APAT

Agenzia per la protezione dell'ambiente e per i servizi tecnici

SERVIZIO GEOLOGICO D'ITALIA

Organo Cartografico dello Stato (legge n. 68 del 2. 2. 1960)

DIPARTIMENTO DIFESA DEL SUOLO

MEMORIE

DESCRITTIVE DELLA

CARTA GEOLOGICA D'ITALIA

VOLUME LXXXIII

Areas of the Lagoon of Venice on the Official Geological Map of Italy:

Sheet 128 *"Venezia"*, Sheets 148-149 *"Chioggia-Malamocco"*

Le aree di laguna nella Carta Geologica Ufficiale d'Italia:

Foglio 128 "Venezia", Fogli 148-149 "Chioggia-Malamocco"

Editor

REGIONE VENETO

DIREZIONE GEOLOGIA ED ATTIVITÀ ESTRATTIVE

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SYSTEMCART - Roma - 2008

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PREFACE

On occasion of the 33rd International Geological Congress (Oslo, 2008) the Italian Geological Service requested the Veneto Region, in its quality as one of the parties to the CARG Project, to present a special monograph, the Official Geological Sheets, no. 128 for Venice and nos. 148-149 for Chioggia-Malamocco, recently published.
I particularly appreciated the kindness of the staff members of the Veneto Region who accepted this request and made possible the publication of this volume in the series Memorie Descrittive della Carta Geologica d'Italia.
This work presents the Official Geological Map, scale 1:50.000, of the CARG Project covering two particular lagoonal areas of Italy, already famous on an international level (maps attached to the volume in the version with legends in English).
Special thanks go to Dr. Toffoletto and Dr. Campana who, on behalf of the Veneto Region, worked so hard on the preparation of this volume, and to the authors and others who revised and edited it. They are all aware that it is not only an efficient instrument of geological knowledge, but also supportive material for all those who are interested in the problems of protection, safeguarding and planning of the "territory" covered by these unique areas – half-water, half-land.
I sincerely hope that this volume may represent a first approach to future and further scientific knowledge of areas subjected to specific protection, as described here.

N. Accardi

CONTENTS

SHEET 128 VENEZIA

I - INTRODUCTION

In this volume, chapter II (GEOLOGICAL SETTING AND HISTORICAL OUTLINE.) and III (INTEGRATED METHOD OF SURVEYS AND ANALYSIS) have been partly condensed from the respective chapters 2 and 3 of the original work in Italian, written by Tosi[(1)], Rizzetto[(1)], Bonardi[(1)], Donnici[(1)], Serandrei-Barbero[(1)] and Toffoletto[(2)], for the illustrative notes to Geological Sheets 128 Venezia and 148-149 Chioggia-Malamocco (2007a, 2007b). The remaining part of this work is the translation of the corresponding chapters of the original publications.

The Veneto Region is responsible for the entire translation.

We would like to thank Adriano Zanferrari, University of Udine, for having edited and translated section II-1.1 (PRE-QUATERNARY EVOLUTION), of which he is the author.

Sheet 128 "Venezia" and Sheets 148-149 "Chioggia–Malamocco" of the Geological Map of Italy, scale 1:50.000, were prepared within the CARG Project, thanks to an agreement between the Italian Geological Service (*Dipartimento Difesa del Suolo dell'Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici)* and the Veneto Region.

The Veneto Region entrusted scientific coordination to the Italian Research Council (*Istituto di Scienze Marine - ISMAR)* of Venice.

The following persons participated in the CARG project:

- For the Veneto Region: Roberto Casarin, regional secretary of the *Segreteria all'Ambiente e Territorio*; Andrea Costantini, regional director of the *Direzione Geologia e Attività Estrattive*; Federico Toffoletto, of the Regional Geological Service, responsible for the project, assisted by Anna Galuppo, geologist, and by Riccardo Campana, responsible for databases;
- For CNR-ISMAR, Italian Research Council: Luigi Tosi and Maurizio Bonardi, scientific committee; Rossana Serandrei Barbero and Sandra Donnici, micropalaeontology; Federica Rizzetto, geomorphology and sedimentology.
- For collection of data and further in-depth accumulation of material on other topics, special agreements were stipulated with: the Province of Venice, for aspects regarding hydrogeology, prepared by Andrea Vitturi, director of the *Settore Protezione Civile e Difesa del Suolo, Servizio Geologico*; the National Institute of Oceanography and Experimental Geophysics, Trieste, for seismic studies, carried out by Giuliano Brancolini, director of the Department of Geophysics of the Lithosphere; the Department of Geography, University of Padova, for the geomorphological framework on a regional scale, prepared by Mirco Meneghel and Aldino Bondesan; the Department of Hydraulic, Maritime, Environmental and Geotechnical Engineering, University of Padova, for geotechnical aspects, prepared by Paolo Previatello, assisted by Marco Favaretti; the Department of Geology Palaeontology and Geophysics, University of Padova, for seismological analysis, carried out by Vittorio Iliceto; and the Venice Water Authority, director Maria Giovanna Piva.

Remo Bertoldi and Giuseppe Canali, Department of Evolutionary and Functional Biology, University of Parma, collaborated on palynological studies.

Adriano Zanferrari, Department of Geore-

[(1)]CNR-ISMAR, Venice
[(2)]Geological Service, Veneto Region

sources and Territory, University of Udine, carried out analysis of structural lineaments.

Lastly, fruitful suggestions and ideas came from: Giovanni Battista Castiglioni, University of Padova; Fabrizio Galluzzo, director of APAT (Italian Environmental Protection and Technical Services Agency), with his collaborators Maria Teresa Lettieri, Roberto Graciotti, Marco Pantaloni, Silvana d'Angelo, Maria Letizia Pampaloni, Felicia Papasodaro, Roberta Carta, Edi Chiarini and Andrea Fiorentino.

Thanks also go to Domenico Tacchia, of the APAT Mapping Unit, for cartographic coordination of the sheets, and his collaborators Vinicio Pannuti, who carried out cartographic editing, and Maria Luisa Vatovec, who prepared this volume for printing.

The sheets "Venezia" and "Chioggia–Malamocco", located in the eastern Veneto (Fig. 1), mainly fall within the Province of Venice. They represent the first important in-depth study of our basic geological knowledge of an area which is so sensitive from the viewpoints of the environment, the landscape, and Italy's cultural heritage, in which phenomena of subsidence, saltwater intrusion and pollution have been accentuated by man's activities. These have all led to the pressing need for more, and more detailed, information on the subsoil, in an attempt to combat further deterioration of the natural environment and to maintain its integrity.

Fig. 1 - *Location of the Sheet 128* Venezia *(upper right) and 148-149* Chioggia-Malamocco *(lower left).*

II - GEOLOGICAL SETTING AND HISTORICAL OUTLINE

Due to the environmental and historical importance of the Lagoon of Venice and the city of Venice itself, numerous studies have been conducted in the past, with the aim of establishing the geological setting of the area (ZANETTIN 1955). To avoid a long list of references, the most important works are cited appropriately in the following sections. In particular, due to the precarious nature of the Venetian soil, notoriously associated with subsidence and soil compaction, several geotechnical, hydrogeological and altimetric surveys have been carried out.

Initial stimuli towards basic studies occurred in the 1970s, as a result of the disastrous flood of 1966.

The drilling of the *Venezia 1 – CNR* boreholes was essential for more information on the geology of the area, and was carried out by the continous boring method to a depth of 947 m. The *Venezia 2 – CNR, Lido 1* and *Marghera 1* boreholes, which reached depths of 400, 1,333 and 602 m respectively, produced several undisturbed samples.

Knowledge on the deepest subsoil until the Mesozoic was acquired in adjacent areas with the drilling of exploration boreholes in the search for hydrocarbons (*Assunta 1* (4,747 m), *Jesolo 1* (1,804 m), *Eraclea 1* (2,502 m), *S. Donà di Piave 1* (3,081 m) and *S. Angelo 1* (2,036 m)). A series of seismic surveys was also carried out by AGIP (national hydrocarbon company).

Also in the 1970s, the Committee for the Study of Defence Measures of the City of Venice (CSP-DV) created several multidisciplinary surveys, which yielded an initial complete framework of the geology of the Venice area.

Several researches covered both the deep subsoil and surface sediments, leading to the detailed descriptions of the Holocene evolution of the area. It should be noted that, as they act as bases for the creation of the Geological Map of Holocene and Late Pleistocene deposits, studies in the 1970s and 1980s provided an initial large-scale description of the geological evolution of the surface cover (GATTO & PREVIATELLO, 1974; ALBEROTANZA *et alii*, 1977; BORTOLAMI *et alii*, 1977; FAVERO & SERANDREI-BARBERO, 1978, 1980, 1983; GATTO & CARBOGNIN, 1981; BORTOLAMI *et alii*, 1984; GATTO, 1984).

In the 1980s and 1990s, a series of targeted, "strategic" projects was started by the ITALIAN RESEARCH COUNCIL (CNR), updating geological knowledge acquired during the previous twenty years.

1. - GEOLOGICAL EVOLUTION AND STRUCTURAL FRAMEWORK

1.1. - PRE-QUATERNARY EVOLUTION

The Venice area lies in the centre of the Neogene-Quaternary foreland, which is shared between the NE-verging northern Apennine thrust belt and the S-verging eastern Southalpine chain (Fig. 2). In a wider regional framework, this foreland is situated at the north-eastern edge of the Adriatic microplate, and a long succession of sedimentary, magmatic and tectonic events are also recorded in the subsurface of the area surrounding Venice and offshore. These events have been brought to light not only by hydrocarbon research surveys and geophysical surveys carried out by AGIP in the second half of the 20th century, but also by the more recent work by the Transalp and CROP-mare Projects.

The oldest records go back to the Palaeozoic and Triassic, and information comes from the stratigraphic log of the *Assunta 1* borehole, integrated with aeromagnetic survey data (CASSANO *et alii*, 1986). Granite (448±18 Ma) found at a depth of 4,711 m, locates the plate boundary between two Palaeozoic microplates (Carnic-Dinaric and

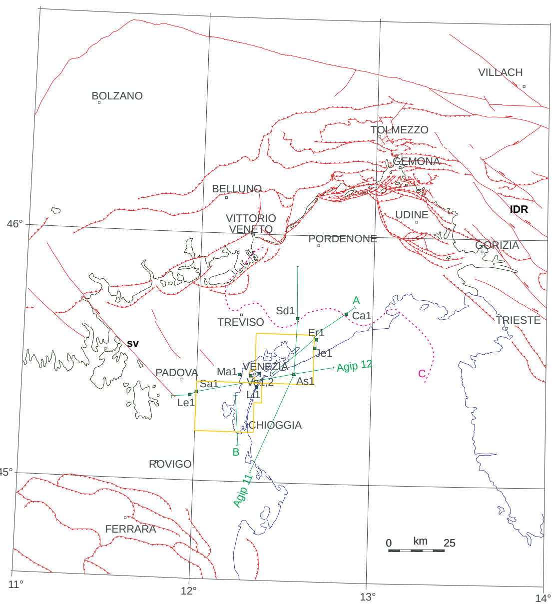

Fig. 2 – *Area of Venezia and Chioggia-Malamocco Sheets in Neogene-Quaternary tectonic framework, characterised by oblique convergence between northern Apennine and eastern Southalpine thrust belts. The latter is kinematically released westwards by Schio-Vicenza fault system (SV) and eastwards by Idrija fault system (IDR). AGIP boreholes: Le1-Legnaro, Sa1-S. Angelo di Piove di Sacco, As1-Assunta, Je1-Jesolo, Er1-Eraclea, Sd1-S. Donà, Ca1-Cavanella, Ce1-Cesarolo, Li1-Lido, Ma1-Marghera; CNR boreholes: Ve1, Ve2-Venice; reflection seismic cross-sections: A, B; geological cross-sections: AGIP 11, 12; dotted line C: buried margin of Friulian Carbonate Platform versus Belluno Basin, situated westwards. Active - and seismogenic - tectonic systems surrounding Venice area are (clockwise): front of eastern Southalpine chain (from Schio-Vicenza fault to Idrija system), dextral strike-slip fault system of Idrija (western Slovenia), part of front of northern Apennine chain (Ferrara), Schio-Vicenza system (west of Padova).*

Austroalpine-Southalpine) between the granite itself and the Variscan metamorphic core of Recoaro. This plate boundary extends NE-SW from Venice to Forni Avoltri (western Carnic Alps). The deeply dismantled structural high of *Assunta 1* (Fig.3), which is characterised by Carnian successions overlapping the plutonic body, suggests that this area was one of the sources of clasts for the Permo-Triassic terrigenous units which now outcrop in the Recoaro Pre-Alpine area.

An aeromagnetic survey also identified a thick body of Ladinian volcanites (Fig. 3), found in other deep boreholes in the Veneto-Friuli plain and related offshore environs. Rhyolite, dacite and andesite with intercalated minor volcanoclastics and terrigenous deposits of Early Permian age were also found in the *Legnaro 1* borehole (Fig. 2). These volcanites represent one of the effects of the intensive extensional and strike-slip tectonics which developed in the Southalpine realm during the Permo-Mesozoic.

The depositional architecture and framework of the overlying crust, from the Norian "Dolomia Principale", which testifies to relative tectonic stasis, to the Quaternary units, are clearly reconstructed by the network of industrial seismic lines covering the Veneto plain and the northern Adriatic Sea, calibrated with many boreholes.

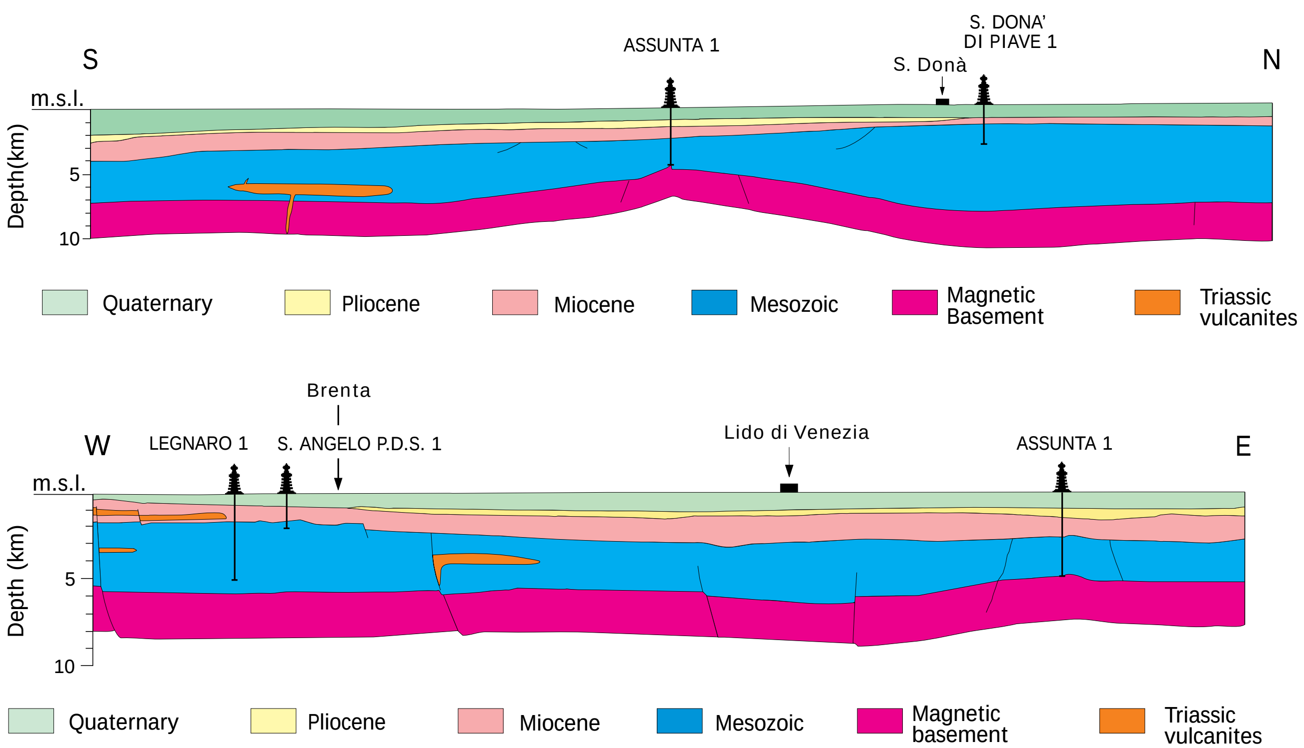

Fig. 3 – *Geological cross-sections (from Cassano et* et alii, *1986, modified), showing structural high reached by Assunta 1 borehole and Pliocene-Quaternary crustal flexure towards northern Apennine chain (AGIP 11, 12 in Fig. 2).*

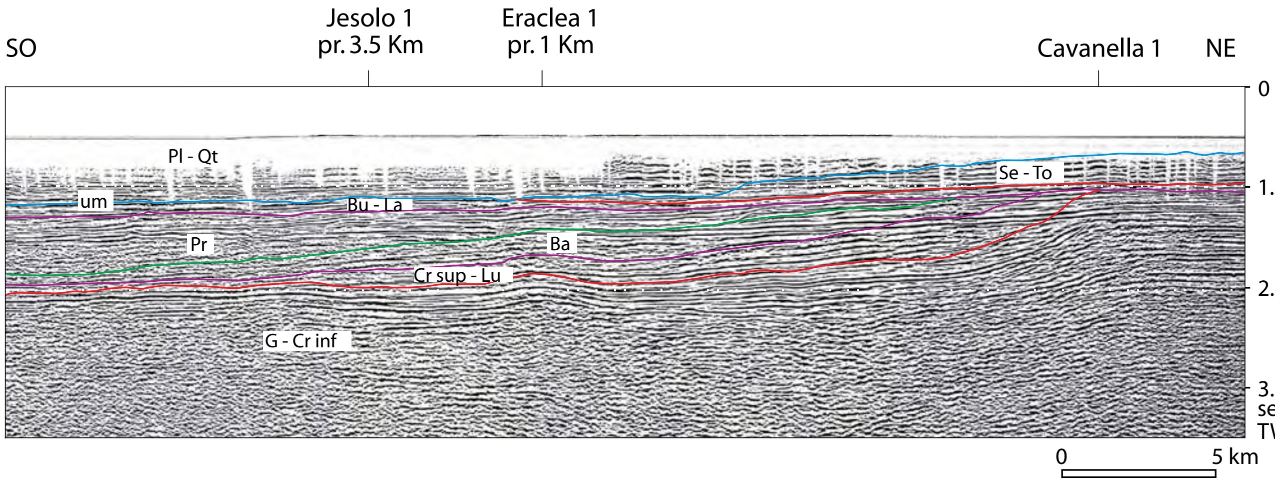

Fig. 4 – *Seismic reflection cross-sections (A in Fig. 2, from* Fantoni et alii*, 2002, modified), showing relationships between western margin of FCP and Belluno Basin, depositional geometries on the slope, filling of basin first by hemipelagic successions of Late Cretaceous-Lutetian (Cr sup-Lu: Scaglia Rossa, interfingered with resedimented bodies from FCP) and Bartonian (Ba: the Scaglia cinerea), then by distal turbidites (Jesolo Flysch), and lastly by deltaic mudstones (Possagno Marl) of Priabonian age (Pr). "Gruppo di Cavanella" platforms (here Burdigalian-Langhian: Bu-La) prograded on both Eocene successions and eroded top of FCP. Shape of Messinian erosional surface (um) highlights deep fluvial valleys linked to fall in sea level of Mediterranean during Messinian; palaeotopography was then sealed by terrigenous deposits of Pliocene and Pleistocene age (Pl-Qu).*

Throughout the Jurassic and Cretaceous, the palaeogeographic setting is represented by the system of the Belluno Basin-Friulian Carbonate Platform (FPC), starting from the Early Jurassic in an extensional and strike-slip framework linked to the opening of the Alpine Tethys.

The surface projection of the margin of the FCP, which was repeatedly involved by progradations and retrogradations (Cati *et alii*, 1989), is shown in Fig. 2, and is clearly defined by a series of exploration boreholes. Its typical stepped pattern shows the arrangement of the Belluno Basin-FCP system in a tectonic framework, dominated by extensional faults running NW-SE, segmented by NE-SW strike-slip or transtensive faults.

According to Picotti *et alii* (2002), the FCP developed from the Early Jurassic on less subsident blocks (mean subsidence rate: 0.05 mm/y), with marginal drowning at the Early-Middle Jurassic boundary; this fact produces undersupply of the basin, which then achieved its first maximum depth. A second subsidence peak occurred between the Late Oxfordian and the Early Kimmeridgian (0.25 mm/y), and caused rapid aggradation - almost 1 km - of the FCP and strong undersupply of the Belluno Basin, which reached a palaeobathymetry of approximately 1,400 m (Fantoni *et alii*, 2002). During the latest Jurassic-earliest Cretaceous, the speed of subsidence decreased again, to 0.02 mm/y, with a sedimentation rate of 0.01 mm/y. This evolution, which continued into the Late Cretaceous, produced an overall thickness of approximately 4 km of Jurassic-Cretaceous carbonates in the FCP. In the Belluno Basin, and therefore in the subsurface of the Venice area, a palaeobathymetry of over 1,200 m was reached at the end of the Cretaceous, and was subsequently annulled by Palaeogene deposits (Fig. 4).

During the Dinaric event (Late Cretaceous-Late Eocene), which built up the External Dinarides in Friuli and also in the central-eastern Dolomites (Doglioni & Bosellini, 1987; Poli, 1995; 1996; Poli & Zanferrari, 1995), the area of the present Veneto plain became the peripheral bulge of the WSW-verging thrust system of the Dinaric front. In the Venice subsurface, the effects of this event are recorded only in the form of palaeobathymetric and depositional variations, evident in the western sector of the FCP, which was extinguished by uplift. The effects of karst processes, which are visible in the Carnic Pre-Alps, and intense subaerial erosion throughout the Palaeogene, caused the uplift of the FCP. In time, erosion reached the Lower Cretaceous carbonates, as shown by the logs of the *S. Donà di Piave 1* and *Cesarolo 1* boreholes and taken those at the Pre-Alpine margin (*Nervesa 1, Arcade 1, Merlengo 1*; Fig. 2).

Instead, the space inherited by the Mesozoic subsidence in the Belluno Basin (Fig. 4) was filled during the Palaeocene and Eocene by deposits coming from N and NE: at first hemipelagic (Scaglia Rossa: Maastrichtian-Lutetian; Scaglia cinerea: Bartonian) and then by distal turbidites up to deltaic deposits (respectively Jesolo Flysch and Possagno Marl: Priabonian).

During the Oligocene, the subaerial erosion of the western sector of the old Mesozoic FCP continued. At the same time, in the area of the present Veneto plain, located NW of Venice, a depocenter with terrigenous, volcanic and volcano-

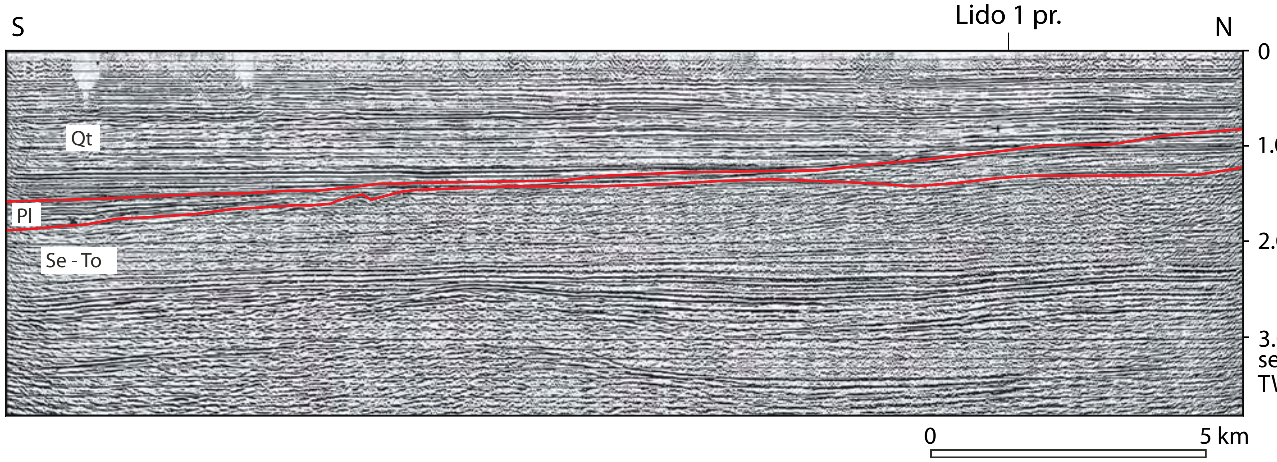

Fig. 5 – *Seismic reflection cross-section (B in Fig. 2; from* Fantoni et alii*, 2002, modified), showing southward progradation of Serravallian-Tortonian terrigenous platforms (Se-To) and complex shape of Messinian erosional surface, on which Pliocene terrigenous successions were deposited with onlap geometry southwards. Top of Pliocene platform carbonates were reached at bottom of Lido 1 borehole. Note Quaternary clastic wedge (Qt) and thickness of Pleistocene sediments, at times turbiditic, prograding on subsident ramp of Apennine foreland.*

clastic deposits formed (about 700-800 m thick) (*Legnaro 1, S. Angelo di Piove di Sacco 1* and *Villaverla 1*). The basin was bounded by NW-SE extensional faults: the NW-SE-striking *Schio-Vicenza* fault and its related system may have started in this extensional stage.

Between the latest Chattian and the Langhian, the area surrounding Venice was also involved by the Insubric event, like the whole subsurface of the present eastern Veneto and Friuli plain (Massari, 1990), which first became a peripheral bulge and later part of a foreland basin. A weak crustal flexure of less than 1° to the NNE (Fantoni *et alii*, 2002) was the response to the topographical load induced by remote uplift in the Eastern Alps. Uplift and erosion of Austroalpine nappes are testified by the composition of the arenite deposited in the foreland basin (Stefani, 1987). This basin gradually extends SSW, so that the system of thin terrigenous-carbonate platforms of the "Gruppo di Cavanella" (*sensu* AGIP) reached the present coastal area only in the Burdigalian (Fig. 4). Here, the old Oligocene topography was sealed by sediments with thicknesses of the order of tens of metres, as opposed to hundreds in the Veneto-Friuli hills.

From the Serravallian to the Messinian, rapid SE migration of the eastern Southalpine thrust belt (main Neoalpine tectonic phase) caused the formation of a trough, with its depocenter in the eastern Veneto and Friuli Pre-Alpine area. The clastic wedge, over 3 km thick in the Pre-Alps, rapidly becomes thinner towards the Adriatic coast (Fig. 4: 225 m in *Cavanella 1* borehole). The composition of the clasts, with the strong prevalence of carbonates, shows provenance from Southalpine areas (Stefani, 1987).

A very important event also for the Venice subsurface occurred in the Messinian, in response to the drop in sea level of the Mediterranean. The whole area reached continental conditions, with widespread erosional processes and the creation of new drainage basins. One of the largest and deepest palaeovalleys in the Venice area was the Messinian valley of the palaeo-Piave (Barbieri *et alii*, 2004), which eroded the Miocene deposits and reached the "Gruppo di Cavanella" (Fig. 4).

In the Lower Pliocene, the Messinian catchment area influenced marine ingression in the Venice area, with proximal marine deposits and then silty and sandy deltaic ones (*Jesolo 1* and *Eraclea 1*: Fig. 4). Starting from the Pliocene, the Venice area became part of the Apennine foreland, and small Pliocene carbonate platforms formed in this sector (*Lido 1* and *Assunta 1*: Fig. 5). At that time, in-

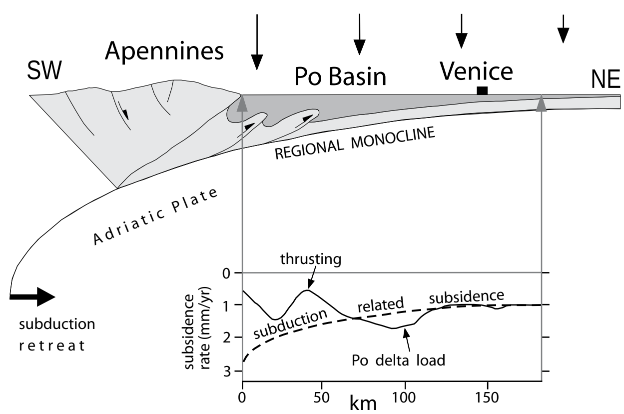

Fig. 6 – *Sketch of present northern Apennine thrust-belt - Po-Veneto plain foredeep system: Venice area is located on foreland ramp (from* Carminati et alii*, 2003). Insert: contribution to lagoon subsidence due to Apennine subduction, representing over half of total subsidence in Pleistocene.*

deed, and with even greater efficiency in the Quaternary, the Apennine thrust belt front migrated NE, causing flexure of the Veneto-Friuli crust (Fig. 6). Therefore, during the Lower Pliocene, a peripheral bulge in the Venice area formed, followed by rapid drowning and the establishment of epibathyal conditions in the Early Pleistocene. The subsidence caused by the tectonic load of the north Apennine thrust belt produced over half (at least 500 m) of the total subsidence recorded in the Venice area in the Pleistocene (Barbieri & Garcia-Castellanos, 2004).

The Schio-Vicenza fault, which borders the Veneto plain towards the Lessini-Berici-Euganei Hills and constitutes a very prominent physiographic element, was reactivated many times with varying kinematics linked to the stress fields that involved the area during the Cenozoic. In the Neogene, the fault was the release boundary between the eastern Southalpine chain and the less shortened Lessini region, acting as a pivotal fault with a throw that is annulled near the Venetian area. According to Pellegrini (1988), it was also active in the Late Pleistocene.

With regard to the Pliocene-Quaternary evolution of the north Apennine chain, the Schio-Vicenza fault separates the peripheral bulge of the Lessinian block from a foreland sector that also underwent the evolution of the Southalpine front: the latter partly contrasts the flexure of the Veneto foreland towards the SW, produced by the load of the north Apennine thrust belt.

Further tectonic features of regional importance have been hypothesised in the subsoil of the eastern Veneto plain by various authors (Zanferrari *et alii*, 1980a; Zanferrari *et alii*, 1980b; Slejko *et alii*, 1989; Carulli *et alii*, 1990; Castaldini).

1.2. - Quaternary Evolution

Due to the effect of foreland subduction under the Appennine front, the clastic wedge gradually thins to the NE in the direction of the northern portion of the Friuli plain, within which the actual South Alpine front is buried. Fig. 7a and 7b show both the NE migration of the onlap of flexured Pleistocene deposits on the flexured Pliocene substratum to the SE and the thinning-out of the same Pleistocene horizons to a wedge.

Biostratigraphic and chronostratigraphic knowledge of the deep deposits of the Venetian area were acquired until the 1970s by in-depth surveys (*Venice 1 - CNR,* 947 m, and *Venice 2 - CNR*, 400 m) undertaken by the Italian Research Council (Consiglio Nazionale delle Ricerche, 1971; Favero *et alii*, 1973; Serandrei-Barbero, 1975; Favero *et alii*, 1979; Favero & Passega, 1980; Bellet *et alii*, 1982; Müllenders *et alii*, 1996).

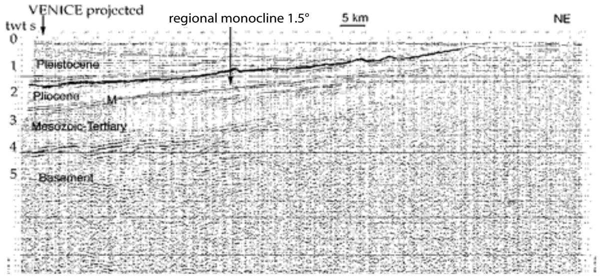

Fig. 7a – *Seismic reflection profile of Crop M-18, in northern Adriatic between Po Delta and Gulf of Trieste, where Pleistocene clastic wedge protrudes (from Carminati* et alii*, 2003). Pliocene/Pleistocene boundary and Messinian erosional surface are highlighted (M).*

Some exploration boreholes are included in the Chioggia-Malamocco Sheet (*Lido 1, S. Angelo di Piove di Sacco* 1*, Codevigo* 1*, Civè* 1), which yielded some information on Quaternary deposits. Conversely, the quoted in-depth surveys *Venice 1 - CNR* (947 m) and *Venice* 2 - *CNR* (400 m) provided extremely detailed information on Plio-Pleistocenic deposits, even those located in the historical city centre of Venice and slightly north of the northern limit of the Sheet.

