an annual cycle that is associated with the position of the subantarcitc front (Vivier and Provost 1999a).

The Brasilian warm current

The Brazil Current is a weak western boundary current carrying warm subtropical water, which runs south along the coast of Brazil from about 9°S to about 38°S and is generally confined to the upper 600m of the water column (Fig. 4).

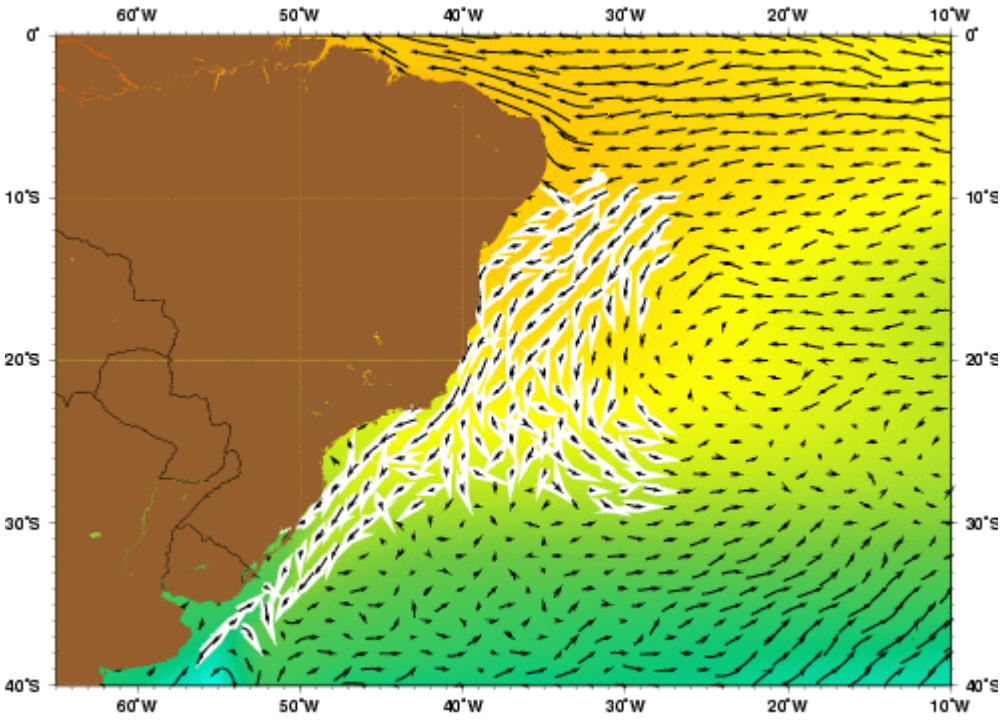

Fig. 4. **The Brazil current as represented by the Mariano Global Surface Velocity Analysis (MGSVA). The Brazil current is the western boundary current of the South Atlantic subtropical gyre. It transports warm water polewards. Near 22 S, the Brazil current splits; one component flows eastward and the other component hugs the coast and flows toward the southwest and interacts with the colder Malvinas Current.**

Its origin begins where the westward flowing trans-Atlantic South Equatorial Current (SEC) bifurcates (or splits) as it approaches the continental shelf off of Cabo de Sao Roque, Brazil (Stramma et al., 1990; Podesta et al., 1991). SEC water flowing north becomes the North Brazil Current, and the branch flowing south becomes the Brazil Current (BC). Although Isaaci Vossius is given credit as the first to recognize and describe the Brazil Current in 1663 in "A Treatise Concerning the Motion of the Seas & Winds," it was James Rennell in 1832 who worked out details of the actual flow, and dubbed the current the Brazil Current. He had been a member of the British Royal Navy and later joined the East India Company, making several trips across the Atlantic under the supervision of John Purdy. In addition to his detailed descriptions of these currents, it was Rennell who first determined that the BC was weaker than the North Brazil Current and was among the first to map out the surface currents along the New World continents (Peterson et al., 1996). The