The Pleistocene stratigraphic successions in the area of the two Sheets have recently been updated as part of the biostratigraphic and chronological profiles of Kent *et alii* (2002) and Massari *et alii*

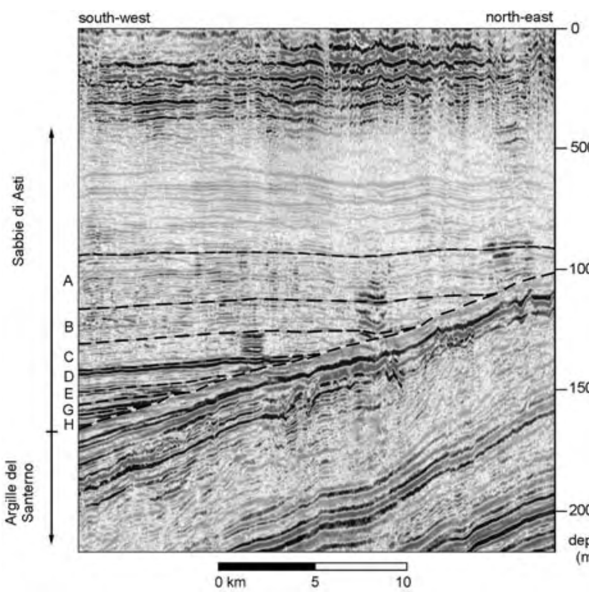

Fig. 7b – *NNE-SSW seismic section off Chioggia, showing setting of Plio-Pleistocene deposits of blue clay (Argille del Santerno) and Asti sands, separated by well-marked discontinuity (from Teatini* et alii*, 2000).*

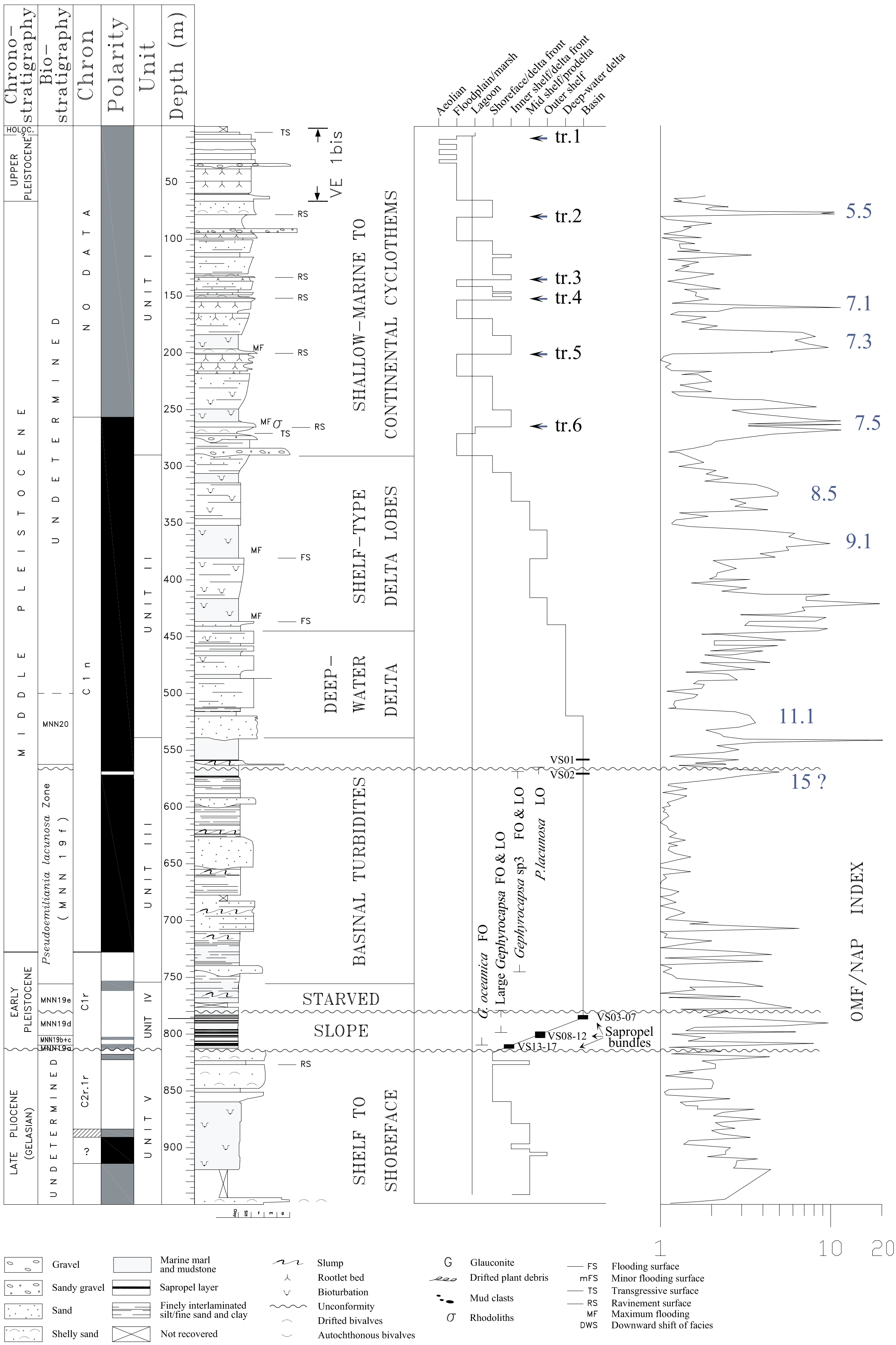

Fig. 8 - *Stratigraphy of Venice 1 – CNR and Venice 1b – CNR boreholes, drilled in historical centre of Venice (from* M*ASSARI* et alii*, 2004). Magnetic polarity analysis is from* K*ENT* et alii *(2002).*

(2004). These authors used biomagnetostratigraphy and stratigraphy of the sapropel, together with analysis of *facies* and *biofacies,* to prepare a detailed reconstruction of the evolution of the Venetian basin in the last 2.15 Ma, partly with the aim of correlating continental chronology with what is defined in the oceanic deposits in this marginal area (MASSARI *et alii*, 2004). This new survey of the Venetian stratigraphic sequence used different approaches - in particular, study of nannofossils, magnetostratigraphic setting of the succession, and comparison of stratigraphic records with astrochronological data.

The results of this research may be summarised as follows (Fig. 8):

(1) In the late Gelasian (late Pliocene), the area was a highly subsident shelf, whose depth was almost reduced to sea level;

(2) During the Lower Pleistocene, after a gap that lasted for at least 0.2 Ma and corresponded to most of the Olduvai Subchron, the shelf sank rapidly to bathyal depth (biozone from MNN 19a to MNN 19e: 1.947 to 0.96 Ma). This interval was characterised by greatly reduced sedimentation rates (less than 10 cm/Ky), represented by interstratified hemipelagic mud interbedded with sapropel layers;

(3) During most of the period of the MNN 19f biozone (zones with *Pseudoemiliania lacunosa*, 0.96-0.42 my), there was a thick layer of basin sludge as a result of considerable terrigenous contributions from the south-eastern Alpine sector;

(4) In the middle of Chron 1n (Brunhes), deltaic sedimentation, mainly linked to the progradation of the palaeo-Po system, caused progressive replenishment of the basin. This episode, which represents the most important construction stage, ended with the first disappearance of continental sediments, tentatively correlated with the marine oxygen isotope substage (MIS) 8.4;

(5) The upper part of the succession shows cyclic organisation, with an upward increase in marginal marine and continental deposits subjected to subaerial exposure. In this interval, the Venetian area was below sea level during the highstand glacio-eustatic tract, but emerged during the successive lowstand conditions.

Some of the stratigraphic layers identified by KENT *et alii* (2002) in the first 300 m of subsoil match the arrangement of acquifers/aquitards, whose development model was processed by analysis and interpretation of the stratigraphies of hundreds of boreholes and calibrations in the 1970s by study of the *Venice 1 - CNR* borehole. As these aquifers/aquitards have good lateral

Fig. 9 – *Map of depth contours (a.m.s.l.) of top of 2nd aquifer, which may correspond to tr.3 described by* KENT et alii *(2002).*

continuity, an attempt was made to extend knowledge of depositional events identified in the surrounding areas to this survey too (BRAMBATI *et alii*, 2003). One example is the map of the second aquifer, which may correspond to the tr.3 described by KENT *et alii* (2002) (Fig. 9).

During the Tyrrhenian transgression, the position of the coastline moved further from its current position, but did not reach the areas now occupied by the cities of Padova and Treviso, which therefore remained above sea level (FAVERO, 1987). As most of the knowledge concerning this event was obtained from wells drilled for water, data are scarce in terms of quantity and are not always of good quality. An historical survey, carried out in 1934 near Correzzola (Padova) deserves mention: a borehole was drilled to a depth of 185 m, and an accurate description of the microfauna and malacofauna found were reported by ACCORDI & SOCIN (1950).

Sources of information increase progressively towards the shallow sediments. In particular, many surveys and multidisciplinary studies conducted on data from hundreds of boreholes drilled for various purposes, with average thrusts of 25-30 m, have documented the depositional events of the last 30,000 years in detail.

Three main depositional stages are recorded in the last 30 m of sediments, which represent the environmental situations established in the Late Pleistocene and following Holocene, due to global changes in sea level: the deposits of the Lowstand Systems Tract (LST), Holocene Transgressive Systems Tract (TST) and Highstand Systems Tract (HST).

During the LST, related to the last glaciation (Last Glacial Maximum; LGM), the area in question appeared as a vast alluvial plain furrowed by watercourses, the palaeobeds of which, now buried, have been identified by high resolution seismic surveys (Stefanon, 1984; Mc Clennen *et alii*, 1997). In that period, as the sea level was approximately 110-120 metres lower than it is now (Mosetti & D'Ambrosi, 1966; Van Straaten, 1967; D'Ambrosi, 1969; Leonardi, 1970; Trincardi *et alii*, 1994; Correggiari *et alii*, 1996a; Correggiari *et alii*, 1996b), the coastline was located near the present-day city of Pescara and almost coincided with the edge of the Fossa del Pomo, where it met the deltaic apparatus of the palaeo-Po.

The main deposits of the LGM are those related to the flow of the rivers Piave, Brenta, Bacchiglione, Adige and Po, whose alluvial fans overlapped locally, creating overall sedimentary successions. The changing dynamics of the alluvial environment processes gave rise to energy gradients responsible for complex lateral-vertical organisations of facies. Therefore, channel deposits of flood plains and lake and marsh basins are currently found arranged in vertical layers or lateral heteropy.

As a consequence of the dry, glacial, and subsequently arid climate, a considerable lowering of the base level (Bortolami *et alii*, 1977) caused erosion and deepening of river beds.

The top deposits of this stage, dated to about 18,000 years BP, show clear signs of pedogenesis developing in conditions of prolonged sub-aerial exposure. A discontinuity surface, representing a stratigraphic gap with a time-frame varying between 7,000 and 13,000 years depending on area, separates these deposits from the overlying ones. This gap, which includes the Post-Glacial and part of the lower Holocene, mainly seems to be due to a lack of deposition and also to local erosion caused by intense fluvial dynamics (Gatto & Previatello, 1974). The latter was reinforced by an increase in river loads. Therefore, the boundary with the subsequent Holocene deposits is marked by a surface, sometimes eroded, at the top of a Pleistocene clay known locally as *caranto*, which is regarded by some writers as a palaeosoil subjected to overconsolidation due to subaerial exposure and the dry, cold climate.

The *caranto* has been studied and described in many works, including those by Matteotti(1962), Gatto & Previatello (1974), Gatto (1980; 1984), Tosi (1993; 1994a; 1994b;1994c), Bonardi & Tosi (1994a; 1995a; 1997; 1999; 2000b; 2000c; 2001), Bonardi *et alii* (1997), Brambati *et alii* (2003) and Mozzi *et alii* (2003).

The *caranto* varies in thickness from a few centimetres to 2 m and is generally composed of clayey silt or highly compacted silty clay. It is pale grey in colour, with ochre pressure marks, and contains carbonatic nodules a few millimetres in diameter. These levels generally accumulated between 20,000 and 18,000 years BP, although younger ages cannot be excluded as regards the upper limit. Bini *et alii* (2003) and Serandrei-Barbero *et alii* (2005b) dated small roots and peaty branches with the Accelerator Mass Spectrometry (AMS) technique, demonstrating the existence of a vegetal cover and occasional sedimentary flows in the Late Glacial and Holocene in the subsoil in the historical centre of Venice. These levels accumulated between 12,000 and 7,000 years BP. Dating of the overlying sediments indicates that the latter mainly belong to the medium-upper Holocene layer (Mozzi *et alii*, 2003). Recent studies place pedogenesis and overconsolidation within the stage corresponding to the stratigraphic gap or the reduced sedimentary flow that occurred between 14,500 years BP and the beginning of the Holocene transgression.

The *caranto* represents an excellent guideline level to identify the boundary between the Pleistocene and Holocene deposits, mainly in the marine and eastern lagoon sectors, where it is macroscopically evident, thanks to the differing sedimentological properties of the upper and lower deposits. Instead, towards the margin of the central lagoon and towards the hinterland, identification may require more exhaustive examination, particularly in cases of contact with continental environments.

Unfortunately - despite its regional extent, not

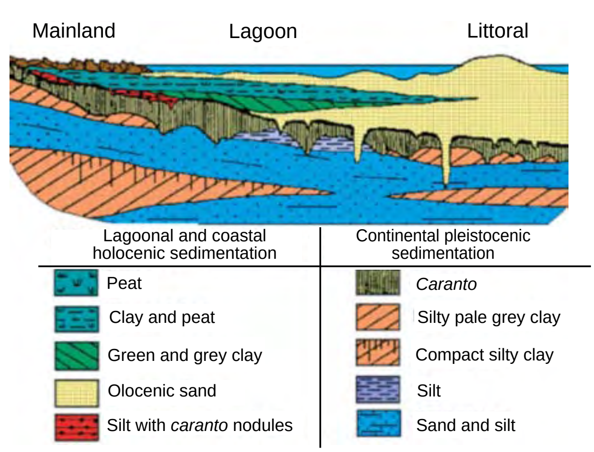

Fig. 10 – *Late Pleistocene and Holocene stratigraphic sequence of central part of Lagoon of Venice (after Gatto & Previatello, 1974).*

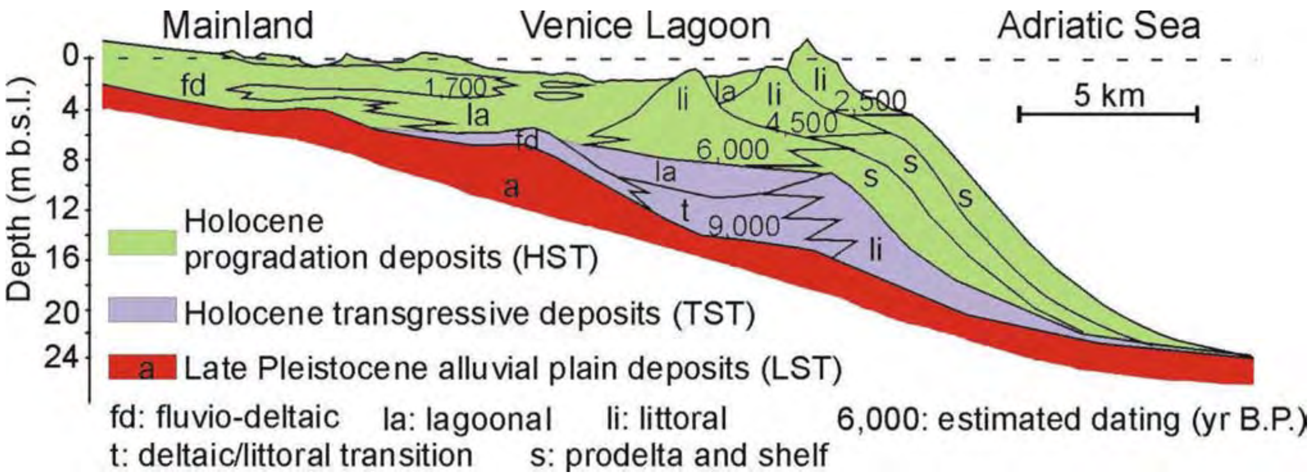

Fig. 11 – *Sketch of depositional systems in southern sector of Lagoon of Venice (from* BONARDI et alii*, 2006).*

only in the Adriatic area, but also in other coastal areas around the world - this overconsolidated layer shows more or less wide-ranging and localised lateral discontinuities. In heteropy with the silty-clayey level of *caranto*, there are facies made up of markedly clayey sediments originating from lakes and marshes that were not overconsolidated, due to their particular textural and depositional properties, and also from sandy deposits, probably from the fluvial ridge, which often show traces of pedogenesis and cementation. Some authors have recently adopted the definition of *caranto* to include non-overconsolidated coeval sediments.

Lastly, interfingerings with marine and lagoon deposits, indicating the presence of palaeo-river beds or replenished channels, which occasionally occur.

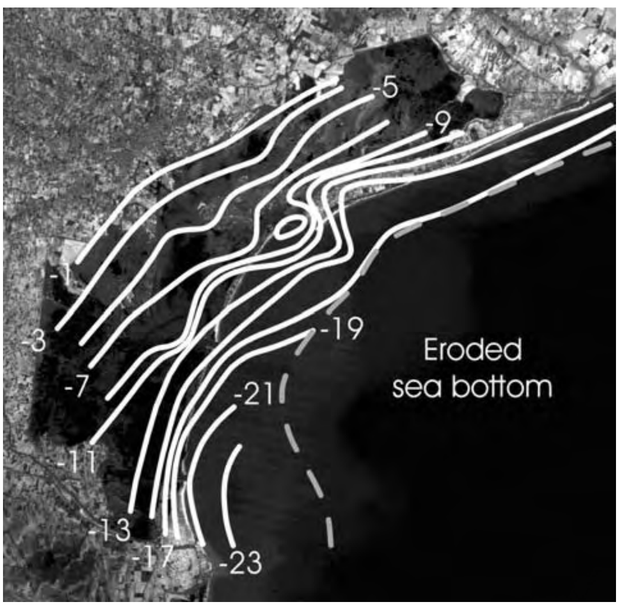

Fig. 11a – *Depth of Pleistocene-Holocene level (a.m.s.l.) on basis of data from boreholes and high resolution seismic analysis (from* BRAMBATI et alii*, 2003). This surface matches that of tr.1 of* KENT et alii *(2002), and shows marine area where Holocene deposits are not found or have been eroded.*

An initial reconstruction of the trend of the Pleistocene-Holocene surface boundary in the lagoon was proposed by GATTO & PREVIATELLO (1974) (Fig. 10).

Subsequent updates by GATTO (1984) and TOSI (1994c) have also identified and characterised this discontinuous surface in the coastal sector, emphasising the lateral variability and identifying two low areas, separated by a morphological high near the present-day Bocca di Lido. These studies have also defined an initial architectural model of the depositional systems from the mainland to 5 km offshore (BONARDI *et alii*, 2006) (Fig. 11).

BRAMBATI *et alii* (2003) recently created a model of the state of this lagoonal surface and the offshore area, revealing the morphological setting of the palaeoplain during the lowstand marine tract (Fig. 11a).

During the initial stage of the Holocene transgression, erosional river furrows were filled with transgressive sea sand (FONTES & BORTOLAMI, 1973) and formed littoral apparatuses (primordial lagoons probably developed behind them), which gradually moved further north. Local levels of reworked sandy silt of uncertain origin, with chaotic structure and containing Pleistocene clay breccias are defined as overflow deposits, as it is hypothesised that they are the result of particularly intense dynamic processes (fluvial channel fill following deglaciation or marine transgression). Transgressive deposition, which lasted approximately 5,000 years, took place in conditions of rapid sea level rise and reduced sedimentary flow, accompanied by a subsidence rate which may have reached 3 mm/y, as estimated by radiodating on organic materials sampled at wide-ranging depths (Bortolami *et alii*, 1984; Serandrei-Barbero *et alii*, 2005a). When the sea influx peaked, the coastline was located in the current lagoon (Favero & Serandrei-Barbero, 1978; Serandrei-Barbero *et alii*, 2001; Serandrei-Barbero *et alii*, 2002).

Having reached the climatic optimum, 5-6,000 years BP, the sea level rise slackened and the highstand tract stage started, involving depositional regression of the coastline, favoured by considerable solid flows from the Piave, Brenta, Bacchiglione, Adige and Po, and subsidence rates which had fallen to average values of 1 mm/y (Gatto & Carbognin, 1981; Bortolami *et alii*, 1984).

Compared with the previous situation, much more complex and differentiated environments started to develop in the transition area between sea and land, in turn characterised by various types of subenvironments.

According to the evolutionary model of the coastline proposed by Tosi (1994c) (Fig. 12), obtained with data from palaeo-ecological and radiometric surveys on coastal subsoil sediments, the transgressive marine trend prevailed in the central-northern area until total replenishment of the morphological high identified at the Lido inlet. Aggradation of deposits was associated with gradual exhaustion of a large branch of the Brenta, of which traces still remain today.

To the south, once the maximum marine influx had peaked, progradation of the littoral began, favoured by abundant solid flows from the Adige, Brenta and Bacchiglione, not balanced by the rise in sea level.

Near the margins of the inner lagoon, which were not directly involved in detritic flows, geological subsidence caused the enlargement of lagoonal basins shorewards.

Within the Holocene sequence, oscillations due to the reduced sea level were recorded by secondary transgressive-regressive depositional events, probably the consequence of minor climatic changes, which were however able to influence the flow and accumulation of sediments and eustatism. The clearest example is the finding of ancient salt marsh on highstand tract Holocene lagoon deposits, on which man-made settlements of Roman age have been found. There follow younger deposits of the lagoonal environment, in which evidence of salt marsh is often found again in the upper part (Serandrei-Barbero *et alii*, 1997; Bonardi, 1998; Bonardi *et alii*, 1998;

Fig. 12 – *Model of Holocene evolution of coastline (from Tosi, 1994c, modified). Arrows: direction of advance of coastline, caused by progradation of river mouths during highstand tract stage.*

Serandrei-Barbero *et alii*, 2004). The top of the Roman level coincides with a discontinuity which extends laterally throughout the Venetian area and may correspond to findings from the Ravenna area, attributed here to the IV-VI centuries AD, which identifies a surface of fluvial erosion correlated laterally with soils (Amorosi, 1999; Regione Emilia-Romagna, 1999).

The historic evolution of the Venetian area has been considerably influenced by anthropic interventions, particularly from about 1000 AD. The most evident transformations are due to direct diversions of rivers from the lagoon, which is otherwise subjected to infilling, partly due to increased solid flows and partly to a reduction in the rate of sea level rise. While limiting replenishment of the lagoonal basin, these operations involved deepening and expansion shorewards, especially because geochemical processes caused an increase in subsidence rates due to salinisation of deltaic areas, which had previously been characterised by freshwater environments.

Man's activities in the last century - for instance, the construction of tidal barriers - have considerably changed coastal and lagoonal hydrodynamics and therefore the processes of resuspension, transport, and deposition of sediments.

III - INTEGRATED METHOD OF SURVEYS AND ANALYSIS

The geological survey of the Venetian coastal area required the integrated use of various methodologies. Remote sensing and a series of laboratory multidisciplinary analyses accompanied on-site surveys including, in particular, micropalaeontological, mineralogical, geochemical and pollen analysis and radiometric dating.

On-site surveys, including direct observations of soil and sampling of sediments, were carried out by means of different methods. For example, in the lagoon and sea, often shallows, specific hand-drilling techniques suited to sediments with different consistencies and textures and a very high resolution seismic survey were used.

Study began with the collection, revision and homogenisation of multidisciplinary data and information from previous studies.

The assessment of shallow geomorphological structures was carried out by remote sensing, historical maps, topographic and bathymetric data interpretation and results were integrated with analysis of samples from cores.

The Sheets of the Regional Technical Map, at 1:10.000 scale, were used as reference topographic maps during the surveys.

The need to define the areal distribution of the various characteristics of the highly heterogeneous deposits, such as Holocene sediments of transition environments, required a very dense mesh sampling, sometimes irregular because of logistic problems due to the inaccessibility of some lagoon sites.

Considering that the first 40-50 cm of subsoil are generally reworked by man activities, such as agriculture, reclamation, fisheries, particular attention was given to the definition of the uppermost layer representative of age, depositional environment, and texture of the stratigraphic unit to map.

1. - SAMPLING

Although thousands of data from bibliographical works and past research on the properties of the subsoil were gathered and processed, the collection of new samples and analysis became es-

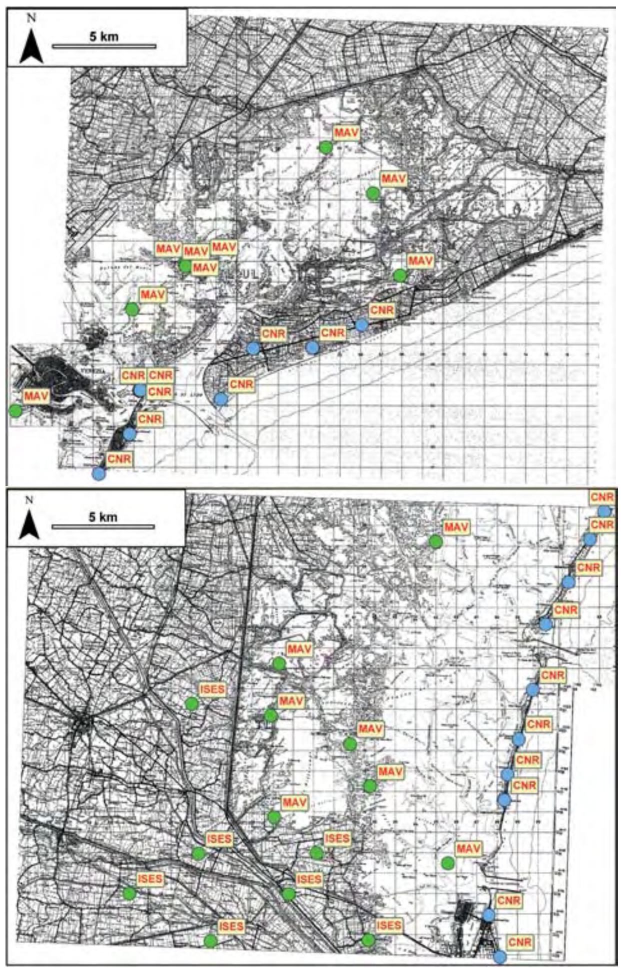

Fig. 13 – *Borehole locations from which samples of Group A and B were taken. MAV: Venice Water Authority; CNR: Institute of Marine Sciences, Venice. (Venice sheet above, Chioggia-Malamocco below)*

sential. Indeed, as a considerable amount of information was almost exclusively of a lithological or geotechnical nature, whereas the main environmental indicators were often scarce or absent (e.g., shells, or particular sedimentary structures), it turned out not to be possible to define in advance the palaeo-environments of deposition and units to be mapped, which was an essential requirement for this work.

The sediment samples on which the new surveys and analyses were carried out for the geological map were divided into two groups. Group A is composed of samples obtained by boreholes made available by the Venice Water Authority and the Institute of Marine Science (ex ISDGM) of the ITALIAN RESEARCH COUNCIL, Venice. The cores had been collected with the same aim as that used by CARG (Regional Geological Mapping Project, leaded by National Geological Survey) to characterise the subsoil, and their data were also used for other projects.

The samples of group B come from field surveys carried out exclusively as part of the CARG project and planned according to information available in the database. Conducted from 2002-2004, these field surveys aimed at collection of continuous, more or less deep borehole sampling, hand-drilling and sinking bucket samples. Figs. 13 and 14 show the locations where the samples of groups A and B were collected.

To improve the stratigraphic reconstruction of the deeper deposits two boreholes were drilled to about 100 m in Cà Nuova, near the town of Portegrandi (Venice), and Valle Averto, near the town of Campagna Lupia (Venice) and 14 boreholes from 20 to 30 m deep both in the lagoon and in the mainland. Exposed and subsurface deposits occurring in lowlands, lagoon and nearshore were sampled with manual coring and sinking buckets.

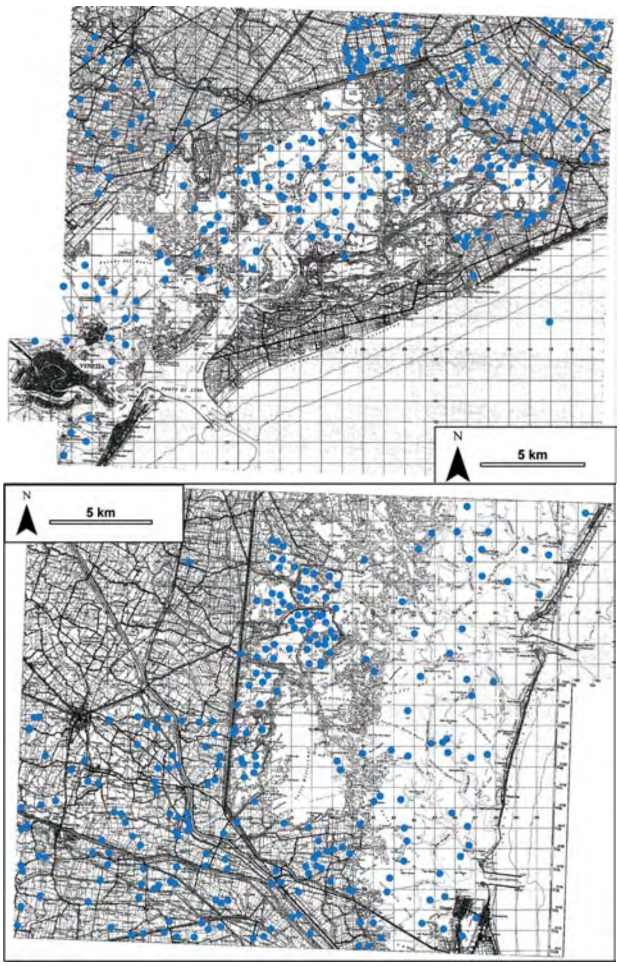

Fig. 14 – *Location of new CARG samples (boreholes, hand-drilling, sinking bucket sampling).*

2. - GEOMORPHOLOGY

In order to create the Geological Map, accurate geomorphological surveys were carried out to enhance the assessment of various kinds of depositional environments.

Investigation were performed by interpreting previous studies, aerial photographs, past and recent maps, and altimetric analyses while new in situ surveys, and sedimentological analyses were carried out.

Many aerophotographs, in colour or in black and white, taken between 1955 and 1999 and belonging to differing series by scale and year, were examined. Some of them were made available by the Veneto Region and the Province of Venice and others by the Institute of Marine Sciences.

Processing and analysis of altimetric data provided an accurate elevation model both of the mainland and the lagoon-sea bottom and showed the morphological setting of the area representative of the natural topography. High resolution seismic surveys gave a contribution to the identification of buried morphological features in lagoon and nearshore areas

Identified geomorphological features were represented on the Geological Map with simplified symbols according to the National Geological Service (APAT) guidelines regarding CARG project. Fluvial ridges, traces of abandoned riverbeds, ancient tidal channels, old beach ridges, and the position of the main old lagoon mouths were pointed out.

Detailed representation of all geomorphological features was mapped at 1:10,000 scale, whereas simplified characteristics at 1:25,000 and 1:50,000 scales to ensure that the final cartographic product was not confusing or illegible.

3. - PALAEONTOLOGY

Both in the lagoon and inland areas of the Venice Sheet, the 485 sediment samples for which organogenic remains were analysed (including 80 samples taken from the CARG 5 core, for analysis of pollen content), were obtained from hand-drilled cores, sinking buckets and boreholes. The study of samples from sinking buckets, hand-drilled cores and surface cores, for a total of 126 samples, provided details useful in the reconstruction of the recent evolution of the survey area. Examination of the organogenic contents of 279 sediment samples from 13 surveys from depths between 10 m and 100 m revealed the evolution of the area on a regional scale and the thickness of the lagoon sediments in the different sectors of the Sheet. Fig. 15 shows the survey locations, from which the samples used for the CARG micropalaeontological studies were taken.

Samples < 0.5 mm grain size showed benthic foraminiferal associations and therefore identified marine and lagoon palaeo-environments, and the fraction > 0.5 mm revealed shells of marine molluscs (*Tellina sp., Chamelea sp., Dentalium sp.*) or lagoon species (*Bittium reticulatum* (DA COSTA), *Loripes lacteus* (LINNAEUS), *Gibbula adriatica* (PHILIPPI)). In addition, it detected the presence of the shells and opercula of freshwater gastropods (*genus Vallonia* and *Valvata*) or those typical of emerging salt marsh, such as *Ovatella myosotis* (DRAPARNAUD).

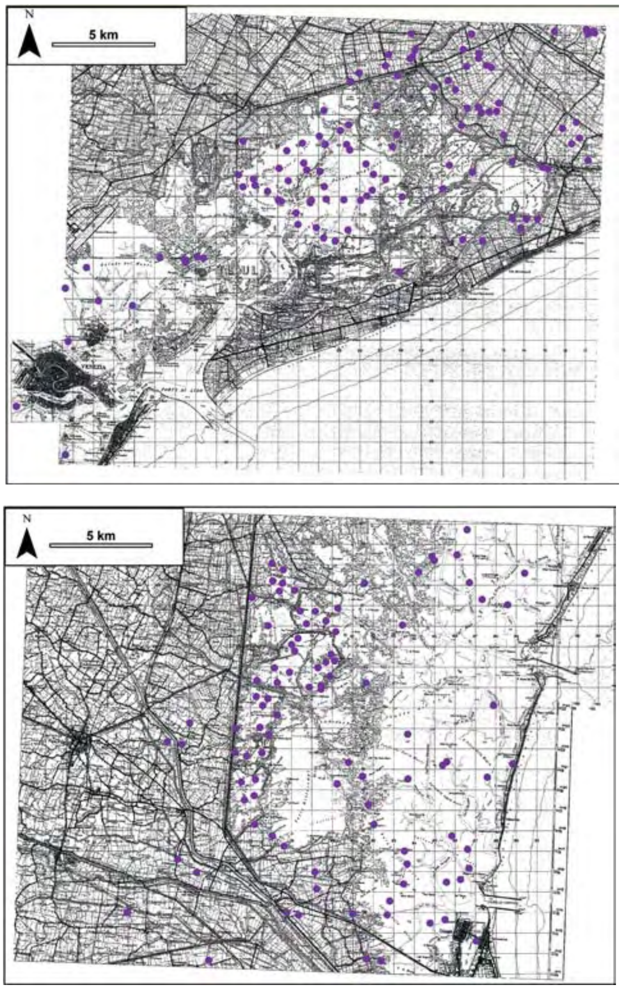

Fig. 15 –*Location of sites from which samples for micropalaeontological analysis were taken.*

On the Chioggia-Malamocco Sheet, micropalaeontological analysis of 85 surface cores, 8 hand-drilled cores, 9 sinking bucket samples and 17 boreholes drilled to depths of between 5 and 100 m was carried out, covering both land areas and the thickness of the lagoonal sediments. Site locations are shown in Fig. 15.

The palaeo-environments were characterised by analysing 870 samples.

Approximately 20 cm³ of sediment was separated from each sample, weighed, washed in a sieve with a 0.063 mm mesh, dried at 50ºC, and reweighed to assess the silty and clayey fraction dispersed by washing. The resulting residue was dry-sieved to separate fractions > or < 0.5 mm.

The fraction < 0.5 mm was further divided into two subfractions, respectively > and < 0.125 mm. The latter was then used for quantitative analysis of foraminiferal fauna. This choice was made due to the presence of many morphotypes of juvenile stages, difficult to classify, and by the fact that, in marginal environments such as the Lagoon of Venice, foraminifera reach maturity later than species in marine environments, for the study of which the fraction < 0.125 mm is normally used. Using the fraction > 0.125 mm allowed not only classification of all taxa in a given volume of sediment, as required by quantitative analysis, but also comparisons with previously identified associations, as the fraction < 0.125 mm was not taken into consideration in early works on the Lagoon of Venice (SILVESTRI, 1950; CITA & PREMOLI SILVA, 1967).

Quantitative analysis, based on a known fraction of total washed residues and on a number of statistically representative individuals (BUZAS, 1990; SERANDREI-BARBERO *et alii*, 1997), was carried out following SCOTT & MEDIOLI (1980), despite the recent criticism of MURRAY (2000), because the total association, given by the set of biocenoses and thanatocenoses, is indicative of the prevalent conditions in a given area (ALBANI, 1993; ALVE, 1995).

The biocenosis, alone, which can identify short-term changes like the intermittent anoxic conditions that occur in the Adriatic (PRANOVI &

SERANDREI-BARBERO, 1994), is not the scope of this work, which aims at finding the most integrated vision of sets possible. This was achieved by quantitative analysis of samples giving information on past faunal associations that could be compared with present-day ones, of which the abundances and distributions in the various areas of lagoon and coastal sedimentation are known.

4. - CHRONOSTRATIGRAPHY

The chronostratigraphy of the Mestre Supersynthem and Po Synthem deposits was carried out by Accelerator Mass Spectrometry (AMS) and the traditional ^{14}C radiometric method, depending on the quantity of organogenic material available.

A set of already published data was initially collected (MARCELLO *et alii*, 1968; FONTES & BORTOLAMI, 1973; FAVERO & SERANDREI-BARBERO, 1983; BORTOLAMI *et alii*, 1984; CORREGGIARI *et alii*, 1996a; CORREGGIARI *et alii*, 1996b; MÜLLENDERS *et alii*, 1996; PAGANELLI, 1996a; MCCLENNEN *et alii*, 1997; SERANDREI-BARBERO *et alii*, 1997; SCHIOZZI & BRAMBATI, 2001; SERANDREI-BARBERO *et alii*, 2001; SERANDREI-BARBERO *et alii*, 2002; BONDESAN *et alii*, 2002a; BONDESAN *et alii*, 2003a; BONDESAN *et alii*, 2003b; MOZZI *et alii*, 2003; SERANDREI-BARBERO *et alii*, 2004), and then unpublished data, which yielded 150 radiometric analyses.

When calibration was not available, the CALIB REV 4.4.2 program was used (TALMA & VOGEL, 1993; STUIVER & VAN DER PLICHTR, 1998; STUIVER *et alii*, 1998) to convert ^{14}C radiodating

Tab. 1a-b – *Radiodatings of CARG samples.*

a

Campione	Profondità	Età ^{14}C (anni B.P.)		Metodo	Materiale datato
	(metri dal p.c.)	Convenzionale	Calibrata		
7	-0,67	1280±90	da 1330 a 980	Radiometrica	Sedimento organico
8	-0,45	1220±60	da 1280 a 980	Radiometrica	Torba
51	-0,65	890±40	da 920 a 710	AMS	Conchiglie
63	-0,82	1060±50	da 1060 a 920	Radiometrica	Torba
73	-0,80	3320±40	da 3270 a 3060	AMS	Conchiglie
83	-0,90	2670±40	da 2450 a 2290	AMS	Conchiglie
86	-1,30	2370±60	da 2710 a 2580 da 2510 a 2320	Radiometrica	Sedimento organico
91	-0,65	3020±40	da 2860 a 2730	AMS	Conchiglie
91	-1,20	3670±70	da 4220 a 4210 da 4170 a 3830	Radiometrica	Torba
108	-0,80	2130±40	da 2300 a 2250 da 2170 a 2000	AMS	Conchiglie
108	-1,30	3010±40	da 2850 a 2720	AMS	Conchiglie
119	-0,60	910±40	da 930 a 730	AMS	Conchiglie
119	-1,20	2750±40	da 2940 a 2770	AMS	Conchiglie
144	-1,15	2250±40	da 2340 a 2150	AMS	Conchiglie
Barena A	-0,73	440±50	da 540 a 430 da 360 a 330	Radiometrica	Sedimento organico
D6	-0,27	920±60	da 950 a 700	Radiometrica	Torba
Carg 10	-4,05	580±40	da 650 a 530	AMS	Conchiglie
CARG 9	-3,60	5.060±40	da 5200 a 4840	AMS	Conchiglie
CARG 9	-9,40	6.840±40	da 7170 a 6900	AMS	Conchiglie
CARG 9	-24,10	22.100±110		AMS	Torba
CARG 9	-41,70	3.600±40	da 3260 a 2970	AMS	Conchiglie
CARG 5	8,15	6740±50	da 7360 a 7180	AMS	gusci
CARG 5	-31,20	30.000±280		Radiometrica	Torba
CARG 5	-34,85	>40.730		Radiometrica	Torba
CARG 5	-44,25	>43.250		Radiometrica	Torba
CARG 5	-49,95	>44.620		Radiometrica	Torba
CARG 12	-1,88	2.950±40	da 2770 a 2690	AMS	Conchiglie
CARG 12	-11,47	19.910±120	da 24280 a 22950	Radiometrica	Torba
CARG 12	-22,71	22.520±210		Radiometrica	Torba
OGS 7	-9,75	19.510±150	da 23870 a 22440	Radiometrica	Torba
Lito 17	-16,50	19400±90	da 23600 a 22450	AMS	Frammenti vegetali
Lito 17	-21,20	20950±180		Radiometrica	Torba
OGS 7	-5,85	4680±40	da 4990 a 4820	AMS	Conchiglie
OGS 7	-14,35	21810±100		AMS	Conchiglie
OGS 7	-29,80	36170±750		AMS	Frammenti vegetali
T3	-0,8	14830±80	da 18200 a 17320	Radiometrica	Torba
T7	-1,35	15710±80	da 19240 a 18300	Radiometrica	Sedimento organico
T9	-1,2	17930±80	da 21250 a 20240	AMS	Conchiglie
T15	-1,3	9030±40	da 10230 a 10170	AMS	Torba
T24	-1,7	7970±50	da 9010 a 8630	AMS	Torba

b

Campione	Profondità	Età ^{14}C (anni B.P.)		Metodo	Materiale datato
	(metri dal p.c.)	Convenzionale	Calibrata		
42 *	-0,59	1760±40	da 1370 a 1250	AMS	Conchiglie
73	-0,45	1160±40	da 770 a 640	AMS	Conchiglie
76	-0,48	1010±40	da 650 a 520	AMS	Conchiglie
95	-0,48	1300±40	da 920 a 750	AMS	Conchiglie
96	-0,70	1630±40	da 1600 a 1420	AMS	Torba
98	-0,55	1610±60	da 1620 a 1360	Radiometrica	Torba
99	-0,56	790±50	da 780 a 660	Radiometrica	Torba
172	-1	2740±50	da 2940 a 2760	Radiometrica	Sedimento organico
253	-0,90	2470±70	da 2750 a 2340	Radiometrica	Sedimento organico
206	-0,90	1040±60	1060 a 890 - da 860 a 8	Radiometrica	Torba
206	-1,30	2010±70	da 2140 a 1820	Radiometrica	Torba
303	-1,10	2490±60	da 2750 a 2350	Radiometrica	Torba
312	-0,60	2360±40	da 2460 a 2330	Radiometrica	Torba
320	-1,30	920±60	da 950 a 700	Radiometrica	Sedimento organico
323	-1,10	1230±40	da 880 a 680	AMS	Conchiglie
328	-0,70	840±60	da 920 a 670	Radiometrica	Sedimento organico
341	-1,10	1580±60	da 1580 a 1330	Radiometrica	Torba
PR6	-0,58	1760±60	da 1830 a 1540	Radiometrica	Sedimento organico
S6	-0,80	1660±50	da 1700 a 1420	Radiometrica	Torba
VA6	-0,82	2240±60	da 2350 a 2120	Radiometrica	Torba
Barena D	-0,70	1150±60	1230 a 1210 - da 1190 a	Radiometrica	Torba
ISES B	-2,20	2740±60	da 2960 a 2750	Radiometrica	Torba
ISES B	-4,30	4000±70	800 a 4770 - da 4630 a	Radiometrica	Torba
ISES 7	-1,90	3740±40	da 4230 a 3980	AMS	Conchiglie
ISES 7	-2,90	5040±40	da 5900 a 5660	AMS	Conchiglie
ISES 7	-11,70	16320±50	da 19580 a 19340	AMS	Conchiglie
ISES 7	-13,08	20860±160		Radiometrica	Torba
ISES 26	-3,30	2580±50	770 a 2710 - da 2630 a	Radiometrica	Torba
ISES 33	-4,48	1040±40	da 660 a 540	AMS	Conchiglie
ISES 33	-6,85	3980±40	da 4530 a 4380	AMS	Conchiglie
ISES 33	-9,50	4820±40	da 5260 a 4970	AMS	Conchiglie
ISES 33	-10,80	4760±40	da 5130 a 4860	AMS	Conchiglie
ISES 33	-17,65	7190±40	da 8040 a 7940	AMS	Conchiglie
ISES 68	-2,05	1860±40	da 1880 a 1710	AMS	Conchiglie
ISES 68	-8,55	4370±40	da 5040 a 4850	AMS	Frammenti vegetali
ISES 68	-12,43	8710±70	da 9920 a 9540	Radiometrica	Sedimento organico
ISES 68	-17,15	18410±60	da 22350 a 21400	AMS	Conchiglie
CARG 11	-1,40	730±60	a 750 a 630 - da 600 a 5	Radiometrica	Sedimento organico
CARG 11	-2,30	1730±70	da 1820 a 1510	Radiometrica	Torba
CARG 11	-7,90	4580±70	da 5470 a 5040	Radiometrica	Legno
CARG 11	-14,45	21520±80		AMS	Conchiglie
CARG 11	-27,35	26990±180		Radiometrica	Torba
1 L	-0,80	2170±70	da 2340 a 1990	Radiometrica	Torba
1 L	-19,40	19930±170		Radiometrica	Torba
1 L	-23,70	23130±160		Radiometrica	Torba
3 L	-13,90	19380±130	da 23670 a 22340	Radiometrica	Torba
Lito 1	-22,85	17860±80	da 21160 a 20160	AMS	Conchiglie
Lito 5	-16,25	15730±100	da 19310 a 18280	AMS	Frammenti vegetali
Lito 5	-17,20	20860±100		AMS	Conchiglie

into years by calculating the probability distribution of the true age of samples. To convert past data, the Intcal98 ^{14}C calibration curve, which limits its calibration to between 0 and 20,265 years BP, was used. This curve is recommended for most non-marine samples. It is based on the ten-year means of ^{14}C measurements of tree growth rings (dendrochronology), coral samples and sediment varves, with a reserve correction of 500 years for marine data going back more than 10,000 y/cal BP.

Within the CARG Project, 40 radiodatings were carried out on the Venezia Sheet. Of these, 17 conventional and 23 AMS, and $^{12}C/^{13}C$ ratios and calibrated ages were also calculated (Tab.1a). Forty-nine datings were made with the ^{14}C method for the Chioggia Malamocco Sheet, 28 conventional and 21 AMS; again, $^{12}C/^{13}C$ ratios and calibrated ages were calculated (Tab. 1b).

An important contribution distinguishing pre- and post-Roman Holocene units was provided by data from geo-archaeological study of anthropic or natural levels.

The relative chronology of the Late Pleistocene and Holocene units was identify by the study of stratigraphic relations between exposed and buried sedimentary bodies, including geomorphological elements.

Tyrrhenian deposits were identify by information about paleoenvironmental analyses according to the palynostratigraphic data of a series of other boreholes known in the literature (PAGANELLI, 1996a; 1996b; CALDERONI *et alii*, 1998; CALDERONI *et alii*, 2000), which allowed correlations on a regional scale.. Reference was therefore made to the biomagnetostratigraphic data of the Venezia 1 - CNR survey (KENT *et alii*, 2002; MASSARI *et alii*, 2004).

5. - MINERALOGY

Data on mineralogy, geochemistry, petrography and the texture of sediments of the Venetian area provide information complementing those from palaeontological and geomorphological surveys carried out to determine depositional environments, their dynamics, and the genetic and diagenetic processes which affected them.

Despite the considerable amount of past data available on the Venetian area, data were often obtained by different methodologies, according to particular research needs. This sometimes led to the need for new analyses.

On the basis of experience acquired during previous studies on the area, it was decided to focus on mineralogical rather than geochemical and petrographic analyses. This was because the usefulness of geochemistry lies in its capacity to identify pollutants of anthropogenic origin and petrography is less rapid and does not allow good characterisation of sediments.

For mineralogical analysis of sand samples, an electron microprobe (EMP), equipped with an Energy Dispersion Spectrometer (EDS), Wavelength Dispersion Spectrometer (WDS) and Back-scattered Electron Detector (BSE) was used as it offers excellent analytical capability, speed, and non-destructive qualitative analysis. Minerals characterised were: dolomite, ankerite, calcite, aragonite, quartz, albite, orthoclase, clinochlore, muscovite, biotite, enstatite, hastingsite, laumontite, titanomagnetite, vermiculite and BASSANite.

In cases of doubtful identification, or to better characterise the samples, quantitative (EDS) and qualitative (BSE) analyses were carried out.

The mineralogical composition of clay sediments was determined on the total sample, and

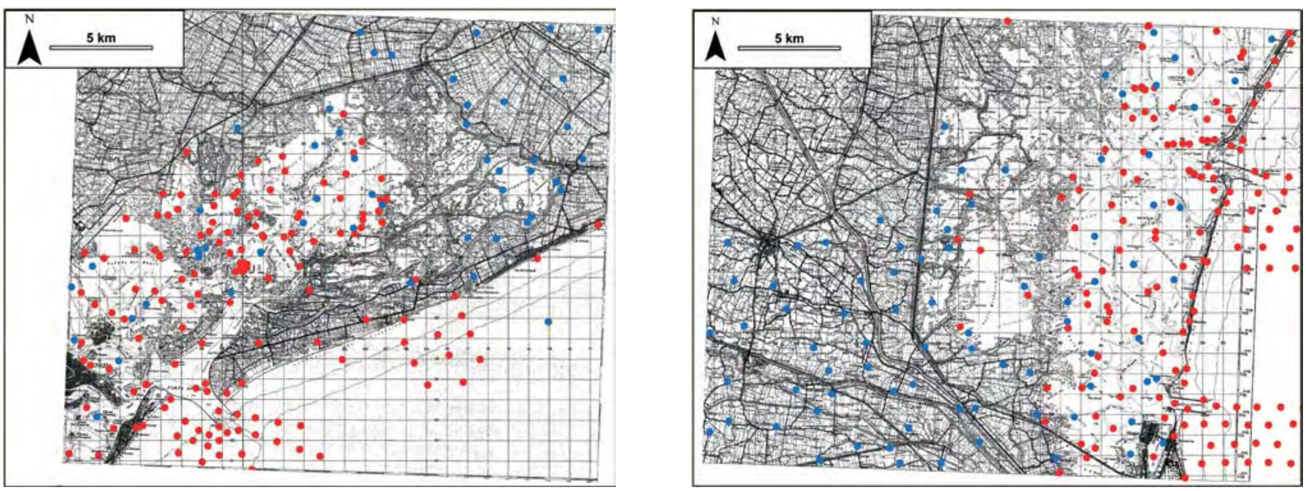

Fig. 16 – *Sites at which mineralogical data were available on sandy fraction of sediments. Past data: red circles; CARG data: blue circles (left: Venezia Sheet; right: Chioggia-Malamocco Sheet).*

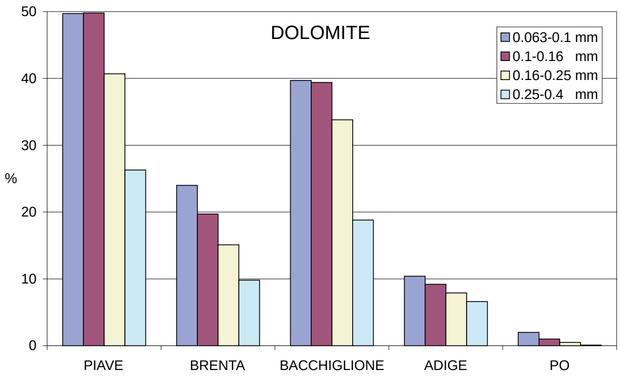

Fig. 17 – *Average percentages of dolomite in sediments of main rivers in Venetian area (from* Jobstraibizer *&* Malesani*, 1973).*

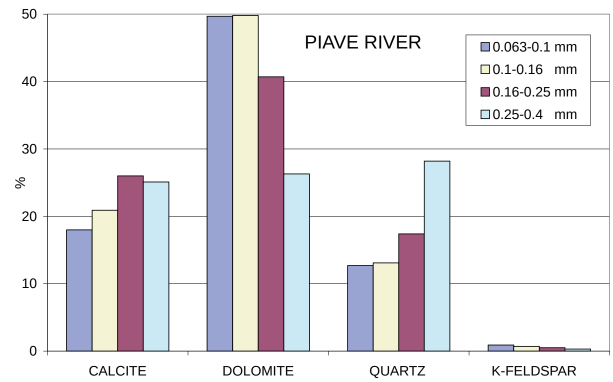

Fig. 18a – *Average percentages of major minerals in sediments of Piave (from* JOBSTRAIBIZER *&* MALESANI*, 1973).*

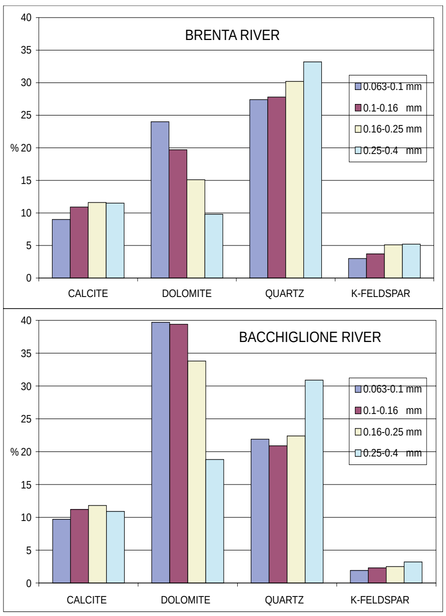

Fig. 18b – *Average percentages of major minerals in sediments of Brenta and Bacchiglione (from* JOBSTRAIBIZER *&* MALESANI*, 1973).*

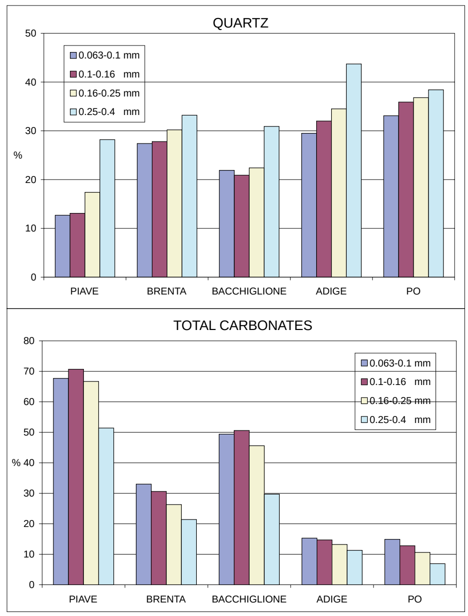

Fig. 18c – *Average percentages of quartz and total carbonates (calcite, aragonite, dolomite, ankerite) in main rivers of Venetian area (from* JOBSTRAIBIZER *&* MALESANI*, 1973).*

chlorite, illite/mica, smectite, quartz, plagioclase, K-feldspar, calcite, dolomite, kaolinite and mixed strata clay minerals were detected. In some cases, analysis was also carried out on the clay fraction (< 2 µm) only. An X-ray diffractometer was used, and semi-quantitative analyses were obtained with appropriate software.

Fig. 16 shows the sites at which mineralogical information on separated sandy sediments was available from CARG and past data. The latter are from VENZO & STEFANINI (1967), GAZZI, *et alii* (1973), BARILLARI & ROSSO (1975), BARILLARI (1978; 1981), DONAZZOLO *et alii* (1984), PERIN *et alii* (1997) and MAGISTRATO ALLE ACQUE & CONSOEZIO VENEZIA NUOVA (1999).

Other data were from ALBANI *et alii* (1989; 1995), RICKWOOD *et alii* (1992), ALBANI & SERANDREI-BARBERO (2001) and RAVAIOLI *et alii* (2003).

The references used by JOBSTRAIBIZER & MALESANI (1973) and GAZZI *et alii* (1978) were applied to determine basins of provenance, together with analysis of some samples collected from the beds of various rivers a few kilometres from their mouths. As examples, the variation intervals of the percentages of some mineralogical types are shown in Figs. 17 and 18, referring to the main watercourses which contributed to the flow of sediments into the Venetian area. The average reference percentages of the main minerals in the sands of the Piave, Brenta and Bacchiglione are given in Fig. 18a, b, c.

6. - GEOPHYSICAL TECHNIQUES

The study area is mainly characterised by shallow lagoon and marine environments, or by situations requiring huge resources for drilling boreholes, which have to be numerous, owing to the considerable heterogeneity of the deposits. Seismic measurement in water is definitely one tool that, relatively inexpensively, improves the main sedimentological and stratigraphic information deduced from core samples.

As regards emerging areas, two radioactive cores were bored (gamma ray logs), enhancing stratigraphic reconstruction of the subsoil, together with other past data.

6.1. - Very high resolution seismics

In order to identify the Late Pleistocene and Holocene deposits in the study area, it was necessary to implement a method satisfying two fundamental requirements: vertical resolution of decimetric order, and the need to survey shallows, less than 3-4 m depth

In 2001-2003, the National Institute of Oceanography and Experimental Geophysics (OGS) of Trieste, together with the Institute of Marine Sciences of Venice, created a reliable system for very high resolution seismic acquisition in the Lagoon of Venice and its coastal area (Fig. 19).

Surveys were made in both lagoon and marine areas. The main objectives were:

- litho-stratigraphic characterisation of seismic facies and their attribution to precise stratigraphic levels, by means of calibration with existing surveys (Brancolini *et alii*, 2005; Brancolini *et alii*, 2006);
- assessment of transition between Pleistocene continental and Holocene lagoon-marine deposits and of main buried structures, especially palaeo-riverbeds, sand ridges
- provide detailed interpreded seismic sections at 1:10,000 scale and simplified profiles at 1:25,000 and 1:50,000 scales
- mapping of the Po Synthem base at 1:25,000 and 1:50,000 scales.

6.1.1. - *Instrumentation and methodologies*

The "Litus" and "Henetus" boats operated by ISMAR-CNR were used for data acquisition.

Seismic data were collected in single tracks (monochannel) with an energisation system composed of a power unit with 150-450 Joule/shot, an electrodynamic transducer (plate) mounted on a towed catamaran, operating at frequency intervals between 300 and 2,400 Hz. Decimetric resolution of layers was obtained in the best conditions. The receiver was a 320 cm-length streamer composed of eight preamplified hydrophones connected in series. Data were acquired by a DELPH II unit in 16-bit SEGY format and shown on the monitor in real time, to allow immediate quality control of the reflected signal. The horizontal offsets of the source and streamer were respectively 5 and 7 m, with a lateral distance of 4 m between the two.

The seismic lines were positioned by a Global Positioning System (GPS) accuracy to within 1 m. Measurements were made while the boat was travelling at a speed between 3 and 5 knots, depending on sea and current conditions, in order to minimise turbulence and background noise.

Within the Venezia and Chioggia Malamocco Sheets more than 150 km of seismic profiles were acquired Furthermore, some profiles acquired in the framework of other ISMAR researches were used to complete the reconstruction of the geometry of the Holocene deposits in the marine sector outside the study area.

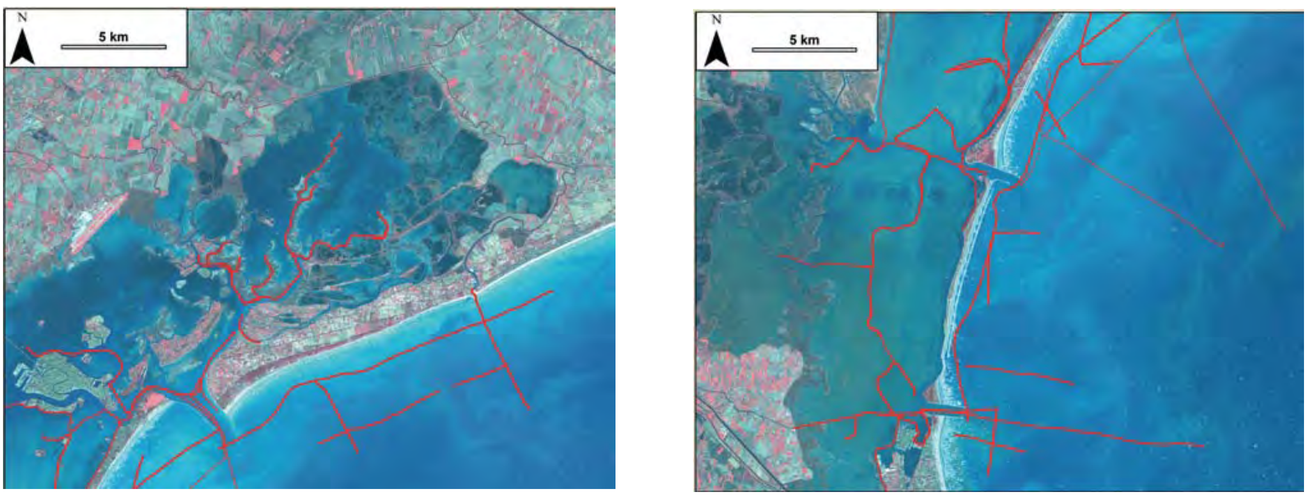

Fig. 19 – *Map of CARG high resolution seismic lines. Background: ASTER image (left: Venezia Sheet; right: Chioggia–Malamocco Sheet).*

6.1.2. - *Processing*

The following processing sequence was applied: signal balancing, deconvolution, pass-band filtering (Tab. 2), resampling of data, sum of two adjacent tracks, further balancing, mixing of six contiguous tracks, mute, production of graphic file for printing.

Tab. 2 – *Variable-interval pass-band filter used to minimise noise*

	F1	F2	F3	F4
0 ms	400 Hz	800 Hz	2400 Hz	4800 Hz
80 ms	200 Hz	400 Hz	1200 Hz	2400 Hz

An average speed of 1.550 m/s was used to convert the vertical scale into depths. This is a reliable estimate, as Holocene sediments are generally made up of quite fine, unconsolidated, water-saturated material. Fig. 20 gives an example of a processed seismic profile.

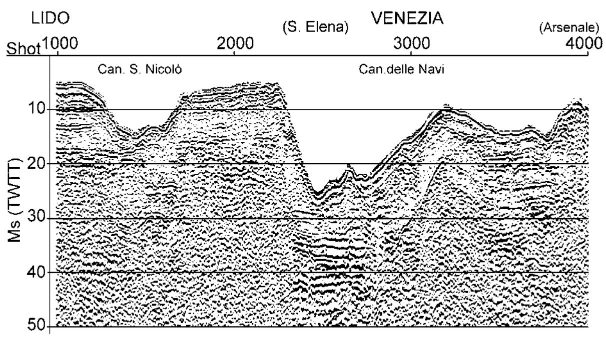

Fig. 20 – *Example of seismic profile.*

Most of the seismic lines acquired in the lagoon are located along present-day tidal channels, where it is possible to navigate with ISMAR-CNR boats.When present tidal channels are superimposed on Pleistocene riverbeds the depth of the Holocene-Pleistocene boundary may be slightly deeper than that of the surrounding areas.

6.2. - Radioactive logging

Radioactive logging (gamma ray), is based on borehole measurements of the natural radioactivity of rocks, and are used for lithostratigraphic and sedimentological purposes. In sedimentary formations, these measurements provide information on the content of clay, which normally tends to be slightly more radioactive than sandy sediments, due to its isotopic properties.

Hydrogeological study of the Venetian subsoil was carried out in the 1970s, and provided

Fig. 21 - *a) Continuous boring for* CARG 12 *survey in Cà Nuova area; b) Continuous boring for* CARG 11 *survey and gamma ray measurements.*

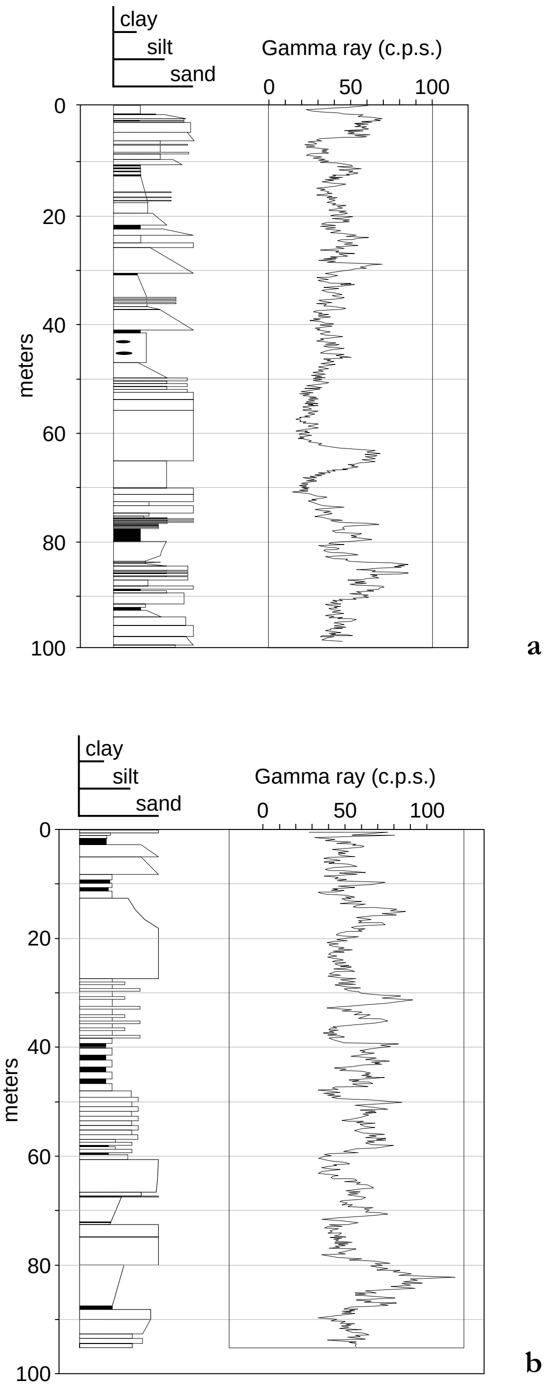

Fig. 22 – *a) Radioactive logging in CARG 12 borehole, compared with prevalent lithology deduced from sample analysis; b) Radioactive logging in* CARG 11 *borehole, compared with stratigraphy deduced from core analysis.*

the first detailed reconstruction of the deep aquifer system. It made use of radioactive data from some boreholes in Marghera, the historical centre of Venice, and the Lido (*Marghera 1*, *Venezia 1 - CNR*, *Venezia 1B - CNR*, *Venezia 2 - CNR*, *Lido 1* and others) (Roccabianca in Consiglio Nazionale delle Ricerche, 1971; Gatto & Favero, 1973; Gatto, 1979) for remote correlation of the main sandy and clayey layers.

This technique was also used in the late 1990s for litho-stratigraphic characterisation of the subsoil involved in saline contamination of the Venetian area. In particular, as part of the CNR "Environment and Territory" Strategic Project, in order to acquire litho-stratigraphic data from sectors where accurate stratigraphic measurements were not available, the Veneto Region drilled five radioactive boreholes in disused wells at depths varying between 100 and 280 m (Baglioni & Toffoletto, 1998).

As these surveys gave positive results, within the context of the CARG Project the Veneto Region performed two gamma ray logs to depths of about 100 m in stratigraphic survey boreholes with continuous drilling (*CARG 11, CARG 12*), located respectively in the Valle Averto and Cà Nuova areas (Fig. 21a, b). The recordings (Fig. 22a,b) show a good correlation between maximum radioactivity values and mainly clayey levels and between minimum values and sandy deposits.

Gamma ray data was calibrated with detailed litho-stratigraphic study on the cores of sediments taken during the creation of the *CARG 11* and 12 surveys, to provide a basic reference for future hydrogeological surveys.

7. - DATABASES

As part of the CARG Project, the Veneto Region created a subsoil database mainly containing geognostic data. Some of these come from the drilling of wells or small borings done manually at shallow depths, with sinking buckets and penetrometric testing.

The data, some of which were provided by many organisations according to project agreements or conventions (Venice Water Authority Information Service, Province of Venice, Venice

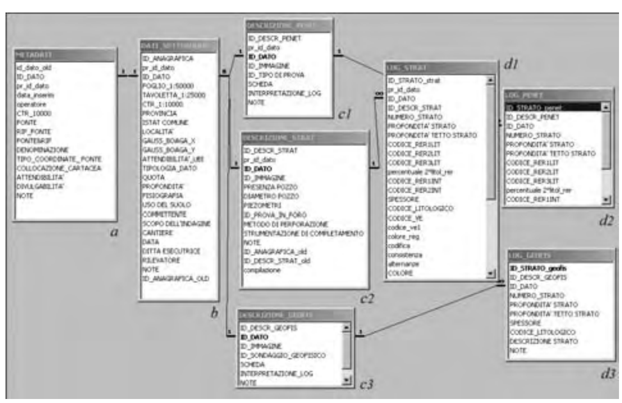

Fig. 23 – *Structure of table and relations with Regional Database: a) metadata; b) administrative and geographic data; c) survey methods; d) textural data deduced from stratigraphic surveys (1), penetrometric testing (2) and geophysical techniques (3).*

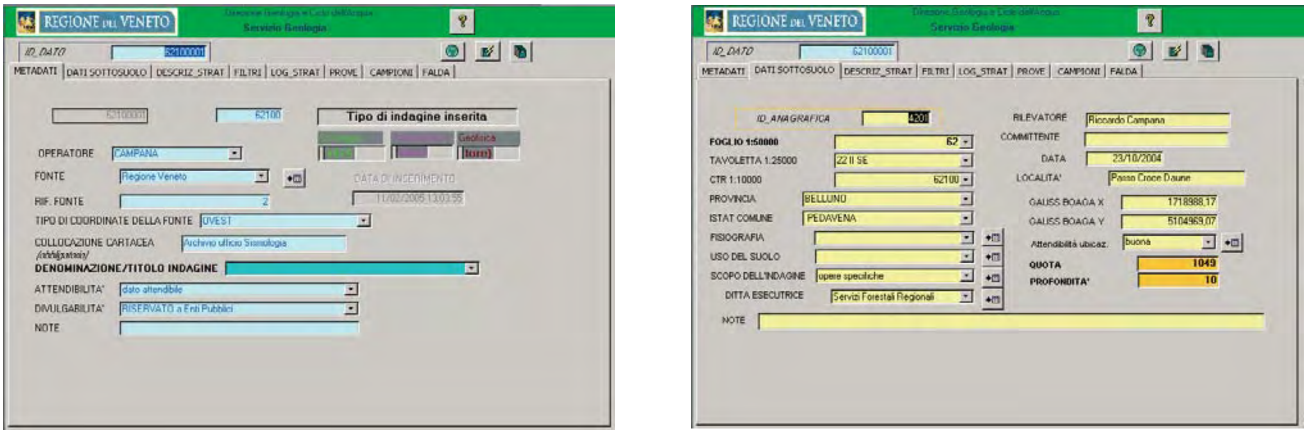

Fig. 24 – *Masks for input of metadata and administrative information, together with survey locations.*

City Council, CNR-ISMAR, Agricultural and Environmental Centre of Regional Agency for Veneto Environmental Protection-ARPAV, Province of Padova, Reclamation Consortia, Municipality of Chioggia, ENICHEM S.p.A., Archaeological Superintendency for the Veneto, Department of Hydraulic, Maritime, Environmental and Geotechnical Engineering and the Department of Geography, University of Padova), were homogenised. They are important to the structure of the Regional Database, and were integrated with further information where possible.