Brazil Current begins at about 10°S, separating slightly from the coast near 12°S where the continental shelf becomes wider (Peterson & Stramma, 1991; Stramma et al., 1990). Satellite images taken over three years (1984-1987) show that the actual point at which the BC separates from the continental shelf varies anywhere between 33°S-38°S, with the average being about 36°S (Olson et al., 1988; Podesta et al., 1991). The BC continues to flow south off the Brazilian coast until it reaches about 33-38°S, when it collides with the north-flowing Malvinas (Falkland) Current. The BC is then, in part, deflected to the east offshore of Rio de la Plata, a region known as the Brazil-Malvinas Confluence Zone (BMC), one of the most energetic regions in all the oceans (Sarceno et al.,2004). Gordon and Greengrove (1986) were the first to label this region the Confluence. The latitude of confluence, which determines where the BC will separate from the continent, is farther north during austral winter and spring. This seasonality is presumed to be related to the general seasonal shift of wind systems and seasonal meridional shift of the subtropical gyre (Peterson & Stramma, 1991). The transport of the Brazil Current is considered small when compared to that of the Gulf Stream, its counterpart in the Northern Atlantic. The problem when estimating transport of the BC is that in its northern region, it is shallow and closely confined to the continental shelf. Transport values between 5 Sv and 6.5 Sv have been observed near surface waters (upper 500m) of the BC around 20°S (Peterson and Stramma, 1990; Stramma et al., 1990). At about 20.5°S, the current encounters the Vitoria-Trindade Ridge, a zonal seamount chain where it has been observed to flow through the inshore passage rather than the passages farther east. In this region, a cyclonic gyre seaward of the Brazil Current, centered at about 17°S and 34°W has been observed and attributed to the southernmost meanders of the South Equatorial Current that are reflected northward by this same seamount chain (Memery et al., 2000; Stramma et al., 1990). At about 20.5°S, near the seamount chain, the current flows at about 50-60 cm s^{-1} as estimated by Evans and others (1983). As the Brazil Current flows south of 24°S, its flow intensifies by about 5% per 100km, which is similar to the growth rate in the Gulf Stream, although transport values in the BC are considerably less (Peterson and Stramma, 1991). Thus, at about 33°S the total transport (which includes a recirculation cell in the upper 1400m) is about 18Sv, and reaches values from 19-22 Sv at about 38°S, where it encounters the Malvinas (Falkland) Current (Olson et al., 1988; Peterson and Stramma, 1991). The mean latitude of the BC's separation from the shelf break is about 35.8°S ± 1.1° and for the Malvinas Current, the mean latitude of separation is 38.9°S ± 0.9°. The coastal ranges of the separation positions are at 950km and 850km respectively (Olson et al., 1988). The combined flow of the two currents causes a strong thermohaline frontal region, called the Brazil-Malvinas Confluence (BMC) in which the BC breaks off into two branches, one turning to the north forming a recirculation cell, while the other continues southward and veers northeast at about 45°S, becoming the South Atlantic Current (Boebel et al., 1999; Saraceno et al., 2004). The mean transport in this region has been measured to be about 11Sv (Garzoli and Bianchi, 1987). Maximum velocities at the confluence (at about 38°S) reach 55 cm s^{-1} with the average value of 35 cm s^{-1} with transports of 18 and 11 Sv respectively. Flow can increase up to 23 Sv at the Brazil-Malvinas Confluence (Garzoli, 1993) Mean conditions of circulation vary significantly, and more recent evidence shows that it is likely related to meteorological anomalies (Assireu et al., 2003). Some short term variability in the southward extent of the BC has also been observed. Occasionally, when a BC meander that has extended unusually far south retreats, it can shed a series of warm core eddies that migrate into the Antarctic Circumpolar Current (Partos and Piccolo, 1988). Values also vary according to measurement method and depth. A comprehensive overview of literature on BC transport estimates prior to 1991 can be found in Table 2 of Peterson and Stramma (1991). The range of the Confluence oscillate between about 54°W and 45°W, a total distance of about 770 km (at 38°S). The meanders appear to occur on a twelve month cycle and are likely correlate to changes in the separation latitude of the Brazil Current (Boebel et al., 1999; Garzoli and Bianchi, 1987; Goni & Wainer, 2001; Maamaatuaiahutapu et al., 1999; Zavialov et al., 1999). The mean speed of the front is estimated to be about 14 cm s^{-1}. The front oscillates around its mean seasonal position (farther north and east during austral winter and farther south and west during austral

summer) within a period of about one month and an amplitude that varies from 10-50 km per day. The mean velocity of the displacement of the front reaches values up to 10 km/day (Garzoli and Bianchi, 1987). This area is also rich in eddies, more often called Brazil Current Rings, averaging to about 7-9 rings per year. These elliptical rings can vary in size from about 56 to 225 km along the semi-major axis, and 23 to 108 km for the semi-minor axis. These anticyclones have a mean lifetime of about 35 days and translational speeds of anywhere between 4-27 km per day (Lentini et al., 2002). On average, the temperature in the Brazil Current is about 18°C-28°C, with essentially three meridional zones that experience several degrees of distinctly different annual temperature fluctuations, which corresponds to their proximity to shore. The first zone is located over the shelf and experiences temperature variability of 7-10 degrees, which is controlled by both winter invasions of subantarctic water from the Malvinas Current and discharges from Rio de la Plata and Patos-Mirim. The second or central portion, closer to the eastern margin of the continental shelf, experiences a 5-7 degree variance. The third, on the seaward-most zone, shows little fluctuation until the Confluence (Memery, et al., 2000; Zavialov et al., 1999). Temperatures in the southern section of the current, near the Confluence, can change by 5-13 degrees, with the cooler temperatures occurring around August-September and the warmer values observed in February (Boebel et al., 1999; Podesta, et al., 1991). Almost yearly temperature anomalies of warm and cold fronts occur that seem to be related to the El Nino-Southern Oscillation (ENSO) events. Anomalous cold water extensions to the north occur on the shelf generally one year after every warm ENSO event, and anomalous warm water extensions occur generally one year after every cold ENSO (Lentini et al., 2001). Surface salinities indicative of Brazil Current waters range from 35.1 to 36.2, with the maximum commonly found at around 20°S, where it can reach a salinity of 37.3 (Memery et al., 2000; Wilson & Rees, 2000).

Main questions

Owing to the oceanic surface current configuration today the main question are:

- Is this configuration stable during the past interglacials?
- If not, was this configuration (or others) changing during a single interglacial?
- What happen during the Holocene (i.e. the last ca 11 ka)?
- Is it possible to track these changes in the past using geochemical proxies using the beach-ridge deposits?
- Which is the best proxy?
- If detected, are these changes related to the “bipolar seesaw”?
- How this environment was affected by sea-level changes?