The database is mainly structured into four main tables (Figs. 23, 24, 25), each of which contains information about data sources and reliability (group a); geographic administrative data, such as survey location, organisation carrying out the work, construction site operator, and depth surveyed (group b); the survey method used (group c); textural data, either direct or interpreted by penetrometric tests and/or geophysical surveys (group d).

Information was assigned to each survey, grouping them homogeneously into three main tables: that for group a has a 1:1 ratio; another table includes information on group b, and the third regards the survey method (c), the latter with a 1:∞ ratio with the table containing textural data on strata (group d).

The location of each survey was assigned to a suitable information level within a Geographical Information System (GIS), with Gauss-Boaga coordinates – west zone. Already processed data were projected directly or, for paper printing, were inserted on-line, after visual checking with the reference of the Regional Technical Map, scale 1:10,00

Once the survey point has been positioned, the program attributes an identification number to the survey, the coordinates, and administrative and cartographic reference data. These are then loaded into the corresponding fields and tables of the database, and completed with textural information.

To consult each survey or group of surveys, the points of interest are selected from the infor-

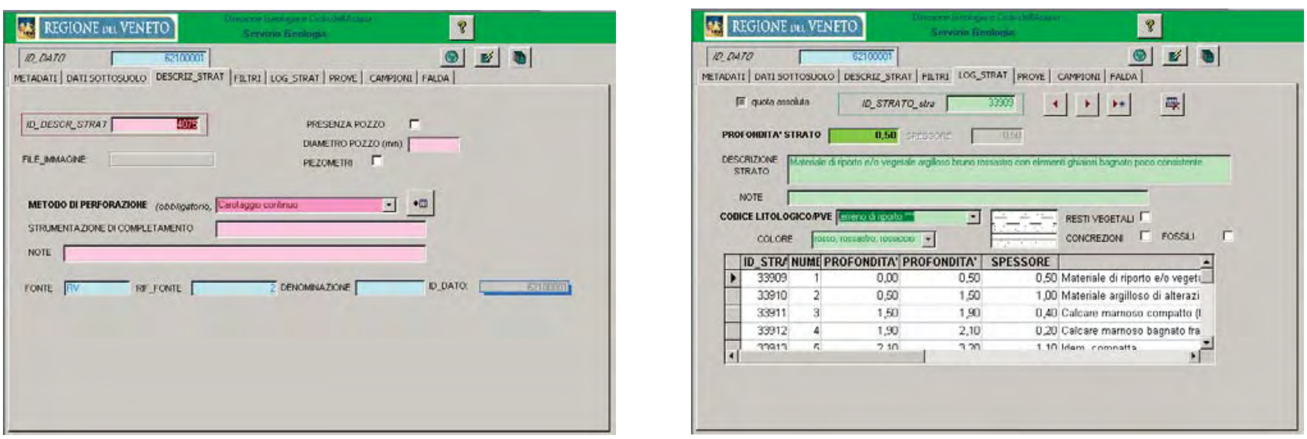

Fig. 25 – *Masks for input of characteristics and methods to implement surveys and stratigraphic data.*

mation level, and restitution in graphic form can be examined on any chosen scale.

7.1. - Databases of Venezia and Chioggia–Malamocco Sheets

To implement the above sheets, thousands of past data were gathered and, as well as preliminary geological analysis, allowed new CARG surveys to be planned.

In addition to litho-stratigraphic information, the CARG database also contains information on laboratory analyses: micropalaeo-ontological, pollen, mineralogical, radiometric and pedological.

Figs. 28 - 31 show some examples of how information is displayed, referring to lithological surveys, laboratory analyses and soil surveys.

Consulting the database during implementation of the CARG project facilitated identification of areas for which little or no information was available for the Geological Map. The new sampling surveys and laboratory analyses were planned according to existing information.

Figs. 32 and 33 show an example of the visualisation of the new CARG surveys (cores, boreholes, sinking buckets), planned to be integrated with existing information.

The geological database is constantly updated, so that the amount of data loaded increases every month. For instance, in September 2004, the Venezia Sheet contained data on about 1000 deep boreholes, 1000 surface samples, and 1500 hand-drilled cores and soil profiles. The Chioggia-Malamocco Sheet contains data on more than 500 deep boreholes, 400 surface samples, and 1100 hand-drilled cores and pedological profiles.

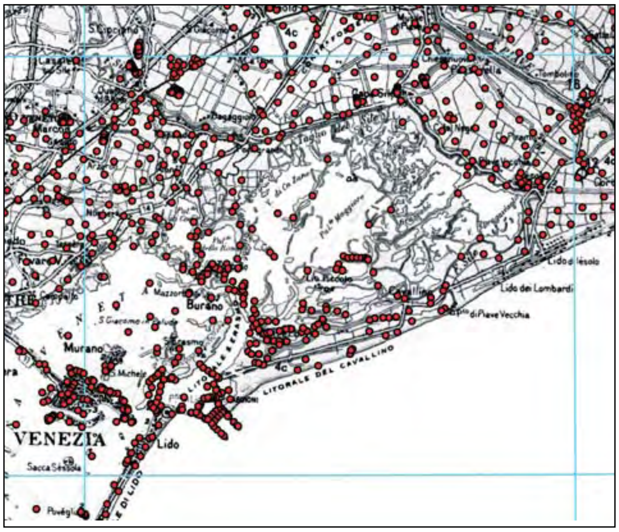

Fig. 26 – *Locations of some previously obtained stratigraphic data - Venezia Sheet.*

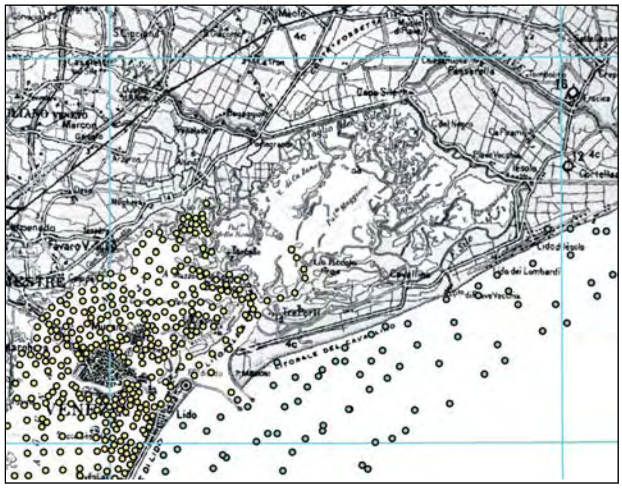

Fig. 28 – *Locations of data on previous micropalaeontological and textural analyses (from* Albani et alii, *1998 and* Albani *&* Serandrei-Barbero*, 2001) -Venezia Sheet.*

Fig. 27 – *Locations of some previously obtained stratigraphic data -Chioggia -Malamocco Sheet.*

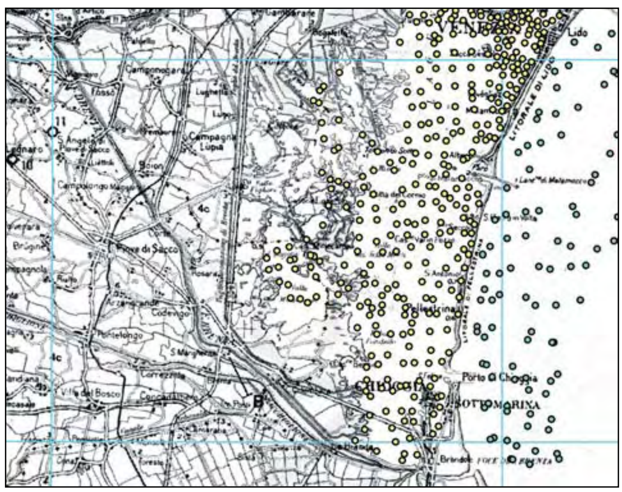

Fig. 29 – *Locations of data on previous micropalaeontological and textural analyses (from* Albani et alii, *1998 and* Albani *&* Serandrei-Barbero*, 2001) – Chioggia-Malamocco Sheet.*

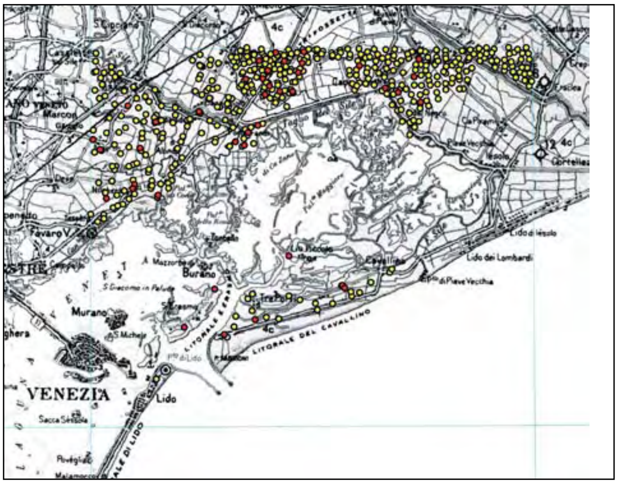

Fig. 30 – *Locations of previous pedological data. Red: soil survey profiles; yellow: hand-drilled cores - Venezia Sheet.*

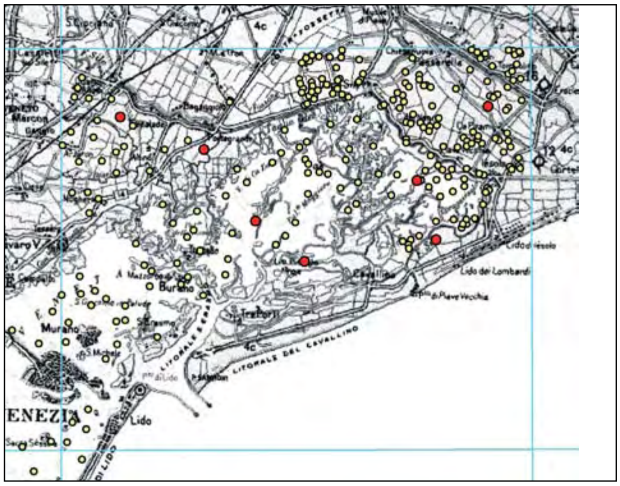

Fig. 32 – *Locations of new samples created for CARG project. Red: boreholes reaching depths between 20 m and 100 m; yellow: hand-drilled cores from a depth of about 1.5 m - Venezia Sheet.*

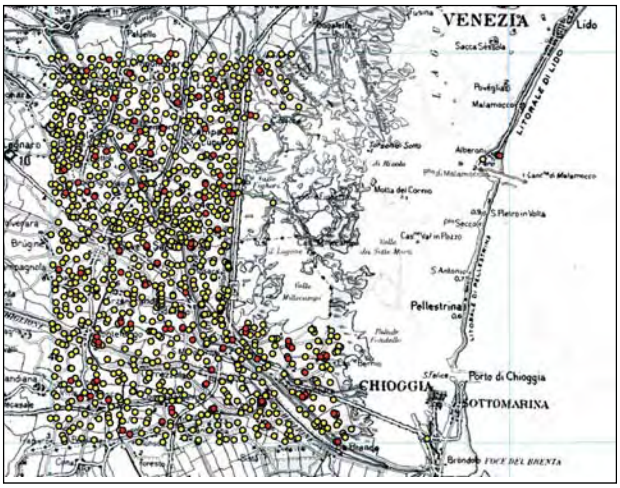

Fig. 31 – *Locations of previous pedological data. Red: soil survey profiles; yellow: hand-drilled cores – Chioggia-Malamocco Sheet.*

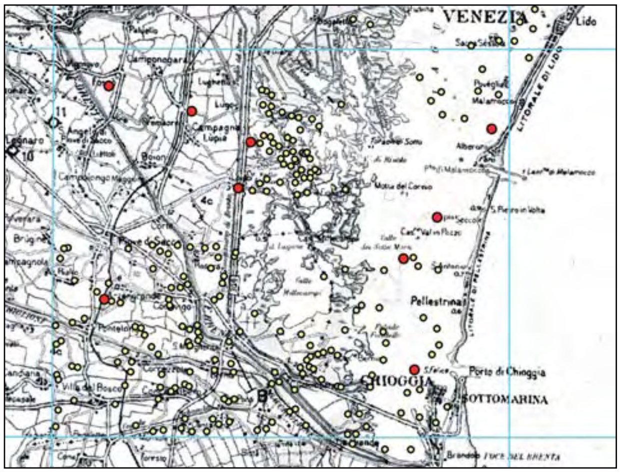

Fig. 33 – *Locations of new samples created for CARG project. Red: boreholes reaching depths between 20 m and 100 m; yellow: hand-drilled cores from a depth of about 1.5 m - Chioggia-Malamocco Sheet.*

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IV - STRATIGRAPHY

1. - DEPOSITIONAL ENVIRONMENTS

Determination of fauna associations combined with study of sedimentary and geomorphologic structures defines the various types of depositional environments.

Four main types of environment are shown in the cartographical context of the Venetian territory: alluvial/fluvial, deltaic, littoral and shelf; within the littoral environment, lagoon deposits were also differentiated from beach deposits.

This choice was made because of the peculiar requirements of this transition area, and the need to create a complete geological picture without losing important information or neglecting certain details that would have overburdened mapping and created difficulties which might have extended to adjacent geological sheets.

The criteria for classification are based on the recommendations of Ricci Lucchi (1978).

1.1. - Foraminiferal associations

Identification of depositional palaeo-environments, based on analysis of foraminiferal associations, was achieved by comparison of fauna living in present-day depositional environments. During the 1980s and 1990s, a far-ranging study of submerged areas in the Venetian territory, with the systematic collection of over 700 samples of the lagoon bottom sediments, supplied an extremely detailed description of the foraminiferal associations occurring in the lagoon areas and in the Gulf of Venice as far as the isobath -18 m (Albani & Serandrei-Barbero, 1982; Serandrei-Barbero *et alii*, 1989; Albani *et alii*, 1991; 1998; Serandrei-Barbero *et alii*, 1999). In addition, studies on the Lagoon of Venice and on the continental Adriatic plate over the last decade have supplied further information on factors controlling the productivity and distribution of the living foraminifera and the abundances of various taxa (Pranovi & Serandrei-Barbero, 1994; Donnici *et alii*, 1997; Serandrei-Barbero *et alii*, 2003b).

Comparisons with the results of another five-year study carried out in the Lagoon of Venice, with monthly monitoring of physical-chemical parameters (Ramasco, 1991), confirmed that the main factors controlling the distribution of biofacies inside the lagoon are the level of confinement, i.e., exchange time, according to the concept expressed by Guelorget & Prthuisot (1983), the anthropogenic pollution, as extensively discussed by Alve (1995), and the presence of freshwater inputs (Donnici & Serandrei-Barbero, 2005).

Morphology also plays an important role, as evidenced by the special foraminiferal association found on intertidal structures (Albani *et alii*, 1984; Petrucci *et alii*, 1983; Hatward & Hollis, 1994; Reinhard *et alii*, 1994; Serandrei-Barbero *et alii*, 1997; Serandrei-Barbero *et alii*, 2004). This association is characterised by the presence of *Trochammina inflata* (Montagu), with varying abundances according to depth compared with mean sea level. Identified control factors are illustrated in the simplified diagram of Fig. 34. They interact at different levels and in different ways which are not always easy to distinguish, but their overall effect is represented by the biofacies found in the present-day lagoon (Tab. 3).

Quantitative analyses of all samples and statistical processing by cluster analysis (Pearson's coefficient) of data consisting of abundance values for all the taxa found in each sample (Sneath & Sokal, 1973), grouped together samples characterised by the same biofacies, revealing the extent of the various subenvironments having similar parameters, and thus also supplying a means of comparison for reference to past faunal associations.

In order to define palaeo-environments, the

Tab. 3 – *Average composition of biofacies identified in Lagoon of Venice (northern basin and central sector as far as Canale Petroli [oil tanker route]) and their relationship with environment (from* Serandrei-Barbero et alii*, 2003a, modified).*

Biotopo	A		B		C		D		F	
Laguna Nord	media	min-max	media	min-max	media	min-max	media	min-max	media	min-max
Trochammina inflata (Montagu)	0,2	0,2 - 0,2	0,2	0,2 - 0,2	1,4	0,2 - 13,4	0,3	0,2 - 1,0	0,3	0,1 - 0,5
Haynesina paucilocula (Cushman)	45,6	33,5 - 55,1	30,5	25,6 - 37,1	10,2	2,6 - 25,1	8,2	3,1 - 17,1	17,1	6,3 - 27,3
Ammonia beccarii (Linné)	38,3	32,4 - 42,6	51,0	48,7 - 54,3	59,2	28,0 - 81,2	60,7	43,0 - 73,3	33,2	20,8 - 43,8
Cribrononion granosum (d'Orbigny)	6,0	4,9 - 7,1	8,4	1,7 - 12,5	17,2	1,1 - 43,0	14,6	4,6 - 25,2	39,2	18,7 - 56,1
altre specie	11,6	4,1 - 19,8	10,1	7,4 - 14,0	13,2	1,1 - 27,8	16,4	8,7 - 37,5	10,4	6,1 - 16,7
numero di specie	7		14		49		60		10	
numero di stazioni	4		6		68		100		11	
% area settore lagunare	1,5		2,2		24,9		36,6		4,0	
% area totale lagunare	0,7		1,1		12,2		17,9		2,0	

Biotopo	G		H		I		J		
Laguna Nord	media	min-max	media	min-max	media	min-max	media	min-max	A- Margine urbano
Trochammina inflata (Montagu)		-		-		-		-	B-Urbano intermedio
Haynesina paucilocula (Cushman)		-		-	3,0	0,7 - 5,3		-	C- Laguna interna
Ammonia beccarii (Linné)		-		-	35,1	35,0 - 35,1		-	D-Laguna esterna
Cribrononion granosum (d'Orbigny)		-		-	22,9	11,5 - 34,2		-	F-Laguna chiusa
others		-		-	39,1	25,5 - 52,7		-	G-Barena alta
									H-Barena intermedia
numero di specie					19				I-Marino
numero di stazioni					2				J-Paleodelta
% area settore lagunare					0,7				
% area totale lagunare					0,4				

same control factors operating in the present-day lagoon were considered as indicative, with the sole exception of pollution. The associations present in buried sediments indicate open or closed lagoon environments, freshwater inputs, no longer active intertidal systems, tide channels, and salt marshes.

In addition, as regards the northern Adriatic, the present-day biofacies and their distribution (Albani *et alii*, 1998; Donnici & Serandrei-Barbero, 2002), related to various depths and varying degrees of mixing of lagoon or fluvial waters, yielded further information on marine palaeo-environments.

In the coastal waters around the Lagoon of Venice, *Ammonia beccarii* (Linnaeus) and *Textularia agglutinans* (d'Orbigny) are considered key species. The former dominates in coastal waters

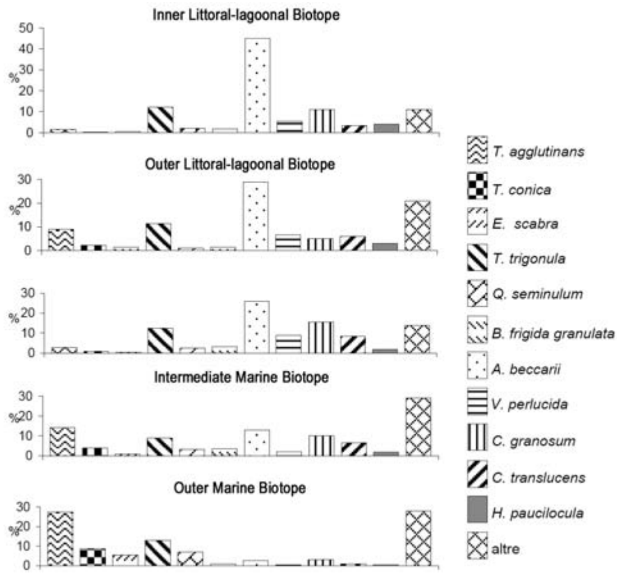

Fig. 35 – *Average composition of foraminiferal biotypes in Gulf of Venice, to isobath –18 m (from* Albani et alii*,1998, modified).*

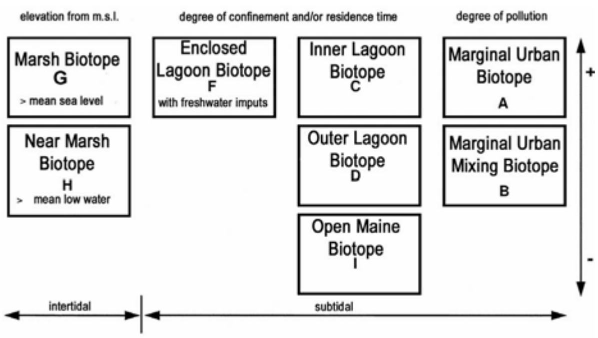

Fig. 34 – *Main factors controlling distribution of benthic foraminiferal biotypes identified in Lagoon of Venice (from* Serandrei-Barbero et alii*, 2003a, modified).*

subjected to mixing with lagoon waters leaving the port mouths. The latter, together with the occasional presence of many neritic taxa, is more prevalent further offshore, in typically marine waters on the shelf, not directly influenced by lagoon or fluvial flows. Their relative abundances are shown in Fig. 35, together with the progressive increase in number of species with increasing proximity to strictly marine waters.

Special mention must be made of *Eggerella scabra*

(Williamson), as its maximum concentrations were observed off the present-day Po Delta, with abundances distributed along the mixing plume of seawater, falling with increasing distance from the mouths (Donnici & Serandrei-Barbero, 2002).

The presence of these key species and their relative abundances, together with the number of species found in studied samples, yielded precise information on the Holocene marine palaeo-environments. They also allowed characterisation of Tyrrhenian marine units reached by the *CARG 12* borehole, represented by sandy sediments of inner shelf environment and containing the typical association of non-detritivorous taxa of nutrient-poor sandy bottoms (Jorissen, 1987), only slightly influenced by supplies from the Po.

Lastly, all identified deltaic environments, internal deltas and prodeltas had an abundant clastic fraction. Although the foraminiferal associations contain some lagoon, coastal or shelf taxa, they generally have fewer species and individuals compared with the typical *biofacies*.

1.2. - Sedimentary and geomorphologic features

Due to the complex dynamics of sediment transport and remixing, the studied depositional environments have very variable lithologies with common features. In addition, as often happens in transition areas, it is not always possible to distinguish the deposits clearly by analysing their faunal associations. It was therefore also essential to combine palaeontological studies with others on sedimentology, stratigraphy, and geomorphologic lineaments.

1.2.1. - *Alluvial and fluvial deposits*

Alluvial plains contain many traces of abandoned riverbeds, often in the vicinity of ridges in the surrounding areas. Crevasse splays were also identified, with dense networks of small distributor channels with dendritic development.

From the lithological viewpoint, active channel and fluvial ridge deposits consist mainly of sand, silty and clayey sand and sandy silt, at times containing organic matter. In sandy-silty rocks, flat-parallel and cross-laminations can be identified, as well as erosion pockets.

Instead, flood-plain deposits are characterised by finer silty and clayey grain sizes, sometimes associated with organic matter. Sandy intercalations, inside which traction structures may be identified, are very rare. Silt prevails in the areas between ridges and depressed interfluvial areas. Clay is found in flood basins and sectors of flood-plain located distally with respect to the watercourse, where suspended sediments settle. Clay bodies with ribbon development represent abandoned channel deposits. Peaty levels represent marshy *facies* in interfluvial basins.

Crevasse splays contain sandy-silty sediments which are therefore coarser than those deposited by overflow: they contain parallel laminations and graded structures and often also pelitic inclusions.

Soils which developed in subaerial conditions are frequent in all the above cases.

1.2.2. - *Deltaic deposits*

In the transition belt between the mainland and the internal margin of the lagoon, several small, variously lobed, delta mouth apparatuses were identified, located near the mouths of ancient watercourses in the lagoon.

It was often difficult to mark the division between deltaic and alluvial deposits, due to their gradual transition. In such cases, the distinction was mainly made on geomorphologic and sedimentological-stratigraphic bases, I.e., by considering the shape of the mouth apparatus, the possible presence and disposition of distributor channels (from which small overflow fans sometimes originate) and the geometry of the deposits, when sufficient information on the subsoil allowed it.

It was easier to mark the division between delta and lagoon units, as back-up came from results of palaeontological analyses.

Freshwater marshy facies with peat deposits were frequently found near the deltaic bodies.

In addition, in interdistributor basins, where low-energy conditions favour settlement of fine sediments, clay and silty clay are often organic and sometimes bioturbated. They sometimes show dense lamination and contain thin bands of sand.

The grain size of deposits gradually increases as the channels are approached, so that clay bodies are replaced by silt with varying contents of clay and sand, often with clearly visible traction structures. Only near interdistributor channels or small crevasse splays can sand, silty and/or clayey sand be identified, since they give rise to slight ridges and show flat-parallel or cross-laminations or pelitic inclusions, indicating environments subjected to higher energy.

1.2.3. - *Littoral deposits*

As in the deltaic environment, the coastal environment is also considered in a transitional stage. From the geomorphologic viewpoint, according to the definitions proposed by Ricci Lucchi (1978), the littoral environment of the Lagoon of Venice is currently identified as a complex coastline in which the beach is found offshore, associated with an emerging sandy ridge (lido, littoral) which forms a discontinuous barrier between the open sea and the protected area behind it (lagoon). In particular, this is a barrier-lagoon. Starting from the Pleistocene in the Venetian area, similar conditions recurred many times, following transgressive marine events.

Therefore, inside the coastline environment, it was considered opportune to distinguish beach deposits (i.e., areas of emerging, intertidal and submarine sand) from those of the lagoon.

The main morphological lines - shown on the Geological Map, as they are viewed as excellent environmental indicators - were the ancient beach ridges (in the littoral beach environment) and the lagoon palaeochannels (in the lagoon littoral environment).

From the lithological viewpoint, beach deposits are usually sand, silty sand and very sandy silt (often with cross-laminations or layers with abundant shells), forming beach ridges and dune systems: the latter often typically have well-sorted sand. Negative vertical granulometric sequences often appear in beach ridges, evidence of beach progradation. Instead, silt and clayey silt, sometimes containing organic matter, are limited to interdune areas.

The lagoon deposits consist of sand and silty sand, deposited near the lagoon mouths, the shallows and high-energy channels, or near the beach, where they are at risk of *washover* splays. These deposits are often the consequence of remixing of beach sediments caused by lagoon currents. Silt, clayey and/or sandy silt, sometimes with organic matter, form the typical lithology of lagoon basins, tidal flats, mud flats and salt marsh; the coarser fractions are found nearer the lagoon mouths.

Clay and silty and/or sandy clay, often rich in organic matter, are deposited in areas of poor water circulation and/or tend to form marshes. Peat, often containing silty-clayey sediments (organic soils), are found in marshy areas near the marginal lagoon belt, in the vicinity of land, in back-barrier areas and the beach ridges beyond. Thin stratifications and dense laminations distinguish the granulometrically finer sequences. Lagoon deposits are also normally bioturbated.

Patches of reddish-brown, oxidised concretions, silty-clayey aggregates and vegetal remains are sometimes found within the typical lagoonal sequences. They often conserve their original growth positions, and are thus indicators of salt marshes created by emergence of previously submerged lagoon bottoms.

1.2.4. - *Shelf deposits*

No particular geomorphologic indicators were identified in the shelf environment, which contains shallow offshore deposits with prevailingly fine sediments.

2. - PALYNOSTRATIGRAPHY OF *CARG 5* BOREHOLE (BH2)

Micropalaeobotanical study contributes towards the reconstruction of the palaeo-vegetal, -climatic and -environmental events of the Venetian area (Favero *et alii*, 1973; Favero *et alii*, 1995; Serandrei-Barbero, 1975; Favero & Serandrei-Barbero, 1983; Paganelli, 1996a; 1996b; Bondesan *et alii*, 1999; Serandrei-Barbero *et alii*, 2001; Serandrei-Barbero *et alii*, 2002; Massari *et alii*, 2004). It also supplies a reference palyno-

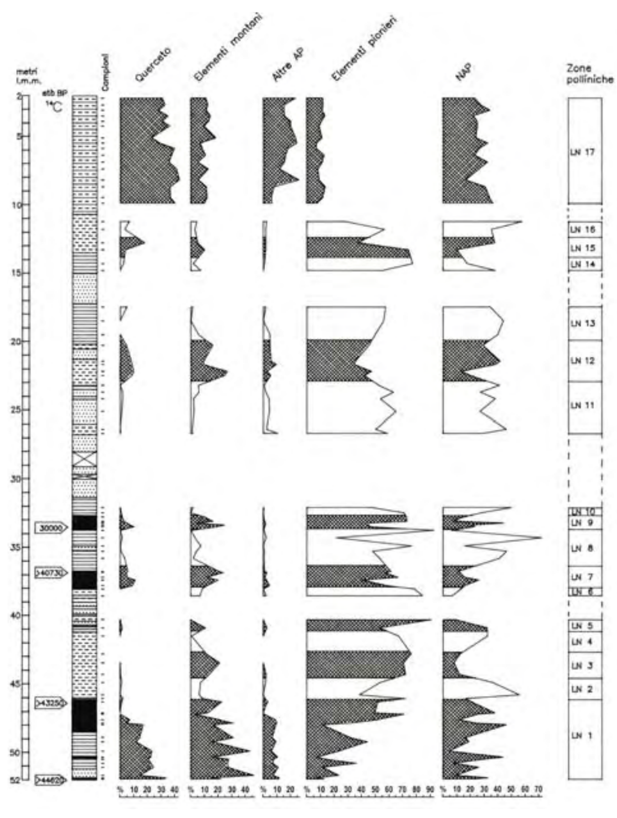

Fig. 36 – *Pollen diagram of* CARG 5 borehole, *showing five vegetational groups.*

chronostratigraphic picture for most of the Late Pleistocene by correlations with other surveys (MÜLLENDERS *et alii*, 1996; SERANDREI-BARBERO *et alii*, 2005b).

The *CARG 5* borehole (BH2), which reached 52 m below sea level, passed through the Holocene sedimentary succession (*Po Synthem*) and the upper part of the Late Pleistocene succession (*Mestre Supersynthem, and* perhaps also the top of the *Correzzola Unit*). Chronostratigraphical verification was possible on deposits by means of ^{14}C analyses (see Section III-4).
For palynological study, a total of 80 samples was selected, mainly from silt and clay levels.

The percentage values of microscopic analysis are shown in Fig. 36, in which the various taxa are grouped, according to their chronological-environmental and climatic significance, into five vegetational groups: mixed oak forest (including temperate-warm non-coniferous and particularly *Quercus* as the main element), mountain elements (*Fagus, Abies and Picea*), pioneer elements (mainly *Pinus*, at times with high values of *Betula and* always low values of *Juniperus and Hippophae*), other AP (other arboreal plants, not climatically significant, usually indicators of local edaphic conditions: *Salix, Alnus*, see *Populus*, *Caprifoliacee*, etc.) and NAP (summation of non-arboreal plants, mainly herbaceous). Standing out specifically are the *Gramineae*, herbaceous taxa of arid/halophile environments like *Artemisia*, *Chenopodiacee* and *Armeria,* with exiguous *Ephedra*, plants from well drained environments (various Compositae, *Heliantemaum* and other Cystaceae, Cruciferae, Leguminosae, etc.); hygro-hydrophytes were few and discontinuous.

A total of about 60 pollen taxa were found, subdivided approximately into equal parts between arboreal (AP) and non-arboreal plants (NAP). The flora is of modern type, now characteristic in northern Italy, with the exception of a few remains of *Carya and Pterocarya* found at the bottom of the profile.

All pollen curves show evident positive and/or negative fluctuations, partly matching and partly in opposition.

These oscillations, significant from the palaeoenvironmental viewpoint, allow the identification of 17 pollen zones, from LN 1 to LN 17, all with AP prevailing over NAP.

In the vegetational succession are clearly recognisable the pollen zones which have significant percentage values of the exigent groups (mixed oak forest and mountain elements), alternating with phases in which only pioneer elements, but with NAP in expansion, dominate.

Among the former, those at the bottom and top of the diagram are clearly distinguishable, as they are also the largest (LN 1 and LN 17 respectively). There is the distinct dominance of temperate-warm and/or temperate-cool elements; the *Pinus* group is more or less contained. They correspond to large forested phases, when pollen concentrations reach their highest values, revealing the existence of a compact forest coverage.

In particular, the most ancient pollen area (LN 1) covers the medium-upper portion of a temperate-warm phase, initially marked by high non-coniferous values and mountain elements that become gradually less dense, favouring pioneer elements, which increase from their extremely low values until they dominate the area. The most recent area (LN 17) is characterised by the constant prevalence of mixed oak forest, followed by mountain elements and other AP; the group of *Pinus* shows only very modest values.

The long intermediate interval in the palynological profile, from LN 2 to LN 16, shows a succession of vegetational cycles characterised alternately by more or less open monotone formations, essentially with Pines, other exiguous pioneer elements, in which NAP always show the tendency to expand (LN 2, 4, 6, 8, 10, 11, 13. 14, 16), and increasing Pine formations, but with a significant representation of temperate and temperate-warm taxa (LN 3, 5, 7, 9, 12, 15) and NAP with a tendency to diminish. The former represent glacial and/or stadial phases, and the latter interstadial phases, in any case with a more or less gentle climate that favoured the expansion of existing non-conifers and conifers. AP concentrations are much lower in the glacial phases, but tend to increase in interstadial phases, with the exception of LN 7 and 9 which show unusually high values, most probably revealing extremely slow sedimentation in swamp environments.

This interval in the vegetational sequence is not continuous, but has at least four evident pollen gaps. A few brief gaps *which* are not palynologically detectable, may exist in the lower portion.

Fig. 37, essentially on palynological bases, represents an attempt to compare, from a cronostratigraphic viewpoint, the pollen zones found in the CARG 5 borehole with several well-known European sites. The upper and lower forested phases are attributed respectively to the isotopic marine phases of $^{16/18}O$ (MIS) 1 and 5, probably substage 5a, matching results from boreholes in the lower Po Valley (AMOROSI *et alii*, 1999). The long interval with recurrent vegetational cyclicity between these two phases is attributed to isotopic phases 2, 3 and 4. The climatic succession of the *CARG 5* borehole therefore covers, albeit not continuously, the last 80,000 years. It begins with S. Germain II, with floristic-vegetational and therefore

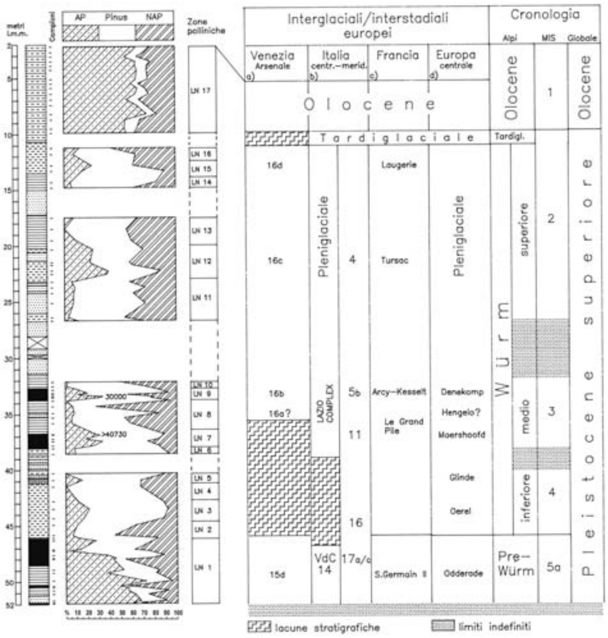

Fig. 37 – *Attempt at palynochronostratigraphic organisation of CARG 5 pollen sequence of northern Lagoon of Venice, comparing it with other palynological sites of Italian and central European Upper Pleistocene (*HAMMEN VAN DER et alii*, 1967;* LEROI-GOURMAN*, 1968; 1980;* FOLLIERI et alii*, 1988;* BEHRE*, 1989;* BEAULIEU DE *&* REILLE*, 1992;* BEHRE *&* VAN DER PLICHTR*, 1992;* MÜLLENDERS et alii*, 1996;* WATTS et alii*, 1996;* FOLLIERI et alii*, 1998;* ALLEN et alii*, 1999).*

climatic characteristics which differ completely from the overlying phases, for which a tentative link with the cyclicity of the long Eemian phase has been made.

The succession follows with a long sequence of stadial and interstadial cycles and terminates, with a stratigraphic gap, in the mid-upper Holocene.

Of the four radiometric datings on the peat layers in the lower part of the profile, only the two top ones (-33.20 m, -36.85 m) could be used, although with caution. LN 9 was correlated with the Denekamp interstage of mid-European authors, as testified by ^{14}C dating. LN 7, going back to more than 40,730 years BP, is referred to a more ancient favourable phase of the Hengelo interstage, probably also the Moershoofd interstage, with the consequent possibility of a sedimentary gap in LN 8.

Interstadial phases LN 3 and LN 5 are clearly older, and they are tentatively attributed to the early Würmian. The two lower ^{14}C datings (- 46.25 m, -51.95 m) only provide a temporal limit, and therefore match the interpretation given above.

The medium-upper part of Fig. 37 almost entirely embraces the Last Glacial Maximum (LGM). The two favourable phases, LN 12 and LN 15, are correlated respectively with the mitigated oscillations of the Tursac and Laugerie, palynologically traced and radiometrically dated in the *Arsenale* area (SERANDREI-BARBERO *et alii*, 2005b). As in the *Arsenale* borehole, the sequence of the LGM is followed by a stratigraphical gap, about 13,000 years long, identified in various sites of the historic city centre of Venice and the lagoon (BORTOLAMI *et alii*, 1977), which obliterated the succession of events at the end of the Glacial, Late Glacial and lower-middle Holocene epoch.

3. - REFERENCE STRATIGRAPHICAL UNITS

Initially, guidelines for geological mapping of Quaternary deposits in plain and marine areas required classification in the form of allostratigraphic units (CATALANO *et alii*, 1996; SERVIZIO GEOLOGICO NAZIONALE, 1999), i.e., mapping of "stratified bodies defined and identified on the basis of the discontinuities that limit them" (NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE, 1983), although *Quaderno* 1, serie III, of the SERVIZIO GEOLOGICO NAZIONALE (1992) had already favoured the *Unconformity Bounded Stratigraphic Units* (UBSU). A recent document published by the SERVIZIO GEOLOGICO NAZIONALE (2001), regarding a survey of the continental Quaternary for the Geological Map of Italy, scale 1:50,000, established that, for classification of sedimentary bodies, reference must be made to the UBSU, defined solely on the basis of the presence of two limited discontinuities that are significant and can be documented. Therefore, each unit can be extended laterally only if both discontinuities are visible and can be identified.

As explained previously, the entire sequence of Quaternary deposits of the Venetian district were studied by means of continuous core sampling surveys: *Venice 1 – CNR* and *Venice 2 – CNR* (National Research Council), 1971, FAVERO *et alii*, 1973; SERANDREI-BARBERO, 1975; FAVERO *et alii*, 1979; FAVERO & PASSEGA, 1980; BELLET *et alii*, 1982; MÜLLENDERS *et alii*, 1996; MASSARI *et alii*, 2004).

In view of the aim of geological cartography, study of the first 20-30 m of subsoil was privileged, i.e., units belonging to the Last Glacial Maximum (LGM) and Holocene deposits. These sediments, outcropping or suboutcropping in the Venice Sheet, together with the quantity of available data enabled them to be mapped properly.

In any case, 100-m-deep core sampling (*CARG 12*) was undertaken. Due to correlations with the *Venice 1 –CNR, Venice 2 – CNR* and other adjacent boreholes, this facilitated general reconstruction of the stratigraphy of the deposits of the Eemian

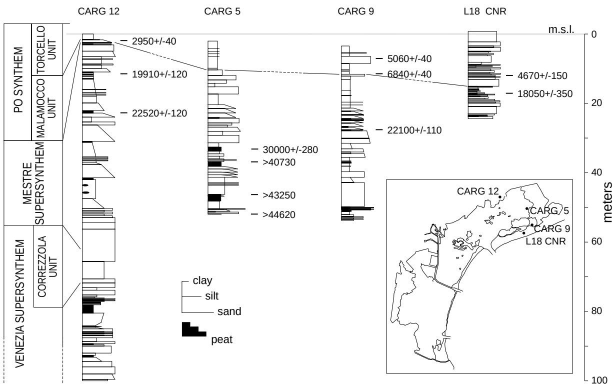

Fig. 38 – *Stratigraphic relations of Venezia, Mestre Supersynthems and Po Synthem. Prevailing lithologies are reported in margins, and confirmed in four core samplings and several radio datings (years BP not calibrated).*

phase in the Venice Sheet and the adjacent Chioggia-Malamocco Sheet. Analysis of three other surveys, drilled down to 50 m (*CARG 4, 5,* and *9*, ex *BH*) and made available by the Venice Water Authority, provided further details on the stratigraphy and the Late Pleistocene depositional conditions after the last interglacial period.

Palynological analyses were also made of the *CARG 5* (*BH2*) samples, and identified several key elements of the Venetian subsoil that were useful for chronostratigraphic correlations.

In addition to the information from the CARG samplings, many other data have recently been acquired in the historic city centre of Venice within the framework of other projects. These analyses have made it possible to reconstruct in detail the stratigraphic layout of the Venetian subsoil to the first 24 m of depth and to characterise the palaeo-environmental evolution of the area, starting from the Late Pleistocene.

Radiometric datings were used to identify sedimentary levels corresponding to the interstadial Tursac and Laugerie periods, dated respectively 21,750 and 19,000 years BP and located at depths between about -22 m to -14 m and from -11 m to -6 m (Serandrei-Barbero *et alii*, 2001; Serandrei-Barbero *et alii*, 2002).

The oldest unexposed stratigraphic unit considered in the Venice Sheet is the *Venice Supersynthem* (Fig. 38), overlain by the *Correzzola Unit*, which identifies Tyrrhenian deposits. It is followed upwards by the *Mestre Supersynthem*, which includes alluvial deposits that end with the LGM.

The *Po Supersynthem* lies on the *Mestre Supersynthem*. In the Venice Sheet, the former consists only of Holocene deposits. Where possible, it was separated into the *Malamocco Unit* and *Torcello Unit*, the latter of post-Roman age.

The *Po Synthem* corresponds to the *Allomember of Ravenna*, drawn in the Sheet 223 "Ravenna" (Amorosi, 1999). The *Torcello Unit* coincides with the *Modena Unit,* shown on the same sheet.

4. - VENICE SUPERSYNTHEM

The unexposed *Venice Supersynthem* includes the post-Messinian units deposited, starting from the Pliocene until the base of the Upper Pleistocene. At the top, it ends with the *Correzzola Unit* (CRZ), which consists of marine sediments of Tyrrhenian age. The lower limit thus coincides with the Messinian discontinuity, whereas the higher limit, which separates it from the overlying *Mestre Supersynthem*, has been related to the passage from units of a lagoonal-deltaic environment to later alluvial-type deposits.

Sedimentological data on the depositional environments of the *Venice Supersynthem* are limited to interpretations of analyses of samples from three surveys: *CARG 12*, *Venice 1 – CNR* and *Venice 2 – CNR* (Favero *et alii*, 1973; Serandrei-Barbero, 1975; Favero *et alii*, 1979; Favero & Passega, 1980; Bellet *et alii*, 1982; Müllenders *et alii*, 1996; Massari *et alii*, 2004) and from a set

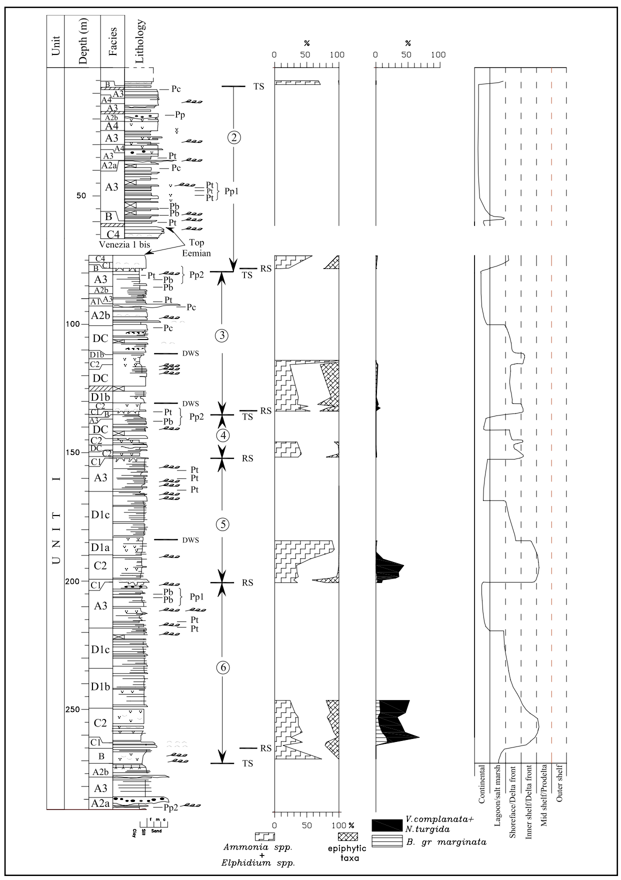

Fig. 39 – *Stratigraphy of upper part of Venice 1 – CNR borehole (from* Kent et alii*, 2002, and* Massari et alii*, 2004). Sequences Pb, Pt, Pc, Pp1, and Pp2 are palaeosols; Pa represents peat levels.*

of selected stratigraphies of wells, many of which were drilled for water. Hoever, available data allowed proper study only of the upper part of this Supersynthem, i.e., the sequence deposited during the Tyrrhenian marine transgression, although its base could not always be defined. Study of the *Venice 1 – CNR* borehole shows that this sequence has neritic *biofacies* at the bottom and lagoonal *biofacies* towards the top (Müllenders *et alii*, 1996; Massari *et alii*, 2004) (Fig, 39).

In the *CARG 12* survey, at -91.6 m the sporadic presence of benthic foraminifera in silty sand containing layers of organic silt identifies a deltaic front environment. Between about -71 m and -65 m, there is a transition from sediments of neritic *facies* to lagoonal deposits. The transgressive event is evidenced by a rich association of benthic foraminifera which, at the base of the latter interval, includes 28 taxa defined by a relatively low quantity of *Ammonia beccarii* (Linné) and many taxa of neritic environments, such as Lagenides and genera *Textularia, Globulina* and *Guttulina*, in addition to numerous Miliolidae. Lithologically, these units consist of compact silt with centimetric sandy intercalations containing abundant marine bioclasts and biosomes.

The neritic deposits at -91 m and -70 m belong to the Tyrrhenian and coincide with stage 5.5 and 5.3 marine isotopes. Instead, between depths of about -90 m and -71 m prevalently silty *facies* of the alluvial plain are found. They are characterised by no organogenic content and sporadic carbonatic concretions and oxidised layers indicative of pedogenesis. Lastly, between -65 m and -55 m, there is another transition to deltaic front sediments, consisting of sand containing very few marine mollusc shells.

Despite the reduced number of core samplings analysed, a lateral correlation of the top of this Supersynthem was attempted with data acquired for processing the adjacent Chioggia-Malamocco Sheet, from surveys in Correzzola (Accordi & Socin, 1950), ISES B (Carbognin & Tosi, 2003), Valle Averto (*CARG 11*) (Donnici & Serandrei-Barbero, 2004) and Malamocco (Paganelli, 1996a; Calderoni *et alii*, 1998; Calderoni *et alii*, 2000). The depth of the Supersynthem was found to be between -50 m and -80 m in the lagoon area and facing drainage basin.

4.1. - Correzzola Unit

The *Correzzola Unit* (CRZ) represents the upper part of the *Venice Supersynthem*, and consists of sediments deposited during the last Tyrrhenian marine transgression. Study of this unit applied data from cores defining the Supersynthem (listed in previous section).

In particular, in the *CARG 12* core, this unit coincides with the sequence between about -70 m and -55 m, characterised by compact silt with sandy intercalations of neritic facies at the bottom and lagoonal facies at the top between -70 m and -65 m, and by sandy deltaic front sediments containing very few marine mollusc shells between -65 m and -55 m.

Depths varying between -70 m and -50 m were found in the area of the Venice Sheet, at the upper limit of the *Correzzola Unit*. This was similar to cores throughout the Venetian lagoon area. Therefore, this unit is not exposed in the Venice Sheet, because the lagoon channels never reached its top.

5. - MESTRE SUPERSYNTHEM

The *Mestre Supersynthem* (MT) lies on the *Venice Supersynthem*, and is represented by alluvial plain deposits consisting of silt, sand and clay, locally pedogenesised. Coarser, prevalently sandy sediments are found near ancient ridges; finer ones are located in interfluvial basins of the flood-plain, where locally marshy conditions are revealed by peat bogs and organic horizons, often containing freshwater bioclasts.

The structure of the fine deposits is generally tabular and laminated, alternating with peat levels which can sometimes be well correlated at a distance. Instead, the distribution of sand often follows winding preferential directions, defining the courses of ancient rivers. Sandy fillings in deep incisions (up to 10-15 m deep) can sometimes be identified.

At the base of the *CARG 5* (*BH2*) borehole, reaching -52 m from sea level, palaeo-ecological and palynostratigraphic studies (see section IV) identified a deposit in alluvial facies, which seemed to correspond to the middle-upper portion of a temperate-warm phase that could be correlated to the Eemian phase. However, the relatively limited depth of this core sample made it impossible to reach the marine sediments of the *Correzzola Unit*. In examining the adjacent deep boreholes, however, the base of *CARG 5* is confirmed to be close to its top. Therefore, the events of the past 80,000 years are hypothetically recorded down to about -50 m.

Unlike the situation in the Venetian subsoil, where study of fossil pollens (Müllenders *et alii*, 1996) revealed four periods of milder climate between 40,000 and 19,000 years BP, preceded by a stratigraphic gap between 60,000 and 40,000 years BP, all the interstadial phases known for the last glaciation were evidenced in the northern part of the lagoon, with the exception of Hengelo. The two most recent phases were found at -23 m and -13 m respectively, and were associated with the oscillations of the Tursac and Laugerie periods (Section 2).

Data from the CARG boreholes and many others drilled in the city centre of Venice provided estimates for the dates of the Tursac and Laugerie oscillations which, in the Venetian subsoil, correspond to sediments at 18-15 m and 10-8 m below mean sea level, and supplied radiometric ages of about 21,000 and 19,000 years BP (Serandrei-Barbero *et alii*, 2001; Serandrei-Barbero *et alii*, 2002).

The top deposits of the *Mestre Supersynthem*, which date back to about 18,000 BP, show evident signs of pedogenesis, which developed in conditions of prolonged subaerial exposure. Therefore, the boundary with the subsequent Holocene units is often marked by a surface of erosional or "non-depositional" type.

At the top, although variable lithologies occur, over-consolidated clay, known locally as *caranto* and considered to be a palaeosoil, is frequently found (Gatto & Previatello, 1974; Tosi, 1993; 1994a; 1994c; Bonardi & Tosi, 1994b; 1995a; 1997; 1999; 2000a; 2000b; 2001; Bonardi *et alii*, 1997; Brambati *et alii*, 2003; Mozzi *et alii*, 2003).

The *caranto* varies in thickness from a few centimetres to 2 m, and generally consists of clayey silt or very compact silty clay. It is pale grey in colour, with ochre speckling, and contains carbonate nodules only a few millimetres in diameter. The accumulation of these levels and the ones immediately below them took place between

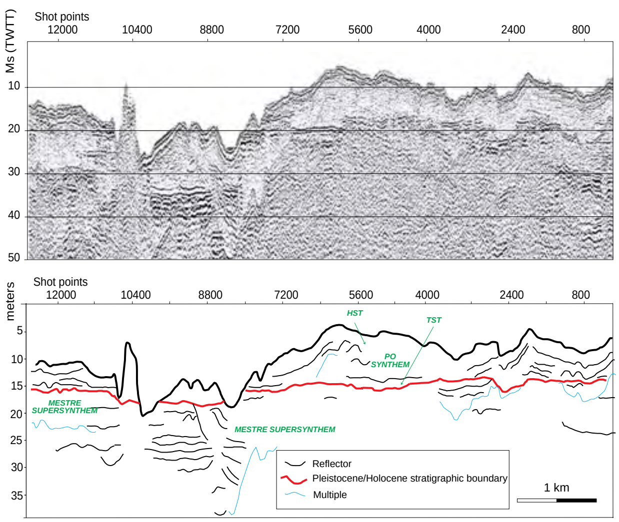

Fig. 40 – *Portion of CH_31 high resolution seismic section.*

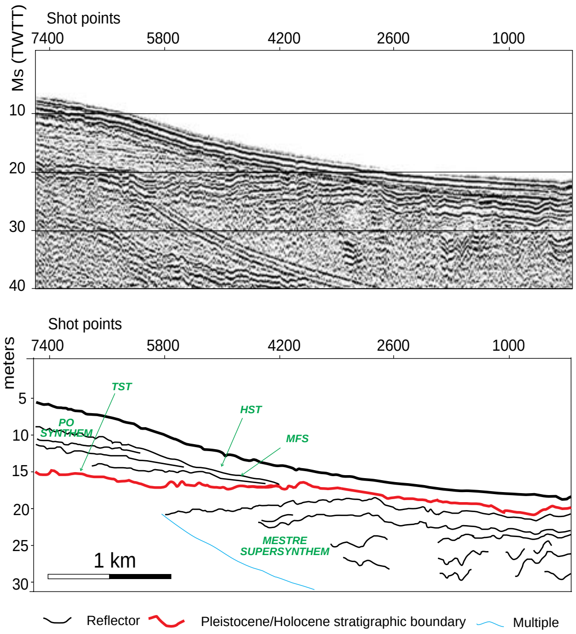

Fig. 41 – *Portion of Li_07 high resolution seismic section.*

20,000 and 18,000 years BP. Recent studies place pedogenesis and over-consolidation within the phase corresponding to the stratigraphic gap, or the phase of reduced sediment supplies which occurred between 14,500 BP and the beginning of the Holocene transgression (Mozzi *et alii*, 2003; Serandrei-Barbero *et alii*, 2005b).

The *caranto* is an excellent guideline layer, identifying the boundary between Pleistocene and Holocene deposits. Unfortunately, however, it has more or less extensive, localised lateral discontinuities, represented by *facies* consisting of sand (probably fluvial ridges), sometimes cemented or markedly non-overconsolidated clay (of lacustrine-marshy origin), but with traces of pedogenesis which may have been impeded by particular features of texture and deposition. Locally, where the Pleistocene units were influenced by fluvial channels and Holocene lagoons, the relative stratigraphic sequences appear to have been interrupted by more recent filler deposits of alluvial or marine type.

An important contribution to the study of the *Mestre Supersynthem* was made by high resolution seismic surveys in both lagoon and sea, which identified a series of extended, laterally easily correlated horizons consisting of erosional unconformities and highly reflective peat levels, probably due to the presence of gas.

Figs. 40 and 41 illustrate two portions of seismic sections, showing the unconformity between the *Mestre* and *Po Supersynthems*, together with a series of minor reflectors.

In the Venice Sheet, the *Mestre Supersynthem* outcrops in the plain sector extending south of the Sile, representing the distal offshoots of the Late - Pleistocene depositional system of the Brenta (section II-2.1) and in the deepest channels of the lagoon (section V-1).

6. - PO SYNTHEM

In the Venice Sheet, the *Po Synthem*, indicated on the Geological Map as POI, is made up of Holocene deposits. The boundary with the underlying *Mestre Supersynthem* is unconformable and erosional. Matching the reports of other authors (Bortolami *et alii*, 1884; Tosi, 1994c), a stratigraphic gap occurs, ranging in time, depending on zones, from about 8,000 to 13,000 years BP and therefore including part of the lower Holocene.

The base of the *Po Synthem* varies in depth, reflecting the morphology of the Pleistocene plain during the LGM. In the area of the Venice Sheet, this synthem is thicker near the present-day northern coast (15-17 m). Thickness falls to less than 1 metre at the underlying Pleistocene-Holocene boundary, proceeding towards the lagoon margin of Mestre-Tessera, and in the Adriatic near the isobath -23/25 m.

The *Po Synthem* is the best represented stratigraphic unit, and its top corresponds to present-day deposition. It is divided into two units of lower rank: *Malamocco Unit* (POI_9) and *Torcello Unit* (POI_{10}). Both consist of sand, silt, clay and peat from alluvial, deltaic, lagoonal, beach and platform environments, distinguished only on chronological bases.

6.1. - Malamacco Unit

The *Malamacco Unit* (POI_9) is the lower and thus older part of the *Po Synthem*. The basic sediments consist of transgressive marine deposits in the central-eastern sector and of alluvial-deltaic deposits in the western sector. The former reflect the progressive landward migration of a coastal barrier, behind which a lagoon had formed. They therefore include sandy-silty beach deposits, at the base of which a fine horizon, abounding in marine bioclasts and biosomes in a scarce detrital matrix and silty-clayey lagoonal sediments (at times organic) of the back barrier, often occurs. Generally, the beach deposits overlie the back barrier ones, from which they are separated by means of a transgressive surface, weakly submerging to the SE. Conversely, in several cases, the transgressive barrier sediments lie with erosional contact on the underlying Pleistocene alluvial units.

Under the back barrier deposits are fine levels of redistributed sandy silt, containing Pleistocene clay breccias, of chaotic structure. This clay is referred to as "overflow", since it originated by breaching resulting from deglaciation or marine transgression.

Near the belt of mainland facing the lagoon, the back barrier deposits are interfingered with those of an alluvial-deltaic environment, the sequence of which often begins with fine levels of "overflow" like the ones described above.

The transgressive deposits are buried under ones belonging to the progradation system formed during the sea level highstand.

The transgressive and prograding units of the littoral belt generated a sandy-silty body thinning to the NW, the geometry of which is particularly complex in the sector close to the present-day coastline. There, the disposition and reciprocal relations between the various *facies* show that the coastline migrated, first landwards and then seawards.

Behind the beach deposits are silty-clayey lagoonal sediments, sometimes organic, of the back barrier, interfingered with deltaic units that are often peaty in marshy *facies* in the sectors close to the internal margin of the lagoon.

Seawards, between the sand body consisting of the transgressive and progradation barrier deposits, is a unit with wedge-shaped geometry, made up mainly of silty shelf sediments. More towards the open sea, the latter completely replace the former.

The outcropping of the *Malamocco Unit* was ascertained in lagoonal channels and, in the eastern sector of the Sheet, near the ancient littoral belts identified on the mainland and in the lagoon (section V-1). The base of the *Malamocco Unit* corresponds to that of the *Po Synthem;* the top is of late-Roman age.

6.2. - Torcello Unit

The *Torcello Unit* (POI_{10}), which corresponds to the top and therefore most recent part of the *Po Synthem*, may refer to the post-Roman deposition that took place from the V-VI centuries AD until the present day. The base of this unit indicates a phase of climatic deterioration which, between the IV and VI centuries AD, caused not only a great increase in precipitation and consequently in flooding (Veggiani, 1994) but also probably a rise in sea level, leading to partial submergence of the lagoon. This event has often been shown by findings of lagoonal deposits above the Roman anthropised level. In the absence of similar

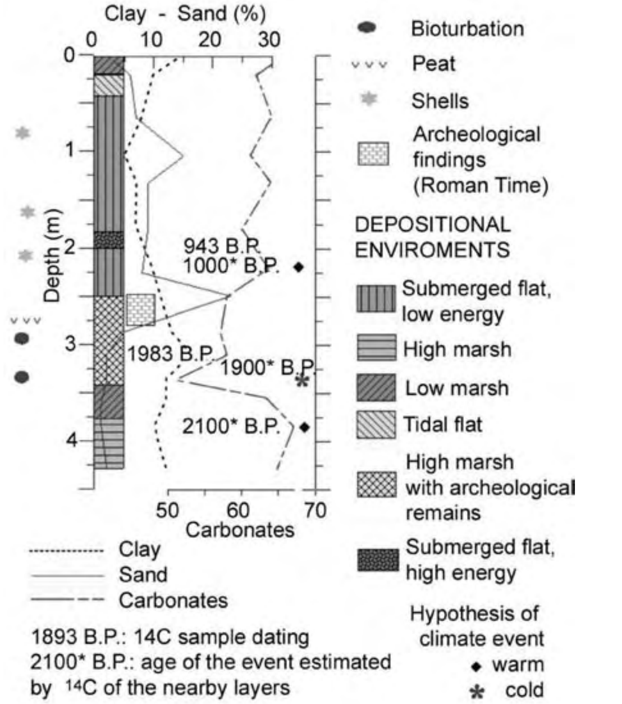

Fig. 42 – *Example of stratigraphy of* Torcello Unit, *obtained from core sample taken from lagoon basin near Burano-Torcello (from* BONARDI *&* TOSI*, 1997).*

evidence, the unit has been distinguished on the basis of other elements like those given in Sheet 223, "Ravenna", for the identification of the corresponding *Modena Unit* (AMOROSI, 1999). On the mainland, the lower limit of the *Torcello Unit* sometimes coincides with areas of fluvial erosion, correlated laterally to yellowish-brown and reddish-brown soils with partial or total decarbonation of surface layers and accumulations of carbonates in deeper ones.

Thanks to study of geo-archaeological levels, which occur extensively in the Lagoon of Venice and adjacent areas, and to interpretation of available chronostratigraphic data, this unit has been mapped wherever possible.

The *Torcello Unit* consists of sand, silt, clay and alluvial peat, deltaic, beach and lagoon deposits. Conversely, starting from the late Roman period until the present day, deposition of fine sediments in the shelf is believed to have been scanty. Overall, the distribution of the various *facies* making up the Torcello unit reflect sedimentation conditions very similar to present-day ones.

The considerable availability of drillings on the mainland and of surface core samples from the lagoon made it possible to reconstruct the geometry, distribution and stratigraphic disposition of the relative deposits in greater detail than for the other cartographic units in the Sheet. In order to interpret the characteristics of the subsoil classified within the framework of the *Torcello Unit* and mapping of relative deposits, information from historical sources was also particularly useful, since it gave valuable support to the reconstruction of the temporal variability of sedimentary environments.

The *Torcello Unit* varies in thickness from about 4 m in the littoral sector to 1-2 m at the periphery of the lagoon. Thicknesses are about 3 m in the central-northern lagoon, near the islands of Burano and Torcello.

An example of the stratigraphy of the *Torcello Unit* is given in Fig. 42, showing the boundary between it and the underlying *Malamocco Unit*. This boundary coincides with the discontinuity separating the Roman ground level from the overlying lagoonal sediments.

The *Torcello Unit* is the structure which outcrops to the greatest extent, both in the lagoon and on the mainland (section V-1).

7. - STRATIGRAPHIC CORRELATIONS AND EVOLUTIONARY MODEL

Attempts at correlating a level consisting of sand and fossiliferous sandy silt at the top of the Tyrrhenian marine deposits and therefore corresponding to the upper part of the *Correzzola Unit*, identified, although only locally, the top of this horizon, lying at a mean depth of between -60 m and -75 m.

The following stratigraphic correlations focus on the succession of deposits of the *Po Synthem*. Their stratigraphy is shown in three geological sections (for locations, see Fig. 43). The first two sections (Figs. 44 and 45) were conducted in a NW-SE direction (the first from Tessera to Punta Sabbioni, and the second across the Palude Maggiore to Cavallino). The third (Fig. 46) runs par-

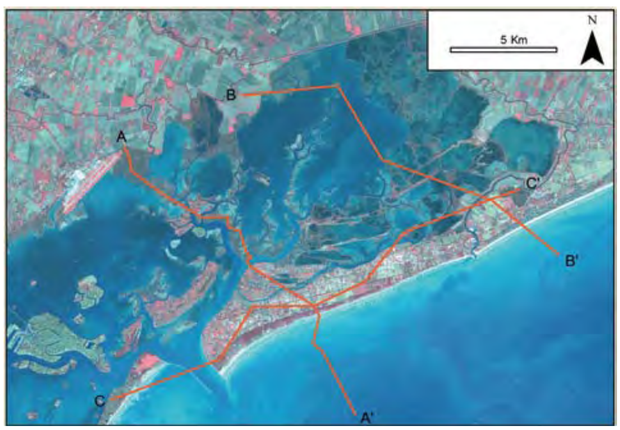

Fig. 43 - *Locations of three geological sections (ASTER image inbackground).*

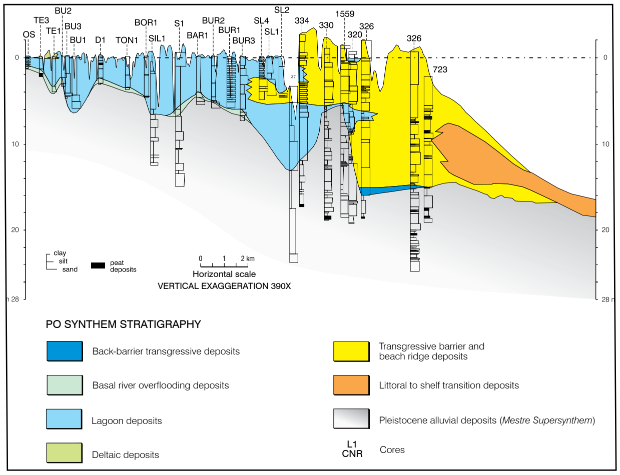

Fig. 44 – *Stratigraphy of Po Synthem, along a section from Tessera to Punta Sabbioni (location shown in Fig. 43).*

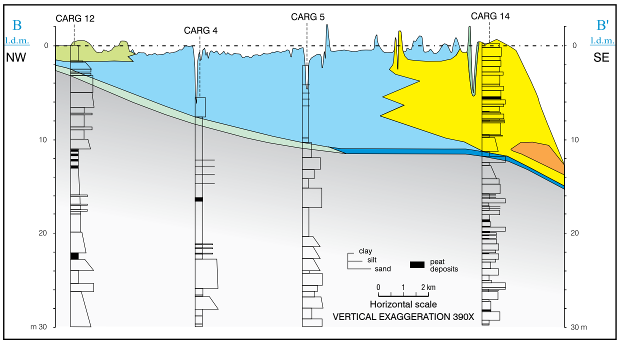

Fig. 45 – *Stratigraphy of Po Synthem, along a section passing across Palude Maggiore to Cavallino (location shown in Fig. 43; legend in Fig. 44).*

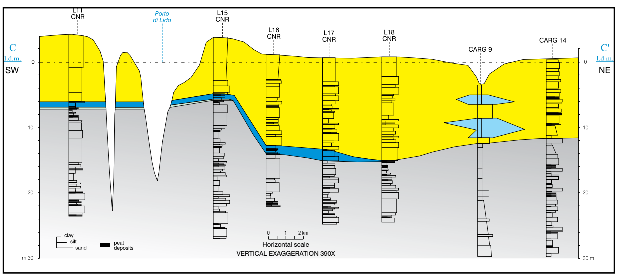

Fig. 46 – *Stratigraphy of Po Synthem, along a section from Punta Sabbioni to Jesolo Lido (location shown in Fig. 43; legend in Fig. 44).*

allel to the coast (from Bocca di Lido to Jesolo Lido).

The *Po Synthem* lies on Late Pleistocene alluvial deposits corresponding to the final phase of the *Lowstand Systems Tract* (LST) of the LGM. It is separated from them by a discontinuity deepening towards the SE, and topographically appears to be very irregular in the median sector of the northern lagoon. The relative geological section (Fig. 44) does show two deep cuts: one in the subsoil of the internal lagoon, towards Tessera, and the other near the San Felice Canal. The latter is followed SE by a ridge. Instead, a particularly evident morphological high appears near the Bocca di Lido (Fig. 46).

Caranto, often identified at the top of Late Pleistocene deposits, began to form when sedimentation near the Bassano megafan ceased, about 14,500 years BP (Mozzi *et alii*, 2003).