Activity of the 2008-2009

Most part of the first six months was devoted to remote sensing analysis and collecting maps and references for the areas. As highlighted in the introduction this allowed the identification of a specific area where focus the fist field campaign for selecting samples.

2009 Filed Trip

The first field trip started on 9 Jannuary 2009 from the Pisa. After two days of technical organization at La Plata, a team of 11 people moved toward Patagonia using a "combi"equipped with a wagon. The team were composed of 3 Argentinean of the University of La Plata, four geologist of the University of Pisa, 1 from the INGV of Pisa and two local "choffers"(drivers).

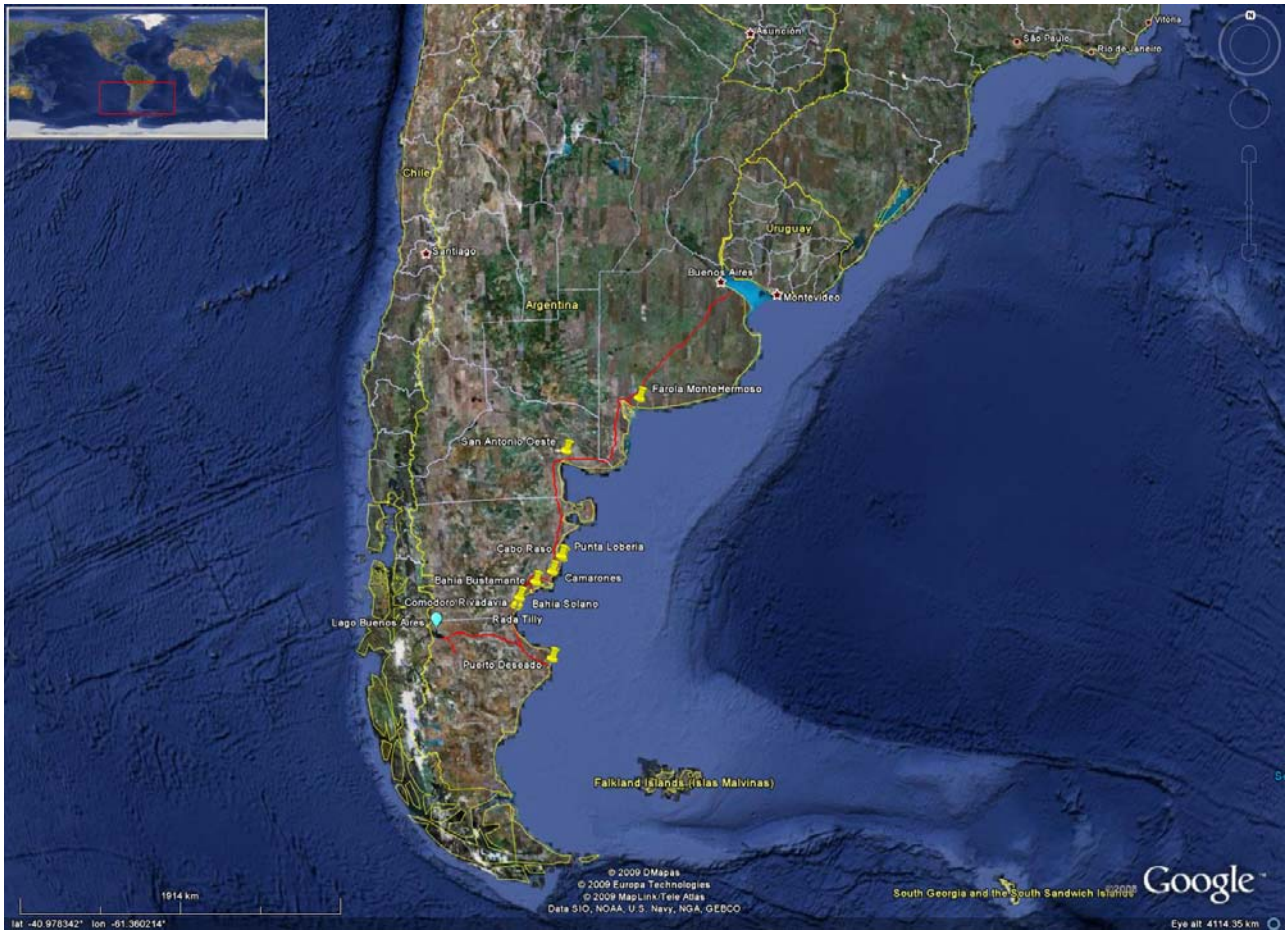

Fig. 5 **Trip path (red).**

The main stopping places were the area of Bahia Vera-Cabo Raso, Bahia Bustamente, Camarones, Bahia Solano and Puerto Deseado. These places allowed the visit and sampling the most important successions described in the older and recent literature (especially those sections containing robust chronological control. Fig. 6), comprising new areas almost unexplored (e.g. Bahia Vera). All the sections were carefully documented and any paths were documented and positioned using GPS. More than 200 samples were collected. A specific area was selected for further investigations in order to propose this area as "natural geological heritage". This is the old "algeros" (seaweed collector) village of Bahia Bustamante which preserve a very important succession of reach beaches setter is a spectacular environment (Fig. 7). A preliminary project for developing the area (e.g. tourist paths) is in progress.

Fig. 6 **– Example of shell accumulation in a Holocene Beach ridge at Bahia Solano. These deposits are well suited for studying sea level and geochemistry evolution of sea water and then evolution of coastal currents.**

Fig. 7 – **Bahia Bustamaznte. For the history, natural beauty and geological interest this locality is potentially eligible as a geological heritage.**

Preliminary results

In January 2009 one PhD student was obtained from the PhD school of the Earth Science department (I. Consoloni) and the student was able to participate to the first field trip. In April 2009 a second PhD student was obtained thanks to the support of the project in Argentina at the University of La Plata (G. Boretto). This student was not able to attain at the first field trip but his participation is foreseen next year. In collaboration with INGV of Pisa a trainee student was also activated for transport part of the collected data in a GIS (P. Della Lucia). The targets of the project concerning the education of student for the first year can be considered fully get.
Geological and geomorphological map was almost accomplished for two of the selected areas (Cabo Raso and Camarones Norte, e.g. see enclosures 1 as an example for details on Cabo Raso) and are in progress for the remaining part. Their final drafting is foreseen before the second field trip.
A significant amount of marine shells, accurately selected in the field are so far prepared for geochemical analyses. 190 samples of paleosoils, mollusk shells and sediment coming from several places of Golfo S. Jorge, between Cabo Raso and Bahia Solano, have been collected during the first field trip.

The preliminary study investigated 68 specimens of Upper Pleistocene, Holocene and modern Bivalve shells coming from Cabo Raso, Bahia San Sebastian and Camarones North (Fig 1).
Specimens of *Protothaca antiqua* (King, 1832) and specimens of Mytilidae Family (e.g. *Mytilus edulis, Aulacomya atra, Brachidontes* spp.), which represent the dominant molluscan species in these deposits, were chosen for the analyses (fig 10).

Fig. 10 - **Specimens of *Protothaca antiqua* (King, 1832) perfectly cleaned and ready to be powdered.**

Fig. 11 – ***Protothaca antiqua* articulated shells in the deposit near Camarones (ca 200 ka)**

In order to decrease the possibility that shells had been reworked from older beds, articulated shells had been preferred for the analyses (fig. 11). One to six whole and well preserved shells were analysed for each layer. The shells were rinsed several times with deionised water and cleaned in an ultrasonic bath. If some part of shells was still dirty, it was cleaned manually with a dental drill. Shells were then dried in an oven at 60°C. Each valve of *Protothaca antiqua* was halved along the axis of maximum growth using a saw and then a half valve was powdered, whereas for specimens belonging to the Mytilidae Family a whole valve was powdered.

These samples were used for bulk carbonate stable isotopic analyses ($\delta^{18}O$ and $\delta^{13}C$). The samples will be analyses (and some data are already available) at IGG-CNR of Pisa using a DeltaXP mass spectrometer equipped with a separate acid injector system, after reaction with 105% H_3PO_4 under He atmosphere at 70°C. Isotopic results have been reported using the conventional δ‰ notation. The $\delta^{18}O$ and $\delta^{13}C$ have been reported relative to V-PDB.

Aragonite, forming the shell of these Bivalves, is the least-stable calcium carbonate phase at the Earth's surface and is diagenetically transformed into low-Mg calcite. For this reason several shell mineralogical analyses determined by qualitative X-Ray Diffraction (XRD) of random samples have been carried out to indicate whether diagenetic mineral transformation had occurred.

Plasma mass spectrometry (ICP-MS laboratory at Earth Science Department of Pisa) was used for high precision trace element measurements. 5 carbonate powder samples for radiometric dating (^{14}C) were taken from Holocene and modern shells coming from Cabo Raso and Camarones North for improving the stratigraphy of Holocene beach-ridges successions.

A small chunk of solid and pristine shell material were extracted from a *Protothaca antiqua* specimen coming from an already dated outcrop (Schellmann, 1998) in order to apply the α-spectrometric $^{230}Th/^{234}U$ dating method.

Large part of the data are foreseen for September as well as trace elements and strontium isotopes.

Stable isotopes data collected in the literature and preliminarily obtained within the project allow to highlight two important points:

1) The selected area is dominated by pure marine influence and then particularly suited for studying the variability of sea water conditions during time; whereas the Bonaerense region (located at north of the study area) is under the influence of local river inflow, so more prone to record the hydrological changes over the land (Aguirre et al., 2003; Fig. 11)