Towards the mainland, the Holocene sequence generally begins with prevalently silty-clayey sediments of a fluvial-lacustrine environment, deposited by flooding during the relative rise in sea level. These sediments are also found locally near the Bocca di Lido, on the above-mentioned morphological high. Elsewhere, particularly in the subsoil of the external lagoon area and the present-day littoral belt, the basic Holocene units consist of fine transgressive marine deposits. These various horizons, which mark the beginning of Holocene sedimentation, discontinously cover the area separating the *Mestre Supersynthem* from the *Po Synthem* and generally do not exceed 1 m in thickness. The frequent presence in them of particular sedimentary structures, such as erosion pockets and chaotic levels containing breccias of soil stripped from the top of the underlying Pleistocene continental units, indicates considerable reworking (Tosi, 1994c).

In the central-eastern sector of the area, the sandy-silty units of a littoral beach environment generally rest on marine deposits. They represent transgressive barrier facies at the base, and prograding littoral ridges at the top. To the SE, a cuneiform body occurs inside these units, consisting of finer pro-deltaic deposits, the thickness of which decreases progressively towards the open sea.

To the NW, transgressive barrier sediments are interfingered with silty-clayey lagoonal ones of the back barrier. They rest discontinuously on Holocene alluvial-lacustrine deposits or, where none exists, on Late Pleistocene continental ones.

The back barrier deposits, transgressive barrier deposits and the lower part of the pro-deltaic wedge constitute the Transgressive Systems Tract (TST). They are followed upwards by deposits representative of the succeeding prograding phase which began around 6,500 years BP. This phase has been identified with the Highstand Systems Tract (HST).

HST units near the internal margin of the lagoon are partially composed of fluvial-deltaic facies laterally heteropic with those of the lagoon environment deposited behind the ancient prograding sandbanks, lying in a more external position.

V - CARTOGRAPHY

1. - SURFACE CARTOGRAPHY

The Geological Map was created with the aim of indicating the age, distribution, reciprocal relations, and lithological characterististics and facies of outcropping and sub-outcropping stratigraphic units in the study area. Topographical data allowed the depositional units and cartographic geomorphological lines to be located immediately.

The final result was achieved by collecting, analysing, processing and interpreting numerous data, some of which came from previous studies and some acquired exclusively within the CARG project. The Map may thus be considered the outcome of highly detailed, reciprocally complementary geological, geomorphological, sedimentological, mineralogical, palaeontological and geophysical studies, carried out over the entire territory. These studies are summarised as follows:

- **Collection, checking and interpretation of existing geognostic data** (surveys, drillings, paedological profiles, soil analyses), supplied by the Veneto Region, Province of Venice, Information Service of Venice Water Authority, and ARPAV, integrated both with data from existing bibliographic and cartographic sources and others from published and/or unpublished studies carried out by CNR–ISMAR within the framework of other research projects.
- **Analysis and interpretation of altimetric data** on submerged areas and of **bathymetric data** on the lagoon bottom and Adriatic bed, for morphological study. For this, the Altimetric Map of the territory, supplied by the Province of Venice, was also consulted.
- **Observation of many aerial photographs** taken between 1955 and 1999, in order to identify the main geomorphological outlines of the area and to differentiate textural variations in the terrain, thus facilitating mapping of lithological boundaries with relation to units to be mapped.
- **Direct survey** of the terrain.
- **New boreholes, hand-coring, trenches, and samplings,** within the CARG Project.
- **Sedimentological and stratigraphic study** of outcropping and sub-outcropping deposits sampled during the surveys mentioned above, or carried out within the framework of other research projects. The Geological Surface Map was created by examining mainland sediments down to about -1.5 m from ground level, excluding – if considered appropriate – the first 40-50 cm of subsurface, which generally represents the ground level worked or reworked by anthropic activities and thus characterised by mixed textures or backfill. Instead, in the Lagoon and Adriatic, difficulties in taking long cores from depth with simple manual instruments often required study of deposits on sediments sometimes no more than 1 m deep.
- **Interpretation** of results by submitting samples (sedimentological, micropalaeontological, mineralogical analyses and datings) to laboratory analysis.
- **High resolution seismic surveys** in the lagoon and northern Adriatic, with the support of the Department of Geophysics of the Lithosphere, National Institute of Oceanography and Experimental Geophysics, Trieste (OGS) and interpretation of results.

Following the indications of the *Servizio Geologico d'Italia* (now known as APAT), the Geological Surface Map, scale 1:50,000, was completed, thanks to interpretation of maps processed during the course of investigations, initially to scale 1: 10,000 and then reduced to 1: 25,000.

The legend was drawn up following CARG regulations for Quaternary mapping and those for identification and cartography of marine areas (SERVIZIO GEOLOGICO NAZIONALE, 2004). It was thus possible to classify and represent clearly the various sedimentary bodies identified and the main geomorphological outlines of the territory.

The legend was submitted to continual modifications and improvements, both as regards needs arising during map processing and also subsequent up-datings proposed by APAT.

Sedimentary bodies were classified according to Unconformity Bounded Stratigraphic Units (UBSU), which identify supersynthems, synthems and subsynthems (see section IV). They were differentiated on the basis of age, depositional environment, and texture of constitutive sediments and their defining discontinuities (RIZZETTO *et alii*, 2005).

These bodies began to form in the Late Pleistocene. However, in the study area, Holocene deposits attributable to the *Po Synthem* are prevalent and, where available information made it possible, the *Torcello Unit* and *Malamocco Unit* were identified and internally differentiated. Instead, Late Pleistocene deposits were classified within the framework of the *Mestre Supersynthem* and the upper part of the *Venice Supersynthem*.

In view of the particular nature and conformation of the territory, the depositional environments within which the mapped sedimentary bodies originated were highly diversified, and alluvial, deltaic, lagoonal littoral, beach littoral and shelf deposits were all identified.

In the northern Adriatic, the boundary between beach units and shelf units coincides approximately with the -10 m isobath, near which a reasonably clearcut transition to finer particle sizes offshore was also verified. Useful information on sediment distribution in this sector was supplied by ALBANI *et alii* (1998).

Lithologically, the considerable granulometric variability of the deposits involved differentiating four main textural classes: sand, silt, clay, and peat. Units with mixed compositions were attributed to each of these, according to prevailing grain size. Occasional reports of outcrops lithologically different from the surrounding ones were disregarded. This was because, if they were believed to be reliable, they would have involved mapping of sedimentary bodies that could not be mapped on the scale required by the survey.

All geomorphological features which valid contributions to identifying the deposits, differentiating the various facies, and attributing them to the proper depositional systems were also traced on the Geological Map. This also involved tracing palaeobeds, lagoonal palaeochannels, and the most prominent ancient sandbanks and ridges.

The positions of the main, once active, lagoonal openings are also marked, for better understanding of the stages which marked the geomorphological evolution of the territory. Other lesser features identified during study were deliberately omitted, although they served in palaeo-environmental interpretation of deposits. This was done in order to ensure that the final cartographic result was easily understandable.

The different types of information are indicated on the map in a combination of symbols and colours. Holocene and Pleistocene deposits belonging respectively to the *Po Synthem* and the *Mestre Supersynthem* were differentiated by colour. In each, different shades were later chosen, to indicate lesser units of order within the same synthem. Lastly, different nuances of each colour were used in order to define depositional environments.

Sediment grain sizes are represented by symbols of different colours, depending on the genetic processes responsible for the formation in question. Similarly, geomorphological features, indicated with appropriate simplified symbols, are marked in different colours, to highlight their origin.

1.1. – GEOLOGICAL MAP OF VENEZIA SHEET

The Venice Sheet includes the northern part of the Lagoon of Venice, its drainage basin, coastal elevations which, starting from the terminal stretch of the river Sile, extend SW as far as the Lido inlet, and a small portion of the northern Adriatic.

The foreland sector consists mainly of cultivated land, most of which has been subjected completely to reclamation, mainly between the end of the 19th century and the first half of the 20th century.

The territory is crossed by the rivers Sile and Piave, which are now embanked, and flow over ridges which are much higher than the surrounding plain. The area is also covered by a dense network of reclamation canals, some of which follow the courses of ancient natural rivers.

In the NW sector of the Sheet, the Sile winds SE as far as Portegrandi, where it once gave rise to a deltaic system extending into the lagoon. The decision on the part of the *Serenissima* (the Republic of Venice) to divert the Sile from Portegrandi to Caposile, which made the waters flow together within the channel of the Piave Vecchia, dates back to the 17th century. The Piave Vecchia is the ancient course of the Piave which predates the present-day one downstream of San Donà. The work, carried out between 1672 and 1682 with the aim of protecting the lagoon from silting up, involved lengthening the terminal stretch of the Sile by about 25 km and, in 1684, the definitive shifting of its mouth to Porto di Piave Vecchia.

The Piave, instead, marginally crosses the NE sector of the Sheet, on which only a short stretch of its rectilinear course appears, in a NW-SE direction. This was the outflow direction of the river at the end of the 17th century, as a result of a series of artificial interventions carried out on its original course, which corresponded to that of the present-day Sile. In the 16th century, because it was feared that the floods of the Piave could damage the nearby Porto di Lido, a proposal was made to divert it NE, without considering the possible imbalances which such work might cause. Initially, the *Serenissima* decreed the execution of a diversion left of the Piave: the "Taglio del Re", which was begun in 1565 and finished in 1579. It was made to favour only the outflow of floodwaters; ordinary waters were to have remained in the old bed, in order to guarantee navigability. Subsequently, since the work did not produce the desired results, another intervention was planned: the Piave would follow a new course immediately downstream of San Donà and feed a lake in the territory south of Palazzetto (near the NE margin of the Sheet) and east of the Taglio del Re. Dams would make the water flow into the Adriatic further east with respect to the previous mouth. The work, which began between 1641 and 1642, was concluded in 1664 when, by flooding the planned area, the Piave created the "Piave Lake", the external embankments of which were soon found to be weak. In 1683, a large breach caused the lake to disappear. Its waters flowed into adjacent channels, while the river established its mouth at Cortellazzo.

The fluvial system of the Piave is considered to be mainly responsible for the Late Pleistocene and Holocene evolution of a large part of the territory. In fact, the "Nervesa Unit" (alluvial fan of the Piave), to which the deposits of the coastal plain sector east of the Sile belong, probably started to form earlier than 20,000 years BP when, on leaving the foothills, the Piave began to flow east of Montello (CASTIGLIONI & FAVERO, 1987; BONDESAN *et alii*, 2002a). Only the surface portion of this unit seems to have been the result of depositional events that occurred in the second half of the Holocene (BONDESAN *et alii*, 2002a). Thus, the plain between the Piave and the Sile consists of terrains belonging to the Upper Pleistocene, on which lie more recent deposits of the Piave and, subsequently, of spring rivers, i.e., the Musestre, Vallio and Meolo (BONDESAN & MENEGHEL, 2004). ^{14}C datings of peat from depths between 2 and 3 m near the central-northern margin of the Venice Sheet supply ages between 22,000 and 16,000 years BP (BONDESAN & MOZZI, 2002)

Studies for the Geological Map, however, exclude the direct outcropping of the *Mestre Supersynthem* left of the Sile, near the plain sector, and attribute all the deposits mapped here to the Holocene, although the Pleistocene units are believed to be very close to the surface. At present, therefore, traces of palaeochannels and remains of fluvial ridges are evidence of the old and changing hydrography that has characterised the area since the Late Pleistocene.

The deposits belonging to the "Sile Unit", along the distal part of the junction between the alluvial fans of the Brenta ("BASSANO Unit") and the Piave ("Nervesa Unit") are also Holocene in age (BONDESAN *et alii*, 2002a).

Most of the mapped units in the plain area SW of the Sile on the Venice Sheet are the result of the depositional activity of ancient ridges of the Late Pleistocene outflow of the Brenta and are therefore attributed to the *Mestre Supersynthem*. Instead, only the terrains outcropping along the southern mainland area, behind the lagoon margin, are of Holocene age. This is confirmed by datings of two peat samples, one of which was collected west of Ca' Noghera, near the western boundary of the Sheet, at -1.3 m, and the other, between Altino and Portegrandi, at -1.7 m. They supplied calibrated ages of respectively 10,230-10,170 years and 9,010-8,630 years BP. These Holocene units, which are almost exclusively from an alluvial-deltaic environment, are probably the result of the depositional activity of the ancient southern courses of the Sile, the delta of which originated near the present-day Altino.

In the plain sector close to the lagoon, the boundary between Holocene and Pleistocene units was traced to include the stratigraphic and sedimentological characteristics of the deposits: in particular, where present, the depth of the *caranto*, made up of levels of silty-clayey sediments, was examined. These levels are often over-consolidated and therefore particularly hard, compact, and rich in carbonate nodules. In places where depth was greater than 1 m from ground level, outcropping units were defined as Holocene.

A first valid contribution towards understanding the Holocene evolution of the territory came from geomorphological studies, which facilitated identification of many extinct ridges of river outflows and traces of ancient deltaic systems, responsible for the modelling and progradation of the coastal area.

The main ridges differentiated are those which follow the courses of the Sile, the present-day Piave, and the Piave Vecchia, as well as the Taglio del Re ridge. The ridge of the Sile ends literally at Portegrandi; the downstream stretch of the Capo-

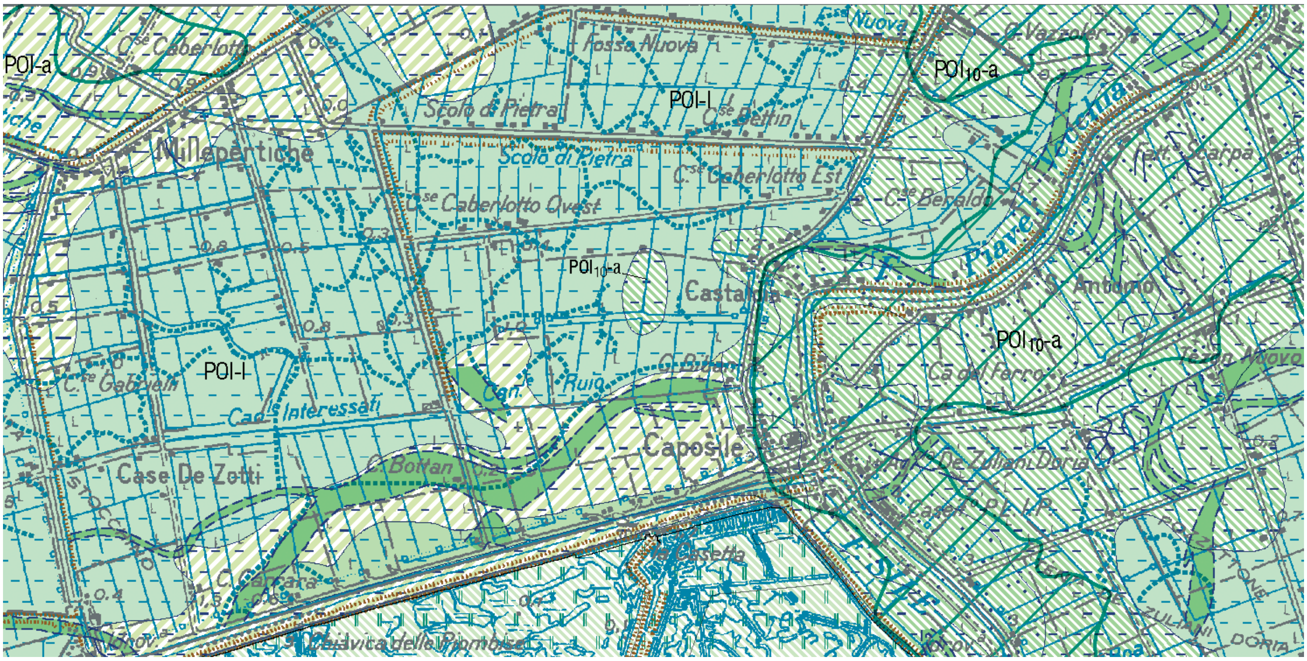

Fig. 47 - *Detail of Geological Map of Venice Sheet: area of Caposile*

sile is the result of depositional activity by the old course of the Piave.

The ^{14}C dating of a peat sample found at the base of the fluvial sand body near Caposile showed that this branch of the Piave was activated only after 530-680 AD (1,440±60 years BP) (Bondesan & Meneghel, 2004).

Other large ridges, extending W-E, with weak reliefs, occur NW sector of the Sheet, and probably belong to Pleistocene watercourses. In particular, those south of Quarto d'Altino may correspond to extinct ridges of the river Brenta (Fig. 15).

Instead, are present many traces of palaeochannels, generally winding, continuous and clearly defined: they are more abundant in the western sector of the mainland, where the direction of the courses changes progressively from NW-SE (north) to SW-NE (south). Thus, many of them converge in the direction of Portegrandi, where a large depression extends behind the lagoon almost as far as Caposile. At this point, some of these traces are interrupted brusquely near the lagoon margin.

In the central-northern area of the Sheet, from Marteggia eastwards, ancient fluvial courses extend continuously WNW-ESE as far as Millepertiche.

West of Caposile, a large palaeochannel was identified, developing parallel to the Taglio del Sile and continuing NE, following the course of the Piave Vecchia (Fig. 47). It very probably represents an ancient outflow ridge of the Piave, activated during the second millennium BC, as ^{14}C dating of the relative deposits give ages of 1390-1540 BC (3,200±50 years BP) (Bondesan & Meneghel, 2004).

Several poorly defined, discontinuous fluvial traces are also found on the left bank of the Piave Vecchia. Their directions indicate that they may have been connected to ancient branches of the Piave system, directed towards what is today the northern sector of the lagoon, now partly obliterated by more recent alluvial and lagoonal deposits. In this regard, the Caligo canal flows SW within a narrow strip of sediments extending into the lagoon, starting from the Piave Vecchia (Fig. 48). It connected the lagoon with the Piave as early as the 15th century, and had undergone interven-

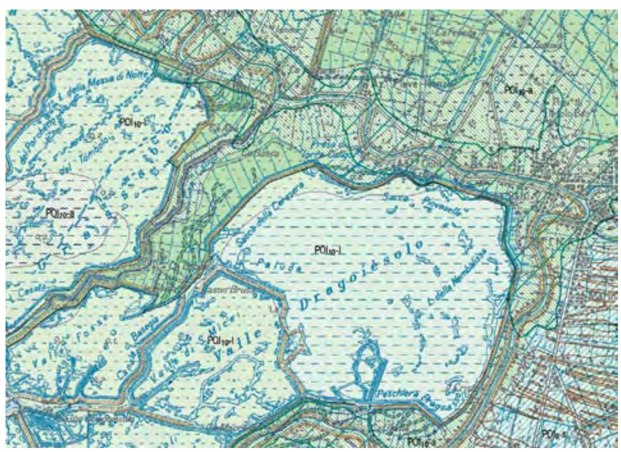

Fig. 48 – *Detail of Geological Map of Venice Sheet: eastern sector of lagoon*

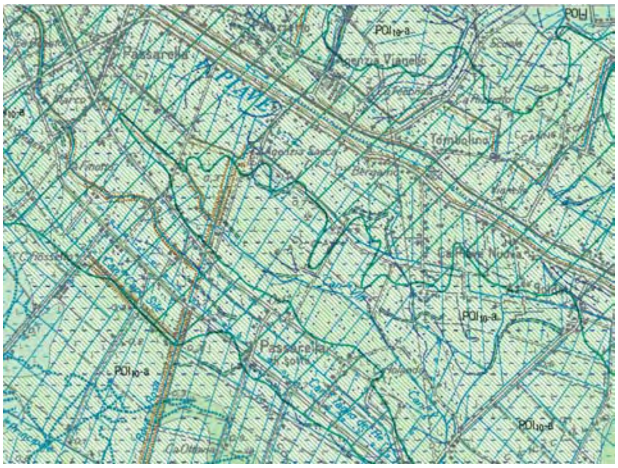

Fig. 49 – *North-western sector of Geological Map, Venice Sheet*

tions to make it navigable and act as an overflow channel in case of floods (Favero *et alii*, 1988). Before being set up as an artificial canal, it may have been a natural alternative course of the Piave (Favero, 1985), as confirmed both by the winding trend of the first stretch of its course, and by its many braided palaeocanals, parallel with the Caligo canal and identified on the same elongated peninsula on which it flows at present.

Other relict hydrographic traces are clearly recognisable on the submerged alluvial deposits flanking the lagoon south of Valle Dragojesolo, where the Piave Vecchia (now Sile) curves widely before flowing into the sea (Fig. 48), and at the sides of the present-day course of the Piave, where these traces appear tenuous, discontinuous, and parallel to it (Fig. 49). Only near the NW sector of the Sheet can several branches facing NE be identified.

All the alluvial deposits outcropping along the course of the Sile and north of it belong to the *Po Synthem*. In particular, the sandy-silty bodies found near the ridges of the Sile, Piave Vecchia and the present-day Piave, and many of the sediments mapped in the territory between the old and the new course of the Piave are attributed to the *Torcello Unit*.

The thickness of the Holocene deposits of the Sile decreases progressively with distance from the watercourse: on the map, the boundary separating them from the Late Pleistocene units lies where this thickness falls to less than about 0.7 m. Therefore, it cannot be excluded that sediments belonging to the *Po Synthem* locally cover the surface of the terrain near areas in which the *Mestre Supersynthem* outcrops.

In view of the stratigraphic and sedimentological characteristics of the terrain in the NW sector of the Sheet, several sandy outcrops mapped here are probably not attributable to the Holocene deposition of the Sile.

Results of datings of two samples taken west of Quarto d'Altino, one at -0.8 m and the other at -1.35 m, both belonging to organic silty-clayey units immediately underlying the sands, supplied calibrated ages of 18,200-17,320 and 19,240-18,300 years BP, respectively. As the sedimentation near the Pleistocene alluvial fans of the Brenta ceased 14,500 years BP, according to ^{14}C dating (Bondesan *et alii*, 2002a; Mozzi *et alii*, 2003), these sandy deposits are believed to have accumulated due to the activity of watercourses active between about 17,000 and 14,000 years BP. Their presence near ancient ridges and traces of palaeochannels not belonging to the Sile system supports this hypothesis.

Elsewhere instead, as already indicated, use of available data did not allow precise definition of the extent of the *Malamocco Unit,* nor could it be distinguished from the *Torcello Unit*. The relative fluvial deposits have therefore been included generically in the *Po Synthem*.

A dense network of ancient lagoonal channels is found in the vast depressed area extending behind the lagoonal margin, between the Fossetta canal and the Piave Vecchia (Fig. 50). Geomorphological and sedimentological evidence indicates that several of these channels established their courses in previous extinct river beds. Here, the ancient presence of a marginal marshy environment is revealed by both faunistic contents and the sedimentological-stratigraphic features of the deposits, such as abundance of vegetal relicts in sediments (fragments of reeds can often be identified) or layers of peat.

Another system of lagoonal palaeochannels was identified in the stretch of plain extending between the Piave Vecchia and the ridge of the Taglio del Re (Fig. 51). Together with palaeo-environmental studies, these elements defined the boundary between the lagoonal transgression and the mainland.

As already mentioned for the northern sector of the Lagoon of Venice (Alberotanza *et alii*, 1977), datings of samples of organic matter and shell fragments collected at depths of generally less than 2 m indicate that this transgression did not occur everywhere at the same time, but was clearly influenced by pre-existing morphological conditions and by river action, deposits from which are sometimes interfingered with lagoonal ones.

From a chronological viewpoint and also in this case, whenever studies did not make it possible to

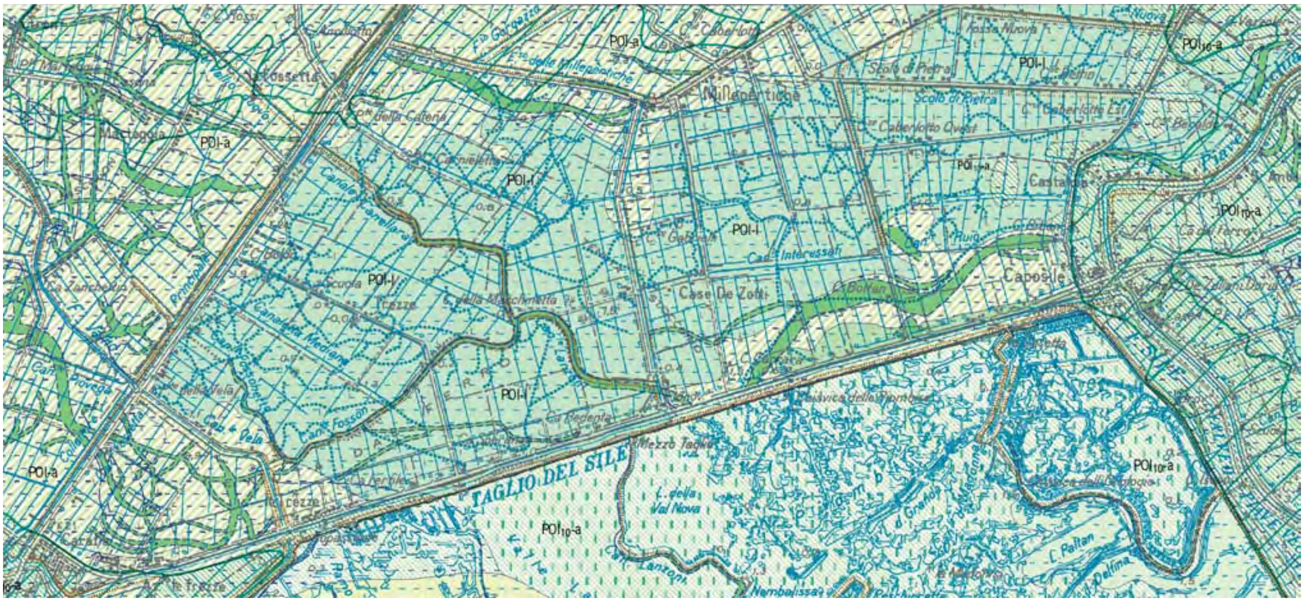

Fig. 50 – *Detail of Geological Map of Venice Sheet: sector north of Taglio del Sile*

differentiate the *Torcello Unit* from the *Malamocco Unit*, the deposits in question were attributed to the *Po Synthem*.

The few datings available indicate that the lagoon transgression in the sector between the Fossetta canal and the Piave Vecchia (Fig. 50) occurred in pre-Roman times: fragments of shells collected east of Millepertiche at -0.90 m have been dated to 3,320±40 BP (cal 1,320-1,110 BC; cal 3,270-3,060 BP). Similarly, further south, behind the Taglio del Sile, bioclasts collected at -0.75 m supplied ages of 3,020±40 BP (cal 910-780 BC; cal 2,860-2,730 BP). Although these dates confirm that the sediments belong to the *Malamocco Unit,* they are not sufficient to establish whether all the lagoonal sediments outcropping in the whole area can be attributed to it. The presence of decarbonated surface horizons, mainly to the west, also indicate that these are ancient deposits.

In the mainland belt along the Taglio del Sile (Fig. 50), the stratigraphy is also complicated by interfingering between lagoonal and alluvial sediments, the latter partly connected to the depositional activity of the ancient waterway, traces of which remain in the palaeobed identified here.

The existence of a lagoon channel along this fluvial route indicates that new lagoon conditions arose after the original river bed had been abandoned, although they do not seem to have reworked the previous alluvial sediments particularly, nor were they responsible for any significant deposition.

On the map, the boundary of the lagoonal units do not in fact coincide with the actual extent of the transgressive event. Near Marteggia, for example, marine bioclasts have been found locally in the first metre of subsoil. As these are sporadic and discontinuous signals in an area in which the presence of fluvial deposits is far better documented, it was considered opportune to include these outcrops in the alluvial environment. Although the hypothesis that these are partly reworked sediments cannot be excluded, they may represent the more internal layers of the ancient lagoon.

Similar considerations may also be made for the Altino area, a site of archaeological interest from the Roman era. It was here that the palaeo-Venetian populations settled in the VII century BC, favoured by the particular position of the area, located as it was near the northern edge of the lagoon, and built one of the most important ports and landing places of the northern Adriatic. During stratigraphical studies, deposits were found locally starting from 50 cm below ground level, for maximum thicknesses of several decimetres, and containing bioclasts, limited to the top and bottom by alluvial origin units. These detailed indications are useful in identifying the position of the internal lagoon edge during Roman times.

The same may be said for the mapped lagoon unit between the ridges of the Piave Vecchia, Taglio del Re and the present-day Piave. In particular, the Geological Map shows how several traces of ancient lagoon channels are found near deposits of alluvial environments (Fig. 51). Whenever these were found, the origin of outcropping deposits was attributed mainly to fluvial processes, as indications of a lagoonal environment are far scarcer.

Fig. 51 – *Detail of Geological Map of Venice Sheet: sector between bed of Piave Vecchia and Taglio del Re.*

To the left of the Piave Vecchia, lagoonal units were mapped in two separate areas, respectively east of Caposile and north of Jesolo (Fig. 51).

Some datings were carried out on shell fragments from the area north of Jesolo. In particular, results were obtained from three samples extracted at different depths SE of the ridge of the Taglio del Re, as chronologically they place the lagoon sediments in the entire outcrop extended down to about -1.5 m. The first, referring to bioclasts collected at -0.75 m, gave an age of 890±40 years BP (cal AD 1,030-1,240, cal 920-710 BP), the second, carried out on shells found at -0.90 m, was 2,130±40 years BP (cal 350-300 BC, cal 2,300-2,250 BP, cal 220-50 B.C, cal 2,170-2,000 BP). Fragments of shells found at -1.40 m date back to 3,010±40 years BP (cal 900-770 BC, cal 2,850-2,720 BP). The chronological data available, together with all other data on the territory for the Geological Map, attribute the lagoon deposits outcropping north of Jesolo to the *Torcello Unit*. It was more difficult to define to which units those east of Caposile belong. However, the single dating available, carried out on shell fragments extracted at -0.95 m, gave an age of 2,670±40 years BP (cal 500-340 AD, 2,450-2,290 BP).

As a network of lagoon palaeochannels, extending with continuity from NW to SE, connects the two areas (Fig. 51), it cannot be excluded that, despite the chronological data reported above, the lagoon deposits outcropping in the latter sector may actually be at least partly post-Roman. Therefore, although doubtfully, they are generically attributed to the *Po Synthem,* although available dating shows that lagoonal conditions were generated in the area before the activation of the Piave Vecchia.

Near the courses of the present Piave and Piave Vecchia, sediments due to the recent depositional activity of these rivers cover those described for the lagoon, with increasing thicknesses. Lithologically, they consist exclusively of silts.

Many traces of ancient beach ridges are found on the strip of coastal plain extending east of the terminal stretch of the Piave Vecchia (Fig. 52), about 3.5 km wide, measured from the coastline northwards. Although hard to distinguish on the field due to the almost total absence of reliefs, these ridges appear very clearly in aerial photographs. Castiglioni & Favero (1987) suggest that they may have been small or had a brief "life" as active shapes, without excluding the possible influence of erosion after their formation. However, large-scale destructive levelling was carried out recently during clearance works and the farming to which the entire territory was subsequently subjected.

The particular disposition of the ridges reveals three morphological units, listed from the most ancient to the most recent (Rizzetto, 2000), as follows: part of a large delta body in the left Piave Vecchia (immediately south of Jesolo), of which only the right wing is still intact, located slightly further inland with respect to the Lido di Jesolo; the remains of the right wing of a delta near the Lido di Jesolo, further forward with respect to the previous one and partially discordant; the body of the mouth of the Piave Vecchia, which probably developed while the previous deltaic bodies were being eroded.

The watercourses which gave origin to these bodies are to be sought among the ancient outflows of the Piave, which probably debouched near Cortellazzo or slightly further east (Favero,

Fig. 52 - *Detail of Geological Map of Venice Sheet: traces of ancient beach ridges at sides of end stretch of bed of Piave Vecchia.*

1985; RIZZETTO, 2000). Their abandonment and the activation of the Piave Vecchia were events that radically changed the evolution of the coastal strip.

Today's morphologically straight coastline is heavily urbanised, and has narrow sandy beaches with very slight gradients containing occasional aeolian reliefs with only slight longitudinal and vertical development, visibly altered by man. They are the remains of extensive dunes which, until the early 20th century, were the main defences against sea storms. They have been almost completely destroyed by coastal erosion and large-scale tourist and residential development. At present, parallel and transversal defence barriers protect the coast from ongoing erosion.

The deposits outcropping throughout the area in which traces of the ancient beach ridges have been detected consist of sands with variable silt contents, deposited in coastal beach environments and often reworked by aeolian processes (RIZZETTO, 2000). The later alignments contain finer, sometimes organic sediments, the clearcut expression of accumulations in depressed interdunal areas.

Despite their common genesis, these deposits have been attributed to various stratigraphical units, on the basis of their age. Previous studies have established the chronology of the events responsible for the evolution of this territory (Fig. 53) (RIZZETTO, 2000; RIZZETTO & BONDESAN, 2000; BONDESAN *et alii*, 2003a).

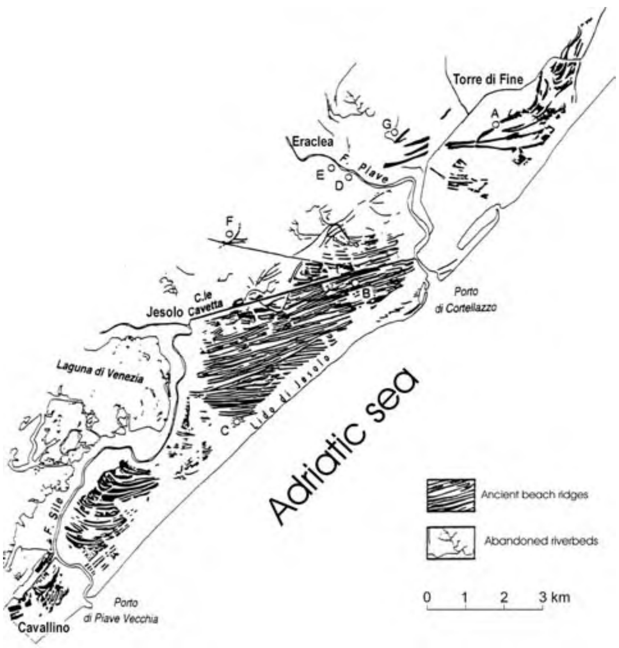

Fig. 53 – *Traces of ancient beach ridges in coastal plain of lower Piave. ^{14}C Datings: A) 5.460±60 years ^{14}C BP; B) 4.380±60 years ^{14}C BP; C) 2,900±70 years ^{14}C BP; D) 955±55 years ^{14}C BP; E) 1,200±190 years BP; F) 660±40 years BP (from* RIZZETTO*, 2000, modified).*

The most northerly alignment, running WSW-ENE along the main Jesolo-Torre di Fine road, provides evidence of the most ancient coastline identified in the low Piave area, probably associated with other coastal deposits further west, in the northern sector of the lagoon, slightly upstream of the S. Erasmo-Lio Piccolo-Lio Maggiore alignment and going back to about 6,500 years ago (FAVERO, 1985; FAVERO *et alii*, 1988; BLAKE *et alii*, 1988). From S. Erasmo the alignment moves towards S. Nicolò di Lido, continues SW, crosses the southern lagoon near Canale di Val Grande, and reaches the Cavarzere area (FAVERO *et alii*, 1988). Its disposition between S. Erasmo and S. Nicolò of Lido was probably influenced by pre-existing morphological conditions, in view of the local presence of a vast Pleistocene ridge attributed to an ancient course of the Brenta, NW of Venice and extending seawards near the Bocca di Lido (FAVERO *et alii*, 1988; TOSI, 1994c).

On the mainland, the positions of the coastline starting from the phase of maximum marine ingression are better documented than those in the lagoon.

On a belt extending about 1.7 km south of the Canale Cavetta, the ancient beach ridges first run W-E and then turn WNW-ESE to form, together with the former, angles of about 15° (Fig. 52). Traces of the latter are truncated from the present-day shoreline at angles 25° and 38° (RIZZETTO, 2000).

Samples of organic clays collected south of the Canale Cavetta near Cortellazzo, at depths of 40-78 cm have been dated to 4,380±60 years ^{14}C BP (3,327-2,883 BC). Their general geomorphologic-sedimentological context indicates that they were deposited near a small interdunal depression. Conversely, a sample recently extracted from -60/-75 cm slightly upstream the coast at Jesolo, consisting of aeolian littoral sands containing abundant vegetable fibres, was dated to 2,900±70 years ^{14}C BP (1,366-900 BC) (RIZZETTO, 2000; BONDESAN *et alii*, 2003a). These results indicate that the formation of the ridges on the right Piave, south of the Canale Cavetta, began during the Atlantic-Subboreal transition. Data from the first sample reveals a considerable chronological gap for the system of beach ridges further south, the formation of which was verified from the second half of the Subboreal, preceded by an erosional phase that may have removed part of the previous ridges and caused the coastline to run WSW-ENE before new progradation commenced (RIZZETTO, 2000).

Lastly, the delta body of the Piave Vecchia, through which the Sile now debouches into the Adriatic, is well developed (Fig. 52). It also contains many continuous, well-defined beach ridges which, thanks to their shape and arrangement, show how the delta changed as it evolved. The activation of the Piave Vecchia in post-Roman times establishes that it consists of a recently formed unit.

The above considerations mean that the outcropping and suboutcropping deposits near the most ancient coastal ridge may be attributed to the *Malamocco Unit,* and those composing the Piave Vecchia delta and now found on the present-day coastline (emerging and submerged) are considered part of the *Torcello Unit.*

Previous mainly geomorphologic and archaeological studies have reconstructed the various stages marking the westward shift of the coastline of the mouth of the Piave Vecchia over the last 2,000 years (Fig. 54). It is deduced that most of the now emerging beach deposits formed relatively recently (as also confirmed by further studies carried out within the framework of the Geological Map) and were attributed to the *Torcello Unit.* Instead, on the basis of these statements, the outcropping sandy sediments near the Lio Piccolo and Lio Maggiore ridges belong to the *Malamocco Unit.* However, the age of some deposits near S. Erasmo and between Lio Piccolo and Cavallino, near which the two units have not been differentiated, are uncertain (Fig. 55).

In any case, in historical times, the evolutional tendency of the coastline was also greatly influenced by massive anthropic interventions, mainly on the hydrographic networks, aimed at safeguarding the lagoonal basin and preventing its river mouths from becoming silted up. With particular reference to the section of coastline studied here, the problem of keeping the Bocca of Lido open - endangered as it was by the arrival of sediments from the NE - had existed since the year 1300 (Colombo, 1970; Favero *et alii,* 1988). The Piave Vecchia floods favoured the development of a sandy bed, with the consequent displacement to the SW of the "Porto di Lio Mazor" (through which, until the 16th century, the waters from the northern had flowed into the sea) until it became an internal channel, the Canale Pordelio (Fig. 56). The lengthening of the Punta di Lio Mazor and its seaward expansion were responsible for the formation of the current coastline of Cavallino, which reaches Punta Sabbioni, as well as for the rearward position to which the beach of S. Erasmo, once in contact with the sea, is now relegated.

Although the Cavallino and S. Erasmo beaches show evident signs of anthropic reworking, traces of ancient beach ridges are still visible on the terrain (Fig. 57). Most of these are poorly defined, due to anthropic alterations, and were not mapped, as only clearly distinguishable lines are shown.

Conversely, the present-day emerging coastal ridge, stretching from the Porto di Lido SW, is heavily urbanised. Sedimentological and stratigraphical studies have shown that, within the first 2 m of subsoil, deposits are generally highly reworked.

As the beach ridges evolved, so did the lagoon: its original basin, which formed against the more ancient coastline, did not reach Burano and Torcello (Favero *et alii*, 1988). The most ancient deposits found until now in the northern lagoon, which lies on pre-Holocene continental sediments, have been identified near Scanello, NE of S. Erasmo, at 5.95 m below sea level, and dated to 5,064±130 years BP (cal age: 2,594-2,202 BC) (Serandrei-Barbero *et alii*, 2004). Therefore, with respect to

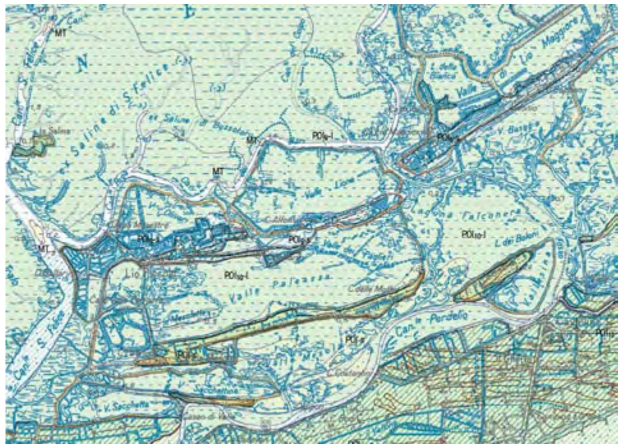

Fig. 55 - *Detail of Geological Map of Venice Sheet: traces of ancient beach ridges in lagoon north of Cavallino.*

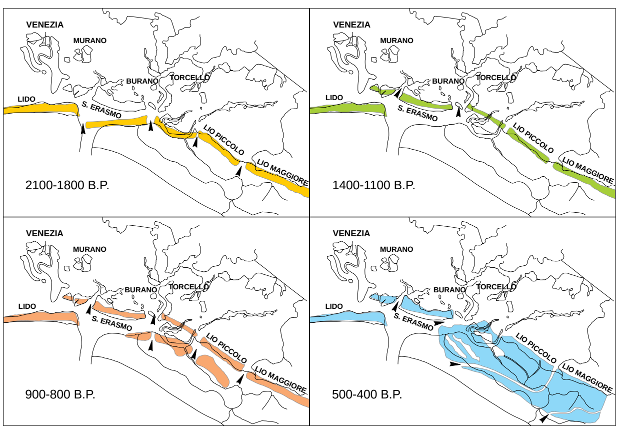

Fig. 54 – *Shifting of coastline deduced from geo-archaeological–geomorphological-environmental indicators, and indications of ancient mouths of inlets (from* Bonardi et alii, *1997, modified).*

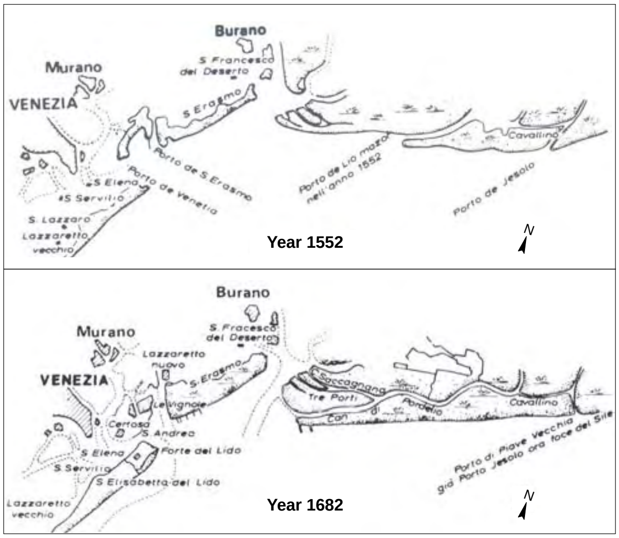

Fig. 56 – *Evolution of inlet of Lido between 16th and 17th centuries (from* Colombo*,1970).*

the southern sector, where the Holocene transgression took place about 11,000 years BP, to the north the marine ingression occurred relatively recently (Bortolami *et alii*, 1984; Tosi, 1994c; Serandrei-Barbero *et alii*, 2001).

The evolution of the northern lagoon was influenced by the ancient courses of the Piave, which crossed the area before the lagoon had formed and perhaps also during its early evolutional phases. It appears, however, that large branches of the Piave were submerged immediately after the Roman period (Favero, 1985).

Although more recently with respect to the Piave, the Sile, a spring river, also influenced the evolution of the northern lagoon. At present, its natural course runs SE from Quarto d'Altino to Portegrandi where once, before the construction of the Taglio del Sile, it flowed into the lagoon. This course represented only one of its seven mouth branches indicated on 15th-century maps; the main ones were the Canale Silone (Canal Dolce), Canale Siloncello and Canale Siletto; other less important ones were diverted (Canale Lanzoni) or re-used by closer watercourses (river Dese) (Comel, 1968). The courses of some of the large lagoon channels now coincide with the terminal stretches of these deltaic branches. The Silone probably flowed along the Canale della Dossa towards the Island of S. Ariano, and the Siletto flowed along the Canale Cenesa, which later joined the Canale S. Felice. Another more westerly course must have led from Quarto d'Altino to follow the final stretch of the Dese, before converging in the Canale di Burano (Comel, 1968).

Therefore, in order not to lose information on the extent of the old delta body of the Sile in the lagoon, it was believed opportune to indicate as "palaeo-river beds" several lagoon channels near the mainland, also with reference to historical maps.

The Sile was already mentioned in Roman times, when the lower section of its course was further east than it is now. Together with the Piave, it probably constituted a single system characterised by a confluence of courses into multiple channels (Favero, 1985; Rizzetto, 2000). Instead, the shift of the river into Altino territory is attributed to the end of the Roman era. The consequent development of a "compound" mouth inside the la-

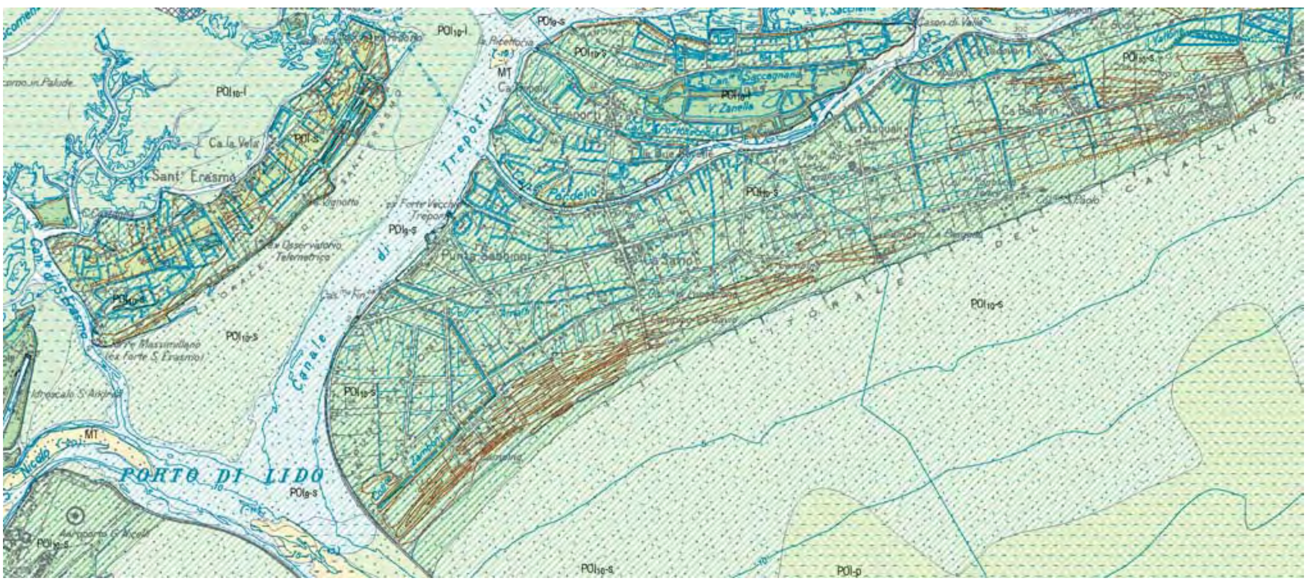

Fig. 57 - *Detail of Geological Map of Venice Sheet: traces of ancient beach ridges near beaches of S. Erasmo and Cavallino.*

goon (as it consists of a series of minor adjacent deltaic bodies located round the periphery of the internal lagoon, each near the outlet of a mouth branch) influenced the entire subsequent evolution between Campalto and the Valle di Ca' Zane, transforming an area previously characterised by lagoonal conditions into freshwater bogs and marshes (Favero, 1985). Archaeological findings and datings define late Roman and above all the related medieval deposits.

From the 17th century onwards, the definite and almost total disappearance of the freshwater environment, replaced once again by brackish waters, is attributed to the exclusion of the Sile from the lagoon itself, although this process had probably already started in the late medieval period as a result of man's large-scale changes to the lagoonal network.

The evolution of this area has been the subject of earlier studies (Alberotanza *et alii*, 1977; Favero & Serandrei-Barbero, 1981; 1983; Favero *et alii*, 1995; Serandrei-Barbero *et alii*, 1997; Serandrei-Barbero *et alii*, 2004) which revealed the depositional and palaeo-environmental conditions of the late Holocene, with particular reference to the post-Roman period. They provide excellent backup for new studies for the Geological Map and, by adding new data to previous ones, confirm and abundantly enrich our knowledge of the territory. As regards the present-day outcropping deposits, there are traces of mainly silty deltaic units near the edge of the lagoon, particularly where the Silone and Lovigno-Dolce canals flow into it, defining a tongue of land extending south, on which a modest ridge with weak relief has been identified (Fig. 58).

The outcropping deposits have been tentatively attributed to the deltaic enviroment, although there are many traces of old lagoon channels and, as already noted by Comel (1968), lagoon bottom sediments are interbedded with these alluvial deposits.

Other deltaic environment deposits contain peat of medieval age east of the Palude della Rosa (Fig. 58) and clay west of the Palude di Cona, at the present-day mouth of the Dese (Fig. 59). All these units rest directly on lagoon sediments.

Stratigraphic considerations, together with chronological data, lead us to exclude the possibility the the edges of the lagoon bordering the mainland contain outcrops of fluvial-deltaic units attributable to ancient watercourses, relicts of which remain in the many palaeo-river beds identified in the adjacent territory.

Somewhat different developments seem to have occurred in the north-eastern part of the la-

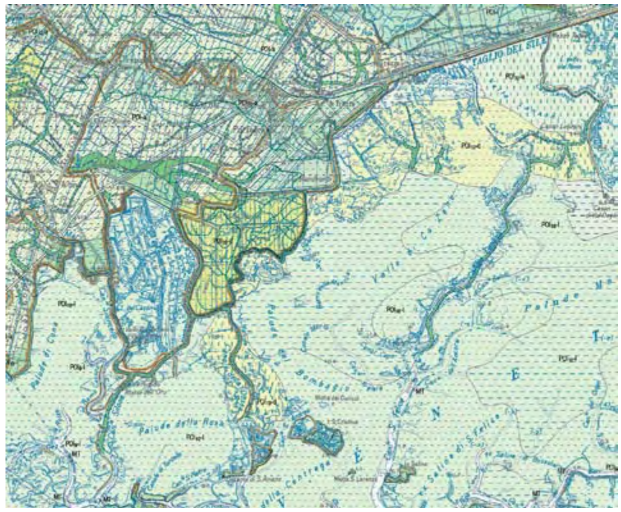

Fig. 58 - *Detail of Geological Map of Venice Sheet: ancient deltaic branches of Sile.*

goon. Until 1500, the Palude Maggiore, Val Dogà, Valle Grassabò and adjacent areas had formed a single basin with its own mouth, the "Porto di Lio Mazor". From the 16th century onwards, this mouth formed part of the more extensive basin of the Lido, due to the disappearance of its lagoon mouth - caused, as already mentioned, by the arrival of large quantities of terrigenous sediments from the NE.

During the Middle Ages, the overflow waters of the Piave also favoured the development of marshes and peat bogs along the entire eastern strip of the northern lagoon. However, from the 18th century onwards, with the eastward displacement of the course of the Piave and the return of the Sile to its old bed, these areas were progressively transformed into saltmarsh and were submerged. The process was favoured by compaction of the substrate and reduced solid flows from the

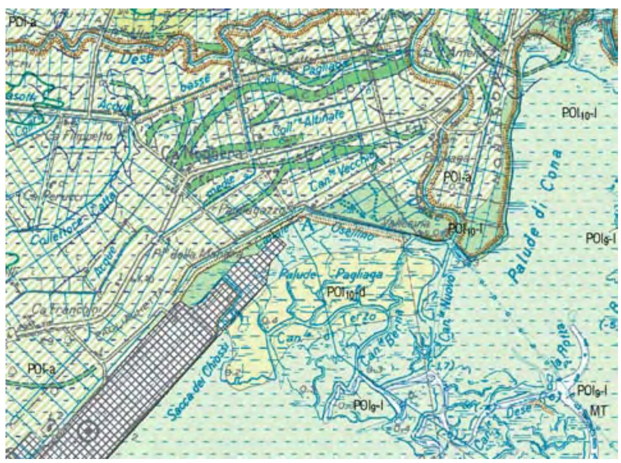

Fig. 59 - *Detail of Geological Map of Venice Sheet: mouth of Dese.*

Sile, the waters of which were less abundant than those of the Piave and therefore less subject to flooding (Favero, 1985). These considerations still characterise the area: alluvial deposits (peat bogs) composed of fine, prevalently clayey-silty sediments occur in Val Dogà (Fig. 60), replaced westwards by lagoonal units. Datings of alluvial marsh deposits, carried out on samples from depths of not more than 1 m from the lagoon bottom, indicate that they are of post-Roman age.

The entire remaining part of the sector of the Venice Sheet most exclusively contains outcrops of a lagoonal environment belonging to the *Torcello Unit*, generally silty and with variable contents of sand and/or clay: finer grain sizes, mainly clay, are found in the more northerly sector in the Valle di Ca' Zane and Palude Maggiore. Instead, the sand outcropping near the bottom south of S. Erasmo accumulated in a coastal beach environment, unlike those mapped between Venice and the Lido di S. Nicolò which, although also originally belonging to beach deposits, show evidence of lagoonal type.

In the city of Venice and nearby minor islands, infill sediments of mixed grain size are found in the more superficial layers.

From the chronological viewpoint, the submerged deposits mapped in the lagoon are attributed almost exclusively to the *Torcello Unit*. There are only outcrops of more ancient sediments in the channels inside which lagoon silt has been found together with sand from the beach belonging to the *Malamocco Unit* and alluvial deposits of the *Mestre Supersynthem*. The lagoonal silt of the *Malamocco Unit* prevails, whereas beach sand has only been found near Porto di Lido and other channels near the coast, such as S. Felice and the Canale Pordelio. The continental sediments of the *Mestre Supersynthem* have mainly been found in Venice and the Porto di Lido: elsewhere, the outcrops found inside the channels and belonging to this unit are sporadic and of little extent.

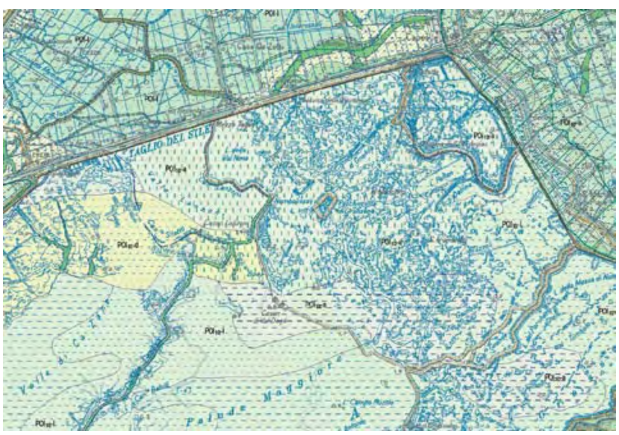

Fig. 60 - *Detail of Geological Map of Venice Sheet: north-eastern section of lagoon.*

As regards the Adriatic domain, recent beach sand has appeared along the submerged strip adjacent to the coast, varying in width between about 1.7 km in the eastern section of the Sheet to over 4 km at the Porto di Lido. Seawards, they are gradually replaced by silt, sand and, subordinately, shelf clay, all attributed to the *Po Synthem*.

2. - SUBSURFACE MAP: THE PO SYNTHEM BASE

The map was created by statistically interpolating the depth of the stratigraphical limit between the *Mestre Supersynthem* and the *Po Synthem* (section IV), obtained from stratigraphic analyses of cores collected in the CARG database and VHR (*Very High Resolution*) seismic surveys (section III).

In general, data distribution allowed good overall interpolation, yielding a map of the depth of the surfaces occurring between Pleistocene (*Mestre Supersynthem*) and Holocene deposits (*Po Synthem*) (Brancolini *et alii,* 2005*;* Brancolini *et alii,* 2006).

The overall topographical characteristics of the *Po Synthem* base are those of the Late Pleistocene plain at the end of the Last Glacial Maximum, although these forms may have undergone partial reworking during the transgression and been modelled by differential subsidence over the territory.

The *Mestre Supersythem* is exposed in the north-western section of the Venice Sheet. Elsewhere the depth of the boundary separating it from the overlying *Po Synthem* varies from 2 m below sea level, near the mainland at the edge of the lagoon and immediately south of Venice airport, to more than 22 m below sea level in the Adriatic (SE sector of Sheet). In the marine sector, the *Mestre Supersythem* or *Po Synthem* is less than 1 m thick.

Eastwards, the morphology of the *Po Synthem* base is quite regular, and the average gradient of the surface is about 0.96‰, whereas in the other parts of the Sheet the setting of the surface is very variable. There are several linear features which, due to their extent and development, are believed to have been generated by ancient watercourses. The most evident ones generally coincide with the main lagoonal channels still active. In particular, the following are worthy of note: (a) the cut from Porto di Lido eastwards, following the course of the Canale di Treporti, Canale San Felice, Canale Riga and Canale dei Bari as far as the Valle del Cavallino; (b) the cut from the eastern extremity of the Canale di Treporti NW, continuing inside the Canale di Burano (with lateral deviations NE along the Canale Scanello in the direction of Torcello - S. Ariano) as far as the mouth of the Dese. Here, reference must be made to subsection 1.1 of section V, which states that, in historical times, the most westerly branches of the mouth of the Sile probably followed the terminal stretch of the Dese, starting from Quarto d'Altino and then converging in the Canale di Burano (Comel, 1968). Therefore, the course identified according to the form and arrangement of the depth contours indicates the local presence of a watercourse (corresponding to the current Dese-Sile) before the sea invaded the plain (now occupied by the lagoon) and its relative continuation SE, thus proving that this part of the course of the Sile, and consequently also of the Dese, is inherited; (c) SW of Burano, a cut follows Scomenzera S. Giacomo and extends NE-SW to the southern shores of the island of Murano; (d) within the city of Venice, there is a cut running WNW-ESE which, after a brief interruption, reappears from S. Pietro to S. Nicolò; two other small cuts lie SE of Murano, running NW-SE towards the Porto di Lido; (e) one last cut touches the internal edge of the Lido coastline.

Two weak forms of erosion are visible near the coastal strip, in the central-northern sector of the Sheet. One is found near the terminal stretch of the natural bed of the Sile (Trepalade - Portegrandi), which may indicate the persistence of its course in a direction which already existed at the end of the Pleistocene. The other identifies a NW-SE trajectory to the edge of the lagoon, where it is diverted south and is visible near Marteggia, where geomorphological studies have revealed many traces of extinct watercourses, all running in the same direction. In the lagoon, the erosional form seems to follow the old branches of the mouth of the Sile, currently replaced by the lagoon channels.

The various forms of erosion are generally differentiated into two groups, according to their preferential direction of development: one runs NE-SW and the other NW-SE, the latter corresponding to fluvial courses partly still in existence, as documented by historical sources or other geomorphologic findings.

Local slopes with very high gradients are found and differences in elevation sometimes reach 6-8 m at distances of only 10 or 20 metres. A significant slope of the boundary surface (up to 2.67‰) is also found in the nearshore sector south of the mouth of the Sile River.

Ridges occur in the Lido and Punta Sabbioni littorals; they formed a single morphological high later cut near the present-day Lido inlet.

The map of the Po Synthem Base, complementing the Geological Map shows three geological sections, described in section IV, and three VHR seismic profiles. Various seismic reflectors of the *Mestre Supersynthem* and *Po Synthem* are shown in the seismic sections, and the one representing the relative stratigraphical boundary is highlighted. The core analyses included of the CARG database were used to identify and calibrate them. A brief description of the seismic sections is given below.

Profile CH_30 was partly acquired in the Canale di Treporti and partly in the initial section of the Canale Pordelio. The asymmetrical cut of the bottom of the lagoon is clearly visible, in which the Holocene reflectors appear to be truncated (shot point 1400). The surface representing the base of the *Po Synthem*, at a depth of about 12 m below sea level, sinks to almost -20 m near a cut. Frequent truncations of the *Mestre Supersynthem* reflectors indicate erosional processes.

Profiles CH_31, VE_05, VE_06 and CH_29 are arranged in a lengthy sequence with a section running SW-NE, located in the lagoon between the Lido and Grassabò. Profile CH_31 shows the very irregular bottom of the lagoon, with signs of erosion, especially near the Lido inlet and also involving the base of the *Po Synthem*. The Holocene deposits, with a sub-horizontal base quite constant depth, are characterised by a semi-transparent seismic *facies*. Profiles VE_05, VE_06 and CH_29 show the base of the *Po Synthem*, at a constant depth of about -15 m, with frequent cuts.

Profiles LI_06 and LI_07, located in the marine sector, are perpendicular to the coast. Profile LI_06, the most northerly, shows the seaward sinking of the base of the *Po Synthem* until it outcrops near shot point 6800.

The *Mestre Supersynthem* contains a series of very wide reflectors, which between shot point 8400 and the final part of the profile appears to be discontinuous and is characterised by irregular trends. In profile LI_07, the base of the *Po Synthem* is represented by a series of sub-horizontal reflectors of high amplitude. Between shot points 5000 and 7400, the Holocene deposits are characterised by a semi-transparent facies, in which reflectors terminate with downlap configurations above the surfaces representing the base of the Holocene.

VI - MINERALOGICAL CHARACTERISTICS

The interpretation of the space-time distribution of the mineralogical content of sediments often provides the key to the palaeogeographical evolution of the Venetian territory.

The Venetian basin is an area in which sediments flowed and still flow although more slowly than in the past, from the rivers Tagliamento, Livenza, Piave, Brenta, Bacchiglione, Adige and Po; smaller quantities came from rivers fed by groundwater discharge, the most important of which is the Sile river.

During the Holocene, this area was one of complex transition zones, including sectors of the mainland, lagoon, littoral and sea, the boundaries of which have changed over the millennia - first for natural reasons and later, and above all, as a result of the actions of man. The past and present-day dynamics of water circulation in the lagoonal waters led to partial remixing of sediments and to a more difficult identification of the provenance of the sediments which make up the submerged deposits (Rickwood *et alii*, 1992; Albani *et alii*, 1995).

Various authors, from Gazzi *et alii* (1973 and Jobstraibizer& Malesani (1973) to more recent ones (Bonardi & Tosi, 1994a; 1995a; 1995b; Ravaioli *et alii,* 2003) have established the mineralogical composition of the sediments carried by the various rivers in the Venetian and Friuli areas, and have also made correlations with those in the Venetian coastal territory.

The following section describes the mineralogical characterisation of clays and sands, for additional information on the palaeogeographical evolution of the area.

1. - MINERALOGICAL COMPOSITION OF CLAY

The average mineralogical composition of clay belonging to the *Po Synthem* (above sea level) and the *Mestre Supersynthem* (Pc and Pa) of the subsoil of the coastal sector between the Bocca del Lido and the mouth of the Sile is shown in Fig. 61. The clay of the *caranto* (Pc), an over-consolidated top level of the *Mestre Supersynthem*, is distinguished from underlying levels (Pa) in order to highlight any mineralogical peculiarities that can be correlated to already known geotechnical parameters.

Considering the qualitative mineralogical characteristics of the total sample if the minimal occurrence of smectite and feldspar is excluded in the Pleistocene deposits underlying the *caranto*, the three groups cannot be differentiated. The most abundant minerals are calcite, dolomite and quartz, with minor chlorite, illite/mica and plagioclases, and traces of smectite, clay minerals with mixed layers, and kaolinite. The average percentages of dolomite and quartz increase from the

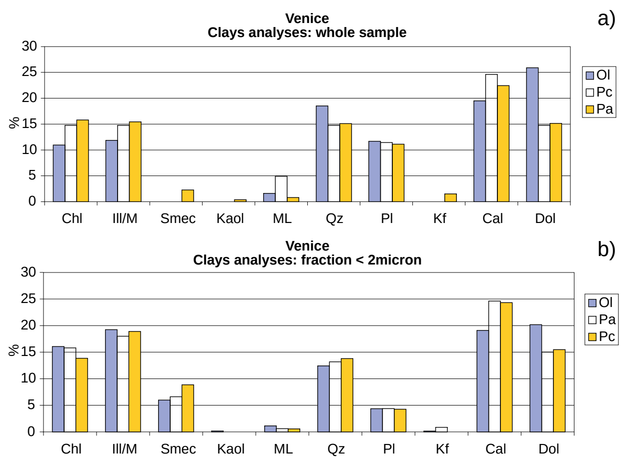

Fig. 61 - *(a) Average mineralogical composition of three sample groups (Ol, Pc, Pa). Chl=chlorite, Il/M=illite/mica, SKM=smectite+kaolinite+clay minerals in mixed strata, Qz=quartz, Cal=calcite, Dol=dolomite. (b) Average mineralogical composition of clay fraction (Ø<2 µm) of three sample groups (Ol, Pc, Pa). Chl=chlorite, Il/M=illite/mica, Smec=smectite, Qz=quartz, Pl=plagioclase, Kf=K-feldspar, Cal=calcite, Dol=dolomite, Kaol=kaolinite, ML= clay minerals in mixed strata.*

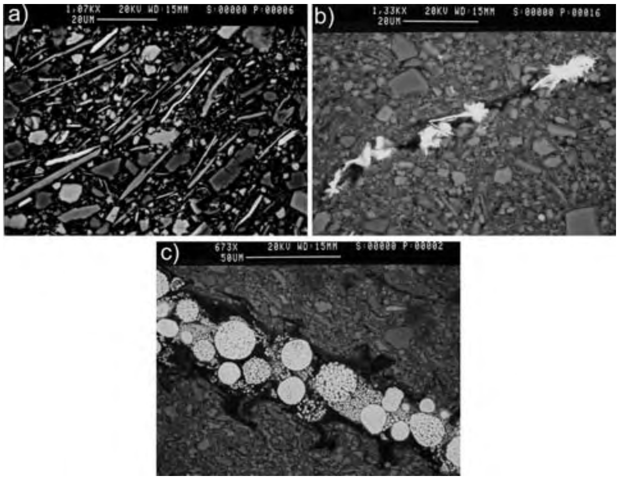

Fig. 62 – *Top of Mestre Supersynthem: over-consolidated clay (caranto). a): phyllosilicates with preferential orientation as a result of compaction: minerals with granular texture are silicates (dark and medium-dark grey) and carbonates (white); elongated minerals are chlorite (pale grey) and mica (grey); black areas are pores; b) and c): barite and autigenous microcrystalline pyrite forming inside fractures (from* BONARDI *&* TOSI, *1994a; 1995b;* BONARDI et alii, *1997;* BONARDI et alii, *2006).*

deposits of the *Mestre Supersynthem* to those of the *Po Synthem*.

Calcite has maximum values in the *caranto* and similar percentages in the other two groups, with lower values in the *Po Synthem*. Plagioclases do not show variations in the three groups, but chlorite and illite decrease from the *Mestre Supersynthem* to the *Po Synthem* .

The clay fraction alone (Ø<2 μm) was also analysed, in order to characterise single clay minerals in particular (Fig. 61b). In the three groups, the main minerals are calcite, illite/mica, dolomite and chlorite; secondary minerals are quartz, smectite and plagioclase; feldspar, kaolinite and clay materials in mixed strata also occur in traces.

Calcite, dolomite and plagioclase show a trend similar to that identified in the total sample. Illite, chlorite and smectite dominate among the clay minerals; kaolinite and clay minerals with mixed strata only occur in traces. Fig. 62 shows several SEM (Scanning Electron Microscope) photos of over-consolidated clay (*caranto*) samples from the top of the *Mestre Supersynthem*.

Following BONARDI & TOSI (1994b; 1995b), in the sand samples of the same borehole an attempt was made to verify the occurrence of significant vertical variations (or ones related to depth) and spatial variations between the southern and northern coastal sectors of the lagoon. Unlike the sand, no marked average quantitative variations were found in coherent sediments between Holocene and Late Pleistocene deposits. Only trends for carbonates were observed, both for total samples and for the clay fractions. The percentage of dolomite increases from other types of Late Pleistocene deposits to Holocene ones, and calcite reaches its maximum concentration in the *caranto* samples. The calcite/dolomite ratio is also similar to the trend of dolomite.

1. - MINERALOGICAL COMPOSITION OF SAND

Mineralogical analyses of sand sediments have contributed to the identification of ancient fluvial supplies originally discharging into the lagoon, the distribution of which underwent subsequent partial modifications due to water circulation.

Generally, for the various lagoon areas and depths, the analytical results show similar mineralogical compositions, but with quite distinct relative percentages. The main minerals are dolomite, calcite, quartz, feldspars (potassium-feldspar+plagioclase), chlorite and mica, while ankerite, aragonite, kaolinite and hastingsite occur in small percentages.