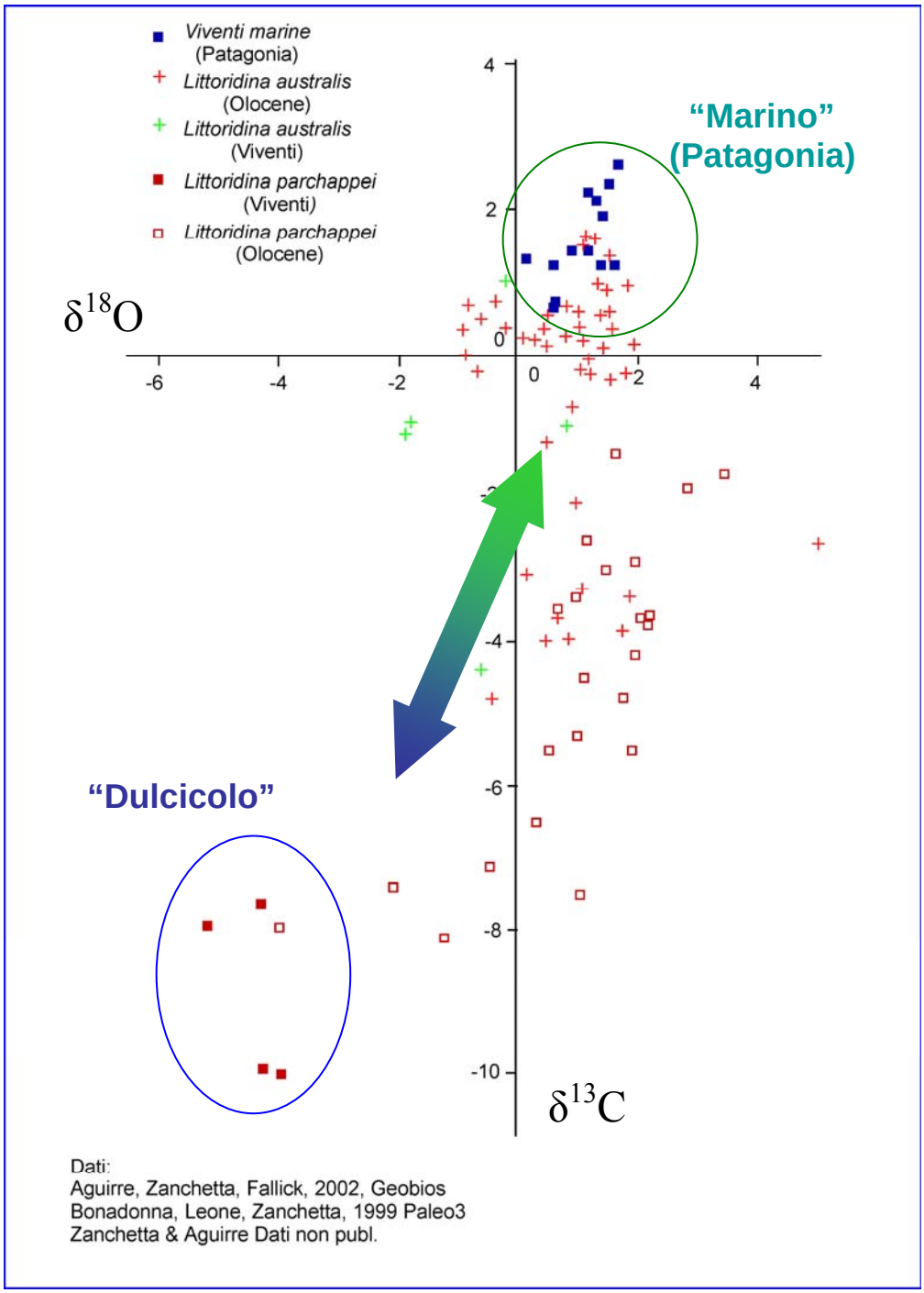

Fig. 12 – **Selected data from literature and produced within the project. The isotopic values comprised between the freshwater data (dulcicolo in the figure) and in the "Marino Patagonia" are the isotopic values resulting from mixing of freshwater and marine waters in the Bonaerense area.**

2) very preliminary results have indicated that, as expected, the selected deposits can be investigated using geochemical proxies and that these proxies seems to indicate (Fig. 12)