Some examples of variations in dolomite and quartz contents in sand samples of the *Po Synthem* and *Mestre Supersynthem* are given below, together with some for the Correzzola Unit, referring to the *CARG 12* borehole at -100 m.

Fig. 63 shows the percentages determined in four cores located along an hypothetical cross-section from the Bocca di Lido (P. Sabbioni) to Cavallino. Dolomite content in present-day deposits decreases with depth more in the *Po Synthem* (40-60%) than in the *Mestre Supersynthem* (10-30%). Similarly, but in an opposite manner, quartz ranges from minimum values of 15-25% to more than 40% in the *Mestre Supersynthem* in the southern beach area at Punta Sabbioni-Cavallino, showing that the main contribution comes from the Brenta system.

Fig. 64 shows dolomite and quartz variations in five cores taken along a cross-section running NW-SE in the northern lagoon, from the edge of the mainland to the beach at Jesolo Lido. In the littoral sector of this cross-section, which includes much of the basin, there are large quantities of dolomite-rich sediments (45-55%) originating from the Piave system within the *Po Synthem* deposits.

Near the edge of the lagoon instead, at the end of the Sile river lagoonal delta, where the *CARG 12* borehole is located, dolomite decreases to 20-25%; quartz, which was 15-20% along the coast, increases to 35-40% inland. These values are compatible with those of sediments belonging to the Brenta Pleistocene *megafan*, along the north-west margin of which the Sile, a spring fed river, now flows.

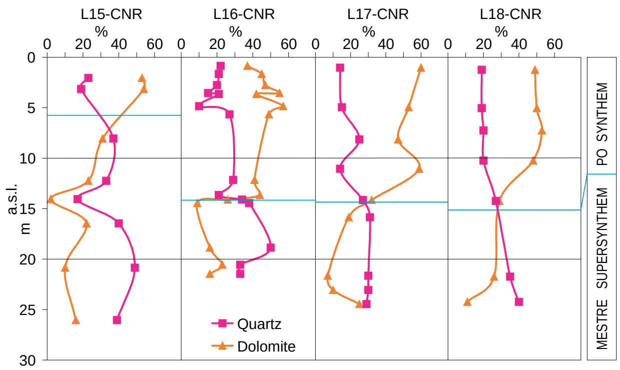

Fig. 63 – *Variations in percentages of quartz and dolomite in* Mestre Supersynthem *and* Po Synthem *sand, found in subsurface of Venitian beach (cf. Figs. 43 and 46).*

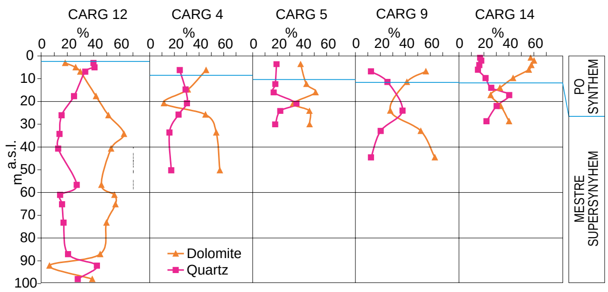

Fig. 64 – *Variations in percentages of quartz and dolomite in* Mestre Supersynthem *and* Po Synthem *sand, along a NNE-SSE cross-section on mainland* (CARG 12)-*lagoon* (CARG 4, 5, 9)-beach (CARG 14) *(cf. Figs. 43 and 45).*

Following the same cross-section, there are no clear mineralogical variations in the *Mestre Supersynthem* sediments when basin, lagoonal and littoral areas are compared. Dolomite varies between 30% and 40% near the boundary with the overlying *Po Synthem*, and tends to increase with depth (40-50%). The *CARG 12* borehole also reached the *Correzzola Unit* marine deposits: from about -58 m to -88 m, dolomite and quartz contents are similar to those of the *Mestre Supersynthem*, which here is composed of Late Pleistocene deposits from the Piave, with dolomite decreasing and quartz increasing with depth. At about -92 m, this trend is reversed, and values are similar to those found for the *Po Synthem* deposits and compatible with those of the sedimentary supplies of the Brenta system.

The content variations of these minerals, in both cross-sections, are generally due to the presence, in the southern lagoon, of sediment supplies mainly from the Brenta system during the low-stand system tract phase and to sediments belonging to the Piave system during the progradation and highstand system tract stage. Conversely, in the northern area, the *Mestre Supersynthem* and *Po Synthem* deposits seem to be related to the Piave system.

The abundant mineralogical data on sub-outcropping sediments (first 2.5 m of depth) allowed mineral distributions to be mapped over most of the study area.

The prevalence of carbonates in the north and total silicates in the south generally confirms the existing lithological diversity of the Piave, Brenta and Bacchiglione sediment supplies which, as already mentioned, come from separate drainage basins. Carbonates (dolomite, ankerite, calcite, aragonite) prevail in the north (60-65%) whereas silicates (quartz + potassium-feldspar + plagioclase) are abundant in the south (55-65%); percentages are similar in the centre. Within the carbonate group, dolomite + ankerite are the most abundant (about 60%); calcite + aragonite are generally less than 25-30%. As an example, we refer to the dolomite distribution map (Fig. 65), which clearly shows that deposits deriving mainly from the Piave sediments prevail in the north, those deriving from the Brenta and Bacchiglione deposits are instead abundant in the south. The sediments carried by the Piave are rich in carbonates, with dolomite prevailing over calcite; quartz is limited (Gazzi *et alii*, 1973; Jobstraibizer & Malesani, 1973).

However, the Brenta sediments have higher quartz and feldspar and lower carbonate contents, with dolomite prevailing, due to the presence of gneissic and acidic volcanites in their drainage basin. The latter are also responsible for significant phyllosilicate and clay mineral contents.

The low percentage of carbonates and significant amounts of clay minerals in a small area of the northern lagoon, near the inner margin, may be due to a local accumulation of sediments by the Sile which, as previously mentioned, runs where

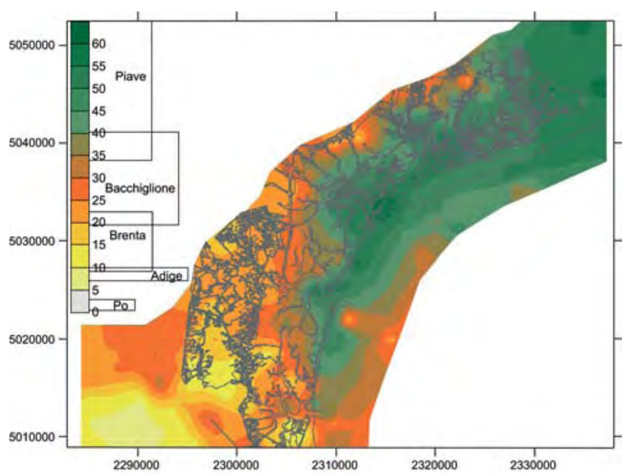

Fig. 65 – *Distribution of dolomite in lagoonal area. Legend: reference intervals of various sources of sediments. For marine area, previous data from literature sources were used.*

the Brenta and Piave *megafans* join. This anomalous mineralogical distribution at the mouth of the Sile, with respect to the surrounding areas, was perhaps accentuated by local selective hydrodynamic processes.

As regards the marine sector, the study of the distribution of various minerals and the comparison with solid supplies from the Tagliamento, Livenza, Piave, Brenta, Bacchiglione, Adige and Po (GAZZI *et alii*, 1973; JOBSTRAIBIZER& MALESANI, 1973), show that the sediments along the beach of Jesolo and the Venetian beaches, belong mainly to the Piave mineralogical domain; contributions from the Tagliamento decrease progressively westwards, disappearing before Punta Sabbioni (GAZZI *et alii*, 1973). This fits local hydrodynamic conditions, according to which the general dispersion of sediments occurs from east to west.

VII - SUBSIDENCE AND EUSTACY

Among examples of land subsidence caused by anthropogenic activities, that of Venice is undoubtedly one of the best-known in the world, not so much because of the amount of lowering, as for the city's uniqueness, its elevation being only a few dozen centimetres above mean sea level. Subsidence in Venice is a problem the seriousness of which became fully apparent in the early 1960s, when the city began to suffer increasingly frequent events of *acqua alta* (literally "high water") - a local idiom used to indicate a tide level that causes flooding of more or less extensive areas of the inhabited centre of the lagoon).

A detailed study of subsidence in the Venice area began in the 1970s, when the CNR *Laboratorio per lo Studio della della Dinamica delle Grandi Masse* was founded. The most important finding of the research group was to show that the main cause of the land subsidence in the area was due to groundwater pumping from the multi-layered aquifer system underlying the coastland, mainly for industrial use (SERANDREI-BARBERO, 1972; CARBOGNIN *et alii*, 1977; CARBOGNIN *et alii*, 1981).

In the last century, Venice has undergone relative lowering of 23 cm with respect to mean sea level, due to three associated causes (Fig. 66): eustacy, anthropogenic and natural subsidence, responsible for a loss in elevation of 11, 9, and 3 cm, respectively (CARBOGNIN *et alii*, 2005).

A lowering of 23 cm represents a serious problem for Venice: it has contributed to increase the frequency and intensity of episodes of *acqua alta* and favoured beach destabilisation (CARBOGNIN *et alii*, 1995a) and erosion of shoals in the lagoon, which has required large-scale initiatives for environmental restoration (CARBOGNIN *et alii*, 2000).

The main past and recent aspects of subsidence in the Venice area are described in the following sections.

1. - NATURAL SUBSIDENCE

The Po area, like all sedimentary basins, and particularly the Venetian coastland, has always been affected by natural subsidence, varying in magnitude in time and space according to various geological events in the course of millennia.

Recent studies on cores from the *Venice 1 – CNR* borehole, drilled at Tronchetto in the 1970s, estimated the average rate of subsidence over the last 2 million years at 0.5 mm/year, showing that this value mainly reflects tectonic events occurred during this period (Kent *et alii*, 2002). Natural consolidation of sediments deposited during the Holocene was responsible for an average lowering of 1.3 mm/year, a figure that was typical of the lagoon environment during its natural evolution (GATTO & CARBOGNIN, 1981; BORTOLAMI *et alii*, 1984). At the outer margin of the southern lagoon, due to the greater thickness of deposits, 1.37 mm/year was estimated over the last 1,500

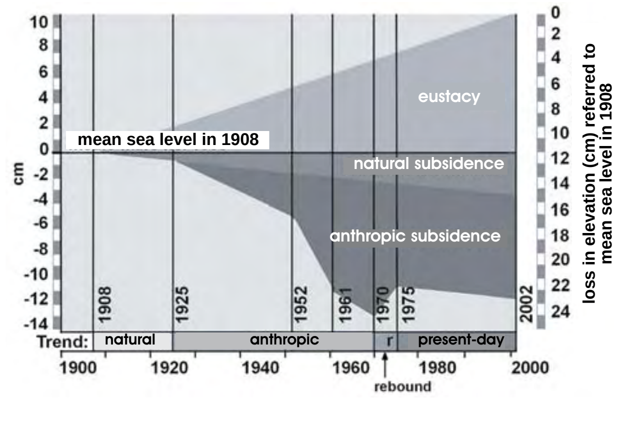

Fig. 66 – *Three phenomena have contributed to reduce the elevation of Venice in the last 100 years (revised by GATTO & CARBOGNIN (1981) in CARBOGNIN* et alii*, 2005).*

years (SERANDREI-BARBERO *et alii*, 1997). Natural subsidence reduced during the last few centuries, and currently is less than 0.5 mm/year in the central basin (BORTOLAMI *et alii*, 1984; CARBOGNIN, 1992; TEATINI *et alii*, 2005; SERANDREI-BARBERO *et alii*, 2005a).

2. - SUBSIDENCE DUE TO EXTRACTION OF GROUNDWATER

Subsidence in Venice caused by groundwater withdrawal is a phenomenon that has been studied over a long period, and is now known in all its aspects. Exploitation mainly for industrial purposes of the multi-layered aquifer system located in the upper 350 m depth of the Quaternary complex, began in the 1930s and increased thereafter, becoming intensive after the Second World War, following the post-war industrial boom. The piezometric head reached minimum levels in 1969, when static levels fell by 20 m in the Porto Marghera industrial area, and the depression cone also seriously affected the city centre of Venice; subsidence rates of 17 mm/year were recorded for that year at Porto Marghera, 14 mm/year in Venice, and 10 mm/year at the Lido (CARBOGNIN *et alii*, 1977, 1981, CARBOGNIN, 1992).

Drastic measures to reduce water pumping were adopted in 1970, and the construction of an industrial aqueduct modified water supplies, reducing the rate of subsidence significantly (Fig. 67) (CARBOGNIN *et alii*, 1977).

Subsidence of the Venice area due to groundwater pumping was also studied with the aid of mathematical models. The first Finite Elements model of land subsidence was developed in the 1970s (GAMBOLATI *et alii*, 1974a; 1974b). This model, that develops along a vertical cross-section joining Porto Marghera, Venice and Lido, was carried out with a two-module approach, the first to simulate the hydrology of the multi-aquifer system of the area, and the second to calculate anthropogenic subsidence in Venice.

Results showed that total subsidence due to water pumping was about 15 cm between 1930 and 1973. These conclusions were confirmed in the 1990s with a more sophisticated model which, applying a quasi-tridimensional approach, eliminated the main limitations of the previous model by means of a detailed three-dimensional geometrical reconstruction of the whole multiaquifer system, and non-linear constitutive relationships for hydraulic and geomechanical parameters characterising stratigraphical formations (TEATINI *et alii*, 1995).

Levelling surveys carried out in 1973 and 1993 confirmed that anthropogenic subsidence due to groundwater extraction in the Venice area had been halted (CARBOGNIN *et alii*, 1995b, 2004).

Monitoring of the piezometric head in the artesian aquifers has provide a fundamental contribution to the study of subsidence. The data have been collected since the 1970s by a monitoring network established by the CNR-ISMAR (DAZZI *et alii*, 1994). An example of piezometry mapping is shown in Fig. 68.

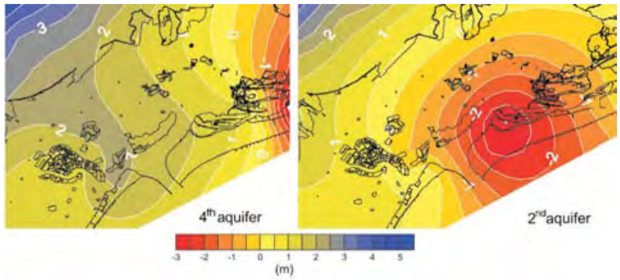

Fig. 68 – *Piezometric maps (m a.s.l.) of fourth and second aquifers in 2003. CNR-ISMAR data obtained from piezometric level monitoring network.*

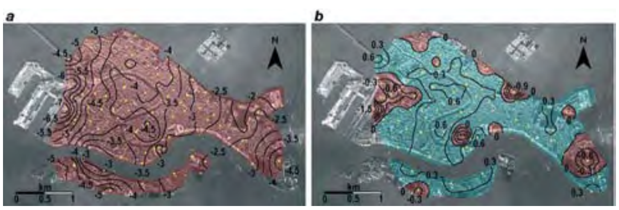

Fig. 67 – *Displacement rate (mm/year) recorded at Venice (a) 1961-1969; (b) 1973-1993. Negative values indicate land subsidence, positive values uplift (from* TOSI et alii*, 2002)*

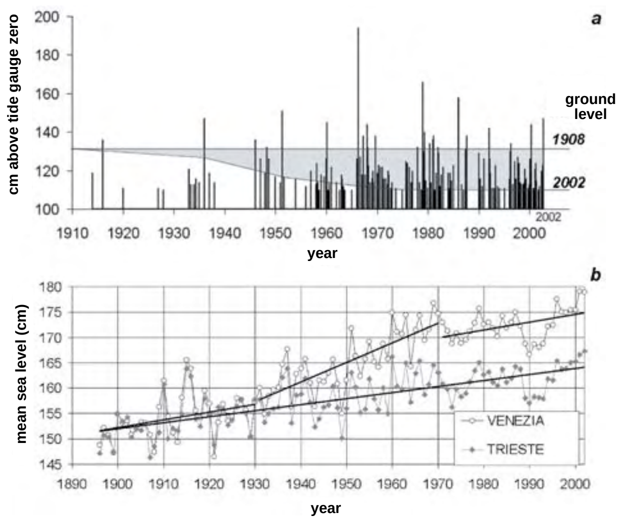

Fig. 69 – *(a) Increase in frequency of episodes of* acqua alta *exceeding 110 cm, caused by relative subsidence in Venice (revised by* CARBOGNIN *&* TARONI*, 1996, in* CARBOGNIN et alii*, 2005); (b) mean sea level at Venice and Trieste.*

3. - EUSTACY

Another important aspect concerning with the relative lowering of the Venice area, and hence the *acqua alta* increasing (Fig. 69a), is the raise of the mean sea level. As regards the northern Adriatic Sea, the most accurate historical series of tide data are those recorded at Venice (Punta della Salute) and Trieste. The length of the series was sufficient to average smaller oscillations due to short-term climatic variations (CARBOGNIN & TARONI, 1996).

The average eustatic rate over the whole period is 1.13 mm/year (Fig. 69b). Comparison of the Trieste and Venice data shows that there is no single trend over the last 100 years due to anthropogenic subsidence. After a 20-year period of quiescence from 1970 to 1990, the data for the last ten years indicate a significant resumption of eustatic increase, accompanied by a higher number of episodes of *acqua* alta (CARBOGNIN *et alii*, 2004).

4. - PRESENT SITUATION

Particular attention has recently been devoted to monitor vertical movements in the lagoon area. The existing levelling network, established along the lagoon edge, was updated within the framework of the ISES and IRMA Projects in the southern and northern parts of the lagoon-coastal area. A DGPS (*Differential Global Positioning*) network with about 150 measuring points was set up, and differential SAR interferometry and persistent scatterer interferometry on the ESA ERS-1 and

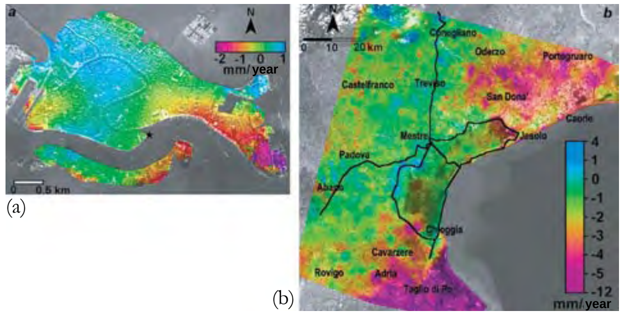

Fig. 70 - *(a) Map of vertical movements in Venice between 1992 and 1996, obtained with SAR differential interferometry (from* TOSI et alii*, 2002); (b) vertical movements in Venice area between 1992 and 2000, obtained with an integrated monitoring system (*STROZZI et alii, *2003).*

ERS-2 satellites images acquired between 1992 and 2000, have been used to map land movements in the Venice area with high resolution.

The various subsidence measuring methods currently available were incorporated in an "integrated monitoring system", which, exploiting the peculiar features of each method, allows a reliable and accurate monitoring of the city of Venice (TOSI *et alii*, 2002) (Fig. 70a) and the surrounding area (STROZZI *et alii*, 2003, 2005; TEATINI *et alii*, 2005) (Fig. 70b).

Measurements confirm the present stability of the central portion of the Venice Lagoon, including the historic city centre, and also reveal that the lagoon margins are sinking at a rate of up to 3-4 mm/year, due to a larger natural component, water pumping from the subsurface (in the northern area), and geochemical processes (in the southern area) (CAMPORESE *et alii*, 2005; GAMBOLATI *et alii*, 2005).

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VIII - STRATIGRAPHY

1. - DEPOSITIONAL ENVIRONMENTS

Following a classification criterion mainly according to RICCI LUCCHI (1978), it was believed appropriate to represent four different types of environment on the Geological Map: alluvial (or fluvial), deltaic, littoral (within which lagoon and beach deposits are distinguished) and shelf. They were identified by combined study of faunal associations, sedimentary structures and geomorphological features in the area. This choice aimed at describing the characteristics of this transition area, avoiding details not essential in defining the various stratigraphic units, since this would have made the final map not clear, preventing its interpretation and immediate understanding.

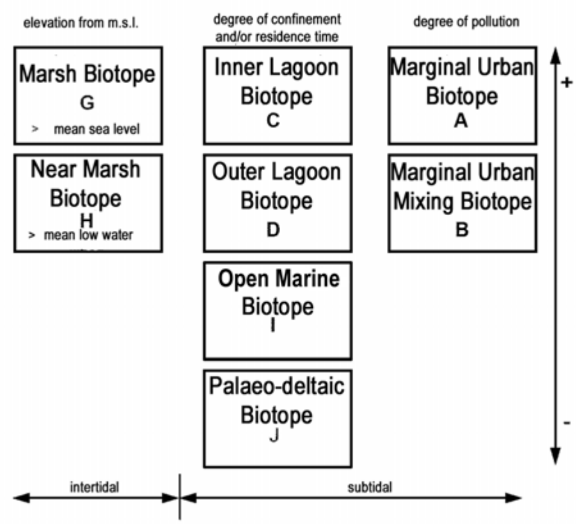

Fig. 71 – *Biotopes present in southern basin of Lagoon of Venice and main factors controlling them (from* SERANDREI-BARBERO et alii*, 2003, modified).*

1.1. - FORAMINIFERAL ASSOCIATIONS

In the Chioggia basin, the distribution of present-day benthic foraminiferal *biofacies* was defined following SERANDREI-BARBERO *et alii* (1999) by means of quantitative analysis of 95 samples of bottom sediments. For this purpose, all the taxa present in a known fraction of the washed residue were identified and counted, and the respective abundance values were used for analysis (BENZÈCRI, 1980), according to classic methods of statistical processing of enumerative data on sampling points and taxa (DAVIS, 1986). Correspondence analysis provides groups from sampling points characterised by similar *biofacies* and therefore indicating uniform environmental conditions.

Each of the identified present-day *biofacies* was characterised by means of a key species. The lagoon waters were mapped according to the descriptions of the present-day *biofacies* and knowledge of their geographical locations. The following were considered in particular: level of confinement, according to the concept of GUELORGET & PERTHUISOT (1983); anthropogenic pollution, as widely discussed by ALVE (1995); freshwater inputs (DONNICI & SERANDREI-BARBERO, 2005); and intertidal morphologies (ALBANI *et alii*, 1984a; 1984b; SERANDREI-BARBERO *et alii*, 2004). Fig. 71 shows the main factors controlling the *biofacies* which are representative of the various biotopes.

The conditions of the outer and inner lagoon are indicated by the different abundances of the dominant taxon, *Ammonia beccarii* (LINNAEUS), and the greater or lesser number of taxa present which, in the Chioggia basin, is between 12 and 22 in those lagoonal areas of greater marine influence, and which falls to less than 9 in the inner areas. In marginal built-up areas, where urban or industrial pollution overlaps natural parameters, *Haynesina paucilocula* (CUSHMAN) becomes dominant at the expense of *Ammonia beccarii;* intermediary values represent transitional environments between natural and anthropised conditions.

Tab. 4 – *Percentage content of main taxa in biotopes identified in southern (Chioggia hydrographic basin) and central lagoon (Malamocco hydrographic basin and sector south of Venezia of Lido hydrographic basin).*

Biotopo	A		B		C		D		F	
Laguna centrale	media	min-max	media	min-max	media	min-max	media	min-max	media	min-max
Trochammina inflata (Montagu)	0,9	0,5 - 1,6	1,2	0,3 - 2,9	1,6	0,2 - 7,6	0,4	0,2 - 1,1		-
Haynesina paucilocula (Cushman)	48,1	30,9 - 66,0	23,8	17,9 - 31,7	13,2	4,7 - 38,6	6,8	0,9 - 18,1		-
Ammonia beccarii (Linné)	38,7	27,7 - 51,0	59,1	53,8 - 62,6	61,5	39,0 - 78,7	74,7	55,7 - 90,3		-
Cribrononion granosum (d'Orbigny)	7,1	1,1 - 20,6	8,4	3,2 - 14,7	9,7	0,3 - 24,7	5,0	0,3 - 16,7		-
altre specie	5.6	2,6 - 10,4	7,6	2,5 - 12,9	15,1	5,2 - 29,7	13,4	4,5 - 32,2		-
numero di specie	13		13		58		60			
numero di stazioni	8		6		91		156			
% area settore lagunare	4,2		3,1		47,6		81,7			
% area totale lagunare	1,4		1,1		16,3		27,9			
Laguna meridionale	media	min-max	media	min-max	media	min-max	media	min-max	media	min-max
Trochammina inflata (Montagu)		-	0,3	0,3 - 0,3	1,7	0,3 - 4,7	1,0	0,3 - 5,3		-
Haynesina paucilocula (Cushman)		-	17,8	16,3 - 19,3	9,3	1,3 - 15,0	3,9	0,3 - 10,0		-
Ammonia beccarii (Linné)		-	46,8	43,0 - 50,7	69,6	58,3 - 81,7	82,1	63,0 - 93,0		-
Cribrononion granosum (d'Orbigny)		-	12,2	9,7 - 14,7	5,3	0,3 - 13,0	2,8	0,3 - 13,0		-
altre specie		-	23,0	20,0 - 26,0	15,1	4,3 - 23,7	11,5	4,0 - 22,7		-
numero di specie			14		32		36			
numero di stazioni			2		21		61			
% area settore lagunare			2,1		22,1		64,2			
% area totale lagunare			0,4		3,8		10,9			

Biotopo	G		H		I		J		
Laguna centrale	media	min-max	media	min-max	media	min-max	media	min-max	
Trochammina inflata (Montagu)	34,3	28,8 - 39,8	8,3	1,4 - 13,4		-	0,3	0,3 - 0,3	A- Margine urbano
Haynesina paucilocula (Cushman)	6,7	5,6 - 7,7	10,3	5,2 - 16,7	3,6	2,2 - 5	19,7	19,0 - 20,3	
Ammonia beccarii (Linné)	50,4	49,4 - 51,3	67,1	64,1 - 71,1	55,6	52,5 - 58,7	71,0	69,4 - 72,6	B-Urbano intermedio
Cribrononion granosum (d'Orbigny)	2,9	2,9 - 2,9	3,9	0,9 - 8,1	7,8	5,4 - 10,2	3,9	2,1 - 5,6	
altre specie	7,3	5,2 - 9,3	11,8	3,8 - 22,7	33	32,3 - 33,7	5,4	5,0 - 5,7	C- Laguna interna
numero di specie	9		21		27		7		D-Laguna esterna
numero di stazioni	2		6		2		2		
% area settore lagunare	1,0		3,1		1,0		1,0		F-Laguna chiusa
% area totale lagunare	0,4		1,1		0,4		0,4		
									G-Barena alta
Laguna meridionale	media	min-max	media	min-max	media	min-max	media	min-max	
Trochammina inflata (Montagu)	18,5	17,7 - 19,3				-	0,3	0,3 - 0,3	H-Barena intermedia
Haynesina paucilocula (Cushman)	4,7	4,0 - 5,3	21,0	21,0 - 21,0	3,7	2,7 - 4,7	10,5	0,7 - 17,3	
Ammonia beccarii (Linné)	57,8	55,3 - 60,3	71,7	71,7 - 71,7	50,2	48,7 - 51,7	68,8	57,1 - 78,0	I-Marino
Cribrononion granosum (d'Orbigny)	0,7	0,7 - 0,7	0,7	0,7 - 0,7	10,2	10,0 - 10,3	2,2	0,8 - 6,0	
altre specie	18,7	16,3 - 21,0	6,7	6,7 - 6,7	36,0	33,7 - 38,3	19,2	13,3 - 24,8	J-Paleodelta
numero di specie	13		5		29		10		
numero di stazioni	2		1		2		6		
% area settore lagunare	2,1		1,1		2,1		6,3		
% area totale lagunare	0,4		0,2		0,4		1,1		

Tab. 5 – *Average composition of foraminiferal biotopes in Gulf of Venice to isobath –18 m.*

Biotopo	Litorale interno ad influenza lagunare		Litorale esterno ad influenza lagunare		Litorale marino	
	media	min-max	media	min-max	media	min-max
Textularia agglutinans d'Orbigny	1,37	0,10 - 5,30	8,71	3,70 - 15,40	3,27	0,30 - 9,20
Textularia conica d'Orbigny	0,63	0,10 - 3,00	2,74	0,30 - 7,30	2,31	0,20 - 9,20
Eggerella scabra (Williamson)	1,06	0,10 - 6,40	2,06	0,50 - 5,50	0,54	0,10 - 1,80
Quinqueloculina seminulum (Linné)	12,51	1,60 - 31,90	11,55	7,30 - 16,80	12,83	4,60 - 20,80
Triloculina trigonula (Lamarck)	2,49	0,10 - 9,10	1,78	0,20 - 4,20	3,05	0,40 - 6,10
Buccella frigida granulata (di Napoli Alliata)	2,01	0,10 - 7,60	1,85	0,30 - 7,30	3,46	0,50 - 9,10
Ammonia beccarii (Linné)	45,36	30,30 - 78,10	29,18	22,60 - 37,10	25,74	13,30 - 38,50
Valvulineria perlucida (Heron-Allen & Earland)	6,05	0,40 - 15,50	6,72	4,90 - 9,10	9,25	0,50 - 24,50
Cribrononion granosum (d'Orbigny)	10,77	0,70 - 28,30	5,26	3,10 - 10,50	16,00	6,50 - 29,00
Cribrononion translucens (Natland)	0,59	0,10 - 2,40	0,98	0,30 - 1,90	1,01	0,10 - 3,20
Haynesina paucilocula (Cushman)	0,58	0,10 - 2,90	0,83	0,10 - 2,20	0,56	0,10 - 2,20
altre specie	18,86	8,60 - 35,20	28,85	20,00 - 39,10	23,81	12,10 - 34,40
numero di specie	47		57		54	
numero di stazioni	88		15		49	
% area	46,07		7,85		25,65	

Biotopo	Marino intermedio		Marino esterno	
	media	min-max	media	min-max
Textularia agglutinans d'Orbigny	13,71	2,90 - 24,20	27,64	10,60 - 42,10
Textularia conica d'Orbigny	4,47	0,80 - 16,50	7,74	2,10 - 28,50
Eggerella scabra (Williamson)	1,43	0,20 - 5,30	6,06	0,60 - 12,00
Quinqueloculina seminulum (Linné)	9,15	4,90 - 12,60	12,74	5,60 - 19,00
Triloculina trigonula (Lamarck)	3,50	0,60 - 7,00	7,05	4,90 - 9,50
Buccella frigida granulata (di Napoli Alliata)	3,75	0,50 - 7,20	1,03	0,20 - 4,10
Ammonia beccarii (Linné)	13,07	5,60 - 22,00	2,66	0,40 - 8,00
Valvulineria perlucida (Heron-Allen & Earland)	2,66	0,50 - 8,30	0,73	0,10 - 3,80
Cribrononion granosum (d'Orbigny)	9,96	4,10 - 13,50	3,15	1,60 - 7,10
Cribrononion translucens (Natland)	1,01	0,20 - 2,60	0,28	0,10 - 0,80
Haynesina paucilocula (Cushman)	0,53	0,10 - 1,20	0,49	0,10 - 1,40
altre specie	37,18	28,10 - 45,60	30,56	20,70 - 41,70
numero di specie	63		63	
numero di stazioni	25		14	
% area	13,09		7,33	

As a result of quantitative analysis of benthic foraminiferal fauna, the definition of the present-day marine and lagoon environments was used to identify Holocene palaeo-environments, comparing 102 sediment samples taken using a grab, drilling or through boreholes, on which quantitative analysis similar to that applied to define the present-day marine and lagoon environments were performed.

As regards lagoonal palaeo-environments, data obtained from comparisons with present-day fauna revealed the presence of buried intertidal morphologies and lagoonal sectors with greater or lesser levels of confinement compared with present-day conditions, corresponding respectively to inner and outer lagoon biotopes. In the inner margins of the lagoon, the top of the continental deposits which preceded the marine transgression, which occurred here in relatively recent times and sometimes only a few centuries ago, was often reached (SERANDREI-BARBERO *et alii*, 2005a).

As regards marine palaeo-environments of Holocene age, coastal belt *biofacies* similar to present-day ones, characterised by many Miliolides, together with *Ammonia beccarii, Elphidium* spp. and neritic taxa including *Textularia* sp. and *Triloculina* sp., are widely represented in the southern part of the Sheet, where they are found to depths, respectively, of -16 m, -18 m, -20 m and -26 m (compared with the present-day sea level) near Chioggia and the *CARG 7*, *CARG 8* and *Lito 1 – CNR* boreholes.

In the deltaic palaeo-environments, the corresponding *biofacies*, although they contain typical species of various lagoonal or marine sub-environments, are poorer in terms of individual samples and total species, and are mixed with a particularly abundant clastic fraction.

Lagoonal and marine Holocene palaeo-environments were also identified in portions of the Sheet which are now land. In particular, there are lagoon deposits under the recent continental deposits in the Foce Fogolana (*FF47 - CVN* borehole), on the southern margin of the lagoon, south of Valle Millecampi. Similarly, subtidal lagoon *biofacies* appear in the sediments underlying the recent Valle Millecampi saltmarsh.

1.2. - SEDIMENTARY STRUCTURES AND GEOMORPHOLOGICAL FEATURES

Sedimentological-stratigraphic analysis of the deposits and geomorphological study of the area defined the depositional environments and established their boundaries, also in view of the fact that the transition between adjoining environments is often gradual, passing through belts of variable extent.

1.2.1. - *Alluvial and fluvial deposits*

The main geomorphological features identified in the coastal plain areas, which are regarded as excellent indicators of alluvial environments, were the traces of extinct watercourses and fluvial ridges. Crevasse splays were also identified, some particularly large, which explained the sandy, silty deposits in the flood plain where pelitic sediments generally prevail. Silty sand and sandy silt constitute mainly active canal and fluvial ridge deposits, within which graded layers, cross- and parallel bedding, erosion pockets and pelitic inclusions were identified.

With distance from the river bed, with or without a gradual transition, the above units are replaced by granulometrically finer lithologies. These are flood deposits composed of clayey-silty sediments sometimes containing thin sandy intercalations, with traction structures and graded levels. Clay and silty clay, often organic, are found almost exclusively in flood basins, or floodable areas located distally with respect to the watercourse, where decantation prevails. Instead, when they appear near the traces of old riverbeds, they reveal replenishment deposits, formed by channel abandonment. Marshy *facies*, which evolved in depressed interfluvial areas, are indicated