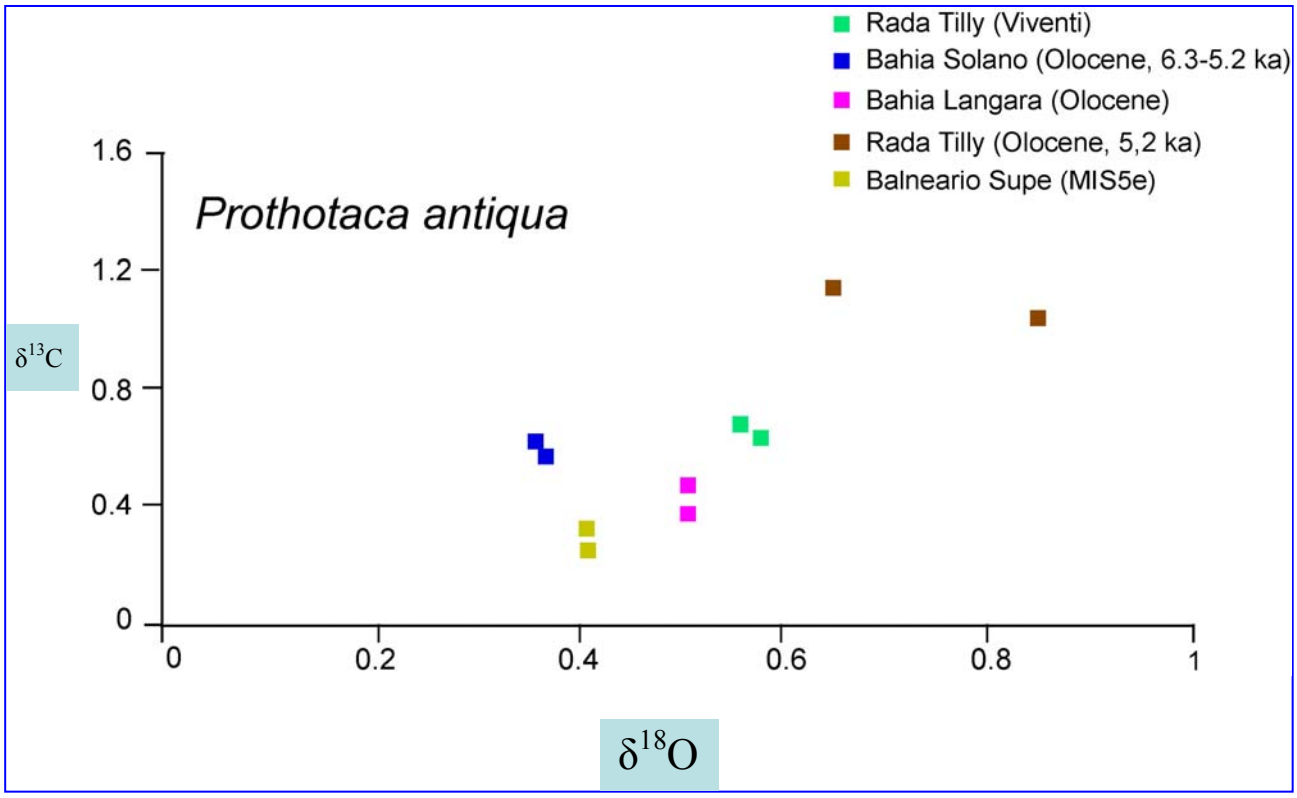

Fig. 13 – **Stable isotope composition of marine shells of Prothotaca antiqua**

These very preliminary data suggest a significant gradient in terms of salinity/temperature during the past and particularly seem to suggest lower salinity and/or higher T during the MIS5e compared to the Holocene and the current conditions.

Project milestones

The project is following its marching list and the main targets of the project for the first year seems to be achieved. They can be summarised:

- educational targets have been obtained with two PhD students now involved within the project;
- The first field work campaign was very positive and a significant number of samples were collected;
- Laboratory analyses are mostly in progress but a significant number of data are scheduled for the end of this summer;
- Preliminary geochemical data seems to confirm the potentiality of the selected natural archives for disentangling the oceanographic and paleoclimatic evolution of Patagonian coast (this was not obvious);
- An area of particular interest have been selected for specifically addressing a preliminary project for selecting it as geosite;
- The second year will be devoted to refining of the data collected during the first campaign and complete the analyses on the samples.
- The second campaign is scheduled for February 2009 and its organization is just started.

Scientific publication

The proposed project was concerned on a new areas to be studied, therefore, the most significant publication can be reasonably foreseen during the second year of the activity and at the end of the of

the two PhD. However, the preliminary results have been (and will be) the subject of scientific communication to national/international congresses. Additional two/three manuscript are now in progress.

Congress abstracts

M.L. Aguirre, G. Zanchetta, G. Boretto, I. Consoloni, L. Dallai, M. D'Orazio, E. Fucks, G. Leone, I. Isola, F. Mazzarini, M. Pappalardo, A. Ribolini, S. Richiano, R. Santacroce 2009. THE PATAGONIAN RAISED BEACH-RIDGES: AN ALMOST UNEXPLORED ARCHIVE FOR SOUTHER HEMISPHERE PALEOCLIMATE. PRELIMINARY RESULTS. La Variabilità del clima nel Quaternario, Roma, 18-20 febbraio 2009. p. 143, oral presentation.

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Ribolini A. M.L. Aguirre, G. Zanchetta, G. Boretto, I. Consoloni, L. Dallai, M. D'Orazio, E. Fucks, G. Leone, I. Isola, F. Mazzarini, A. Ribolini, S. Richiano, R.,:, Cabo Raso (Gulf San Jorge, Patagonia, Argentina), from the work of Feruglio to present day: a strategic area for understanding the evolution of the coastal Patagonia during the Late Quaternary. Geografia Fisica e Dinamica del Quaternario, in progress.

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ENCLOSURE 1 – Details on Cabo Raso Bay

The bay of Cabo Raso (Caleta Cabo Raso in the following) was one of the site to be visited in the first field survey of the project. Instead of this area was among the first studied in the systematic analysis of Patagonian coast (Feruglio, 1950), it was excluded by the following modern investigations. This is surprising because the first observations report of several geomorphological and palaeontological elements, potentially useful for the paleoenvironmental evolution of the Patagonian coast during Pleistocene and Holocene.

Punta Pescadero to the North and the cape of Cabo Raso to the South delimit the Caleta Cabo Raso, which is extended for a total length of about 6 km. Jurassic riolitic and ignimbritic rocks (Marifil Complex) constitute the bedrock.

The preliminary remote sensing survey suggested the presence of some beach ridges, locally spaced by depressions of variable dimensions.

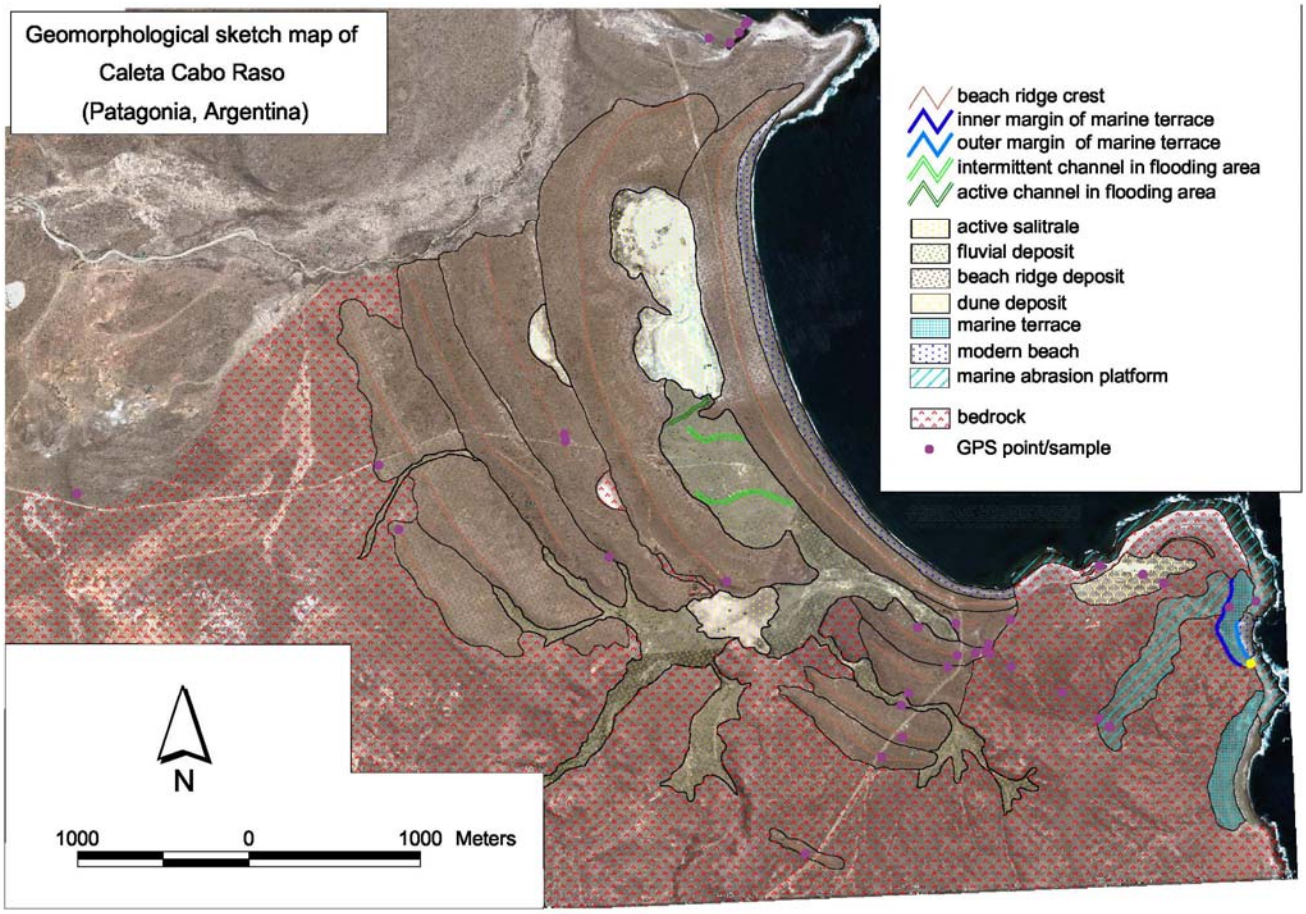
The existence of several beach ridges cross cut (or dissected) by channel prompted this area as potentially interesting to reconstruct the Pleistocene/Holocene coastal dynamic associating landforms and their stratigraphic composition.

In the field, a suite of 6 beach ridges was individuated (mapped) that from the first Holocenic facing the sea (10-12 m asl) extend up to most internal (45-47 m asl) about 2 km from the coast. In overall, the beach ridges are more preserved in the northern sector of the bay, where also the oldest landforms show a lateral continuity. On the contrary, in the southern sector, the oldest beach ridges are discontinuously preserved, and the most internal is made up only by a single small deposit in the proximity of the road from Cabo Raso to Camarones. The south and north sectors are separated by a large fluvial talweg alimenting episodic floods, that could invade the intra-ridge depressions leading to the formation of salitrales.

Each of the beach ridges was inspected in the field to characterize the deposits and the fossiliferous contents, describing and sampling natural section when present or, alternatively, the surface of the landforms.

The area of Cabo Raso quarry ("cantera") -a few hundreds metres south of the village- was particularly useful to inspect the internal structure of Holocenic beach ridges, as well as their relation with continental deposits, i.e. slope debris. Several samples were collected, both of molluscs and of sandy layers for OSL datings.
The rock dorsal the delimits to the south the bay and terminates in the cape Cabo Raso is shaped by a marine abrasion platform, that since the elevation of the lighthouse (42 m asl) extends downward up the cost. Here, it is interrupted by a more recent marine terrace whose inner margin is at 8 m asl. Cobbles in sandy matrix constitute the deposit covering this terrace. A well evident outer margin (3 m asl) marks the passage to the modern sandy- gravel beach.
In the area of the cape, a dune system partly vegetated was mapped, as well as recent beach ridges alimented by the oceanic storms upwashing the active marine abrasion platform.

Schematic geological-geomorphological map of Cabo Rasa obtained within the project



ENCLOSURE 2 – Details on Camarones North

In the study area four orders of raised beach ridges were recognised (B, C+D, E and F) from present-day coastline inland, see fig. 1e2). The B order ridge is rather continuous and its morphology is fairly well preserved. It is about 100 m wide, its crest is parallel to the shoreline and reaches an elevation of about 10 m a.s.l.); its flanks are moderately steep. Seaward it is overlapped by active littoral deposits and landward it is sealed by the marine and evaporitic deposits filling in the backing swale (locally called "salitral"). The C+D order is represented by a double crested ridge, 400 m wide and 15 m high. Longitudinally interrupted by floodplain and outwash deposits, it is totally missing in the central part of the coastline, where the "salitral" fill overlaps the seaward slope of the E order ridge. This order is represented by patches of the original sedimentary body separated from one another by floodplain and outwash deposits. The crest is very smooth and reaches an elevation of 25 m. Its current morphology is probably very different from the original one, being its slopes dissected by a thick network of concave-bottomed gullies normal to the ridge crest. A fourth ridge order can be inferred by the presence of a marine deposit rich in *Protothacha* shells visible in a road cut (WP 69) and displaying a thick pedogenic calcified horizon. The outcrop is at an elevation of 13 m a.s.l., but scattered patches of a deposit that can be virtually interconnected to form a deeply dissected ridge can be found all over the area behind ridge E at elevation up to 30 m a.s.l.

Continental deposits interpreted as dissected floodplain sediments formed in ancient aggradation phases can be observed in the south-western part of the study area, between the C+D and E ridges and bordering the NE edge of these ridge patches.

Streams are ephemeral in the study area, due the very low average yearly rainfall. Their network, though, is well recognisable both in the field and from remote sensing analysis. Three main stream types can be differentiated: wandering streams, incised streams and entrenched meandering streams. They should be temptatively related to different phases of relief evolution. Numerous and different erosional and depositional landforms due to past and present intermittent stream activity were mapped. At the western edge of the study area outwash and stream erosion affected the toe of a wide pediment. A bedrock bulge was mapped in the NW part of the area, displaying an *hammada* like erosional and weathering forms.

Temptatively and on a preliminary basis each couplet formed by a ridge order and the continental deposits associated to it can be related to sediment deposition and landform shaping occurred in a single interglacial-glacial cycle. Aggradation and formation of floodplain deposits should have taken place in cold-climate conditions. During the interglacials transgression should have been followed by regression in warm climate conditions, mainly due to regional isostatic uplift. During the uplift a ridge should have formed at the shoreline; simultaneously the inland landforms should have been raised and dissected down to base-level.

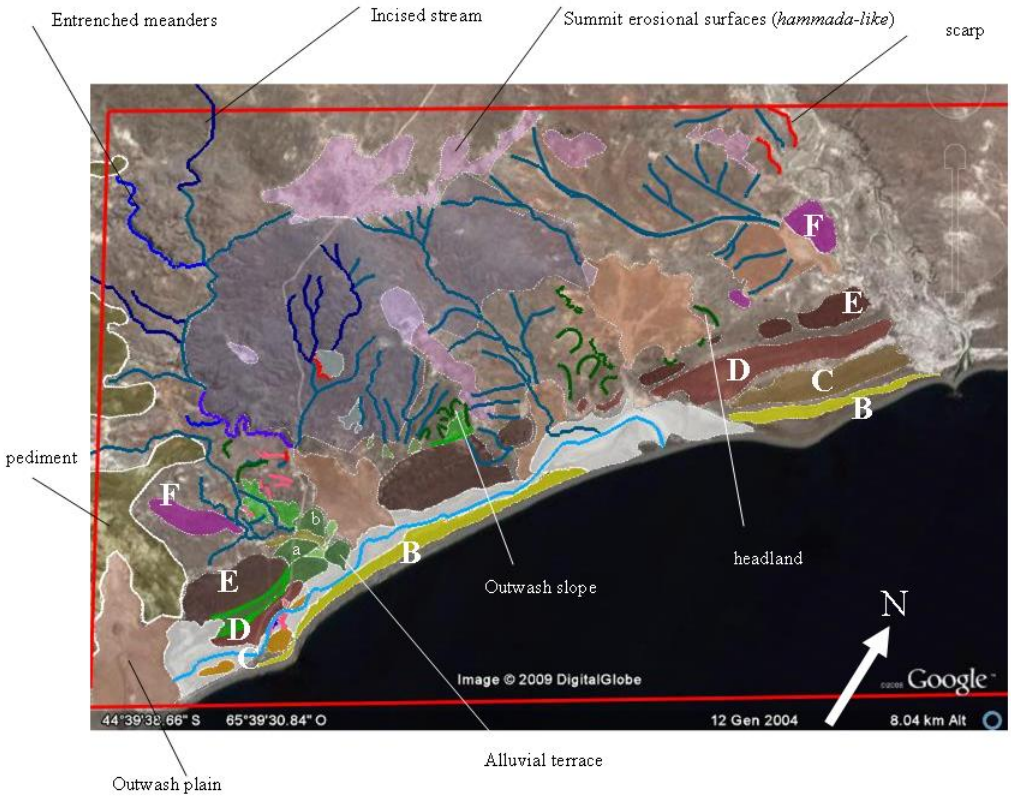


Fig. 1e2 – Schematic geological and geomorphological map of Camarones North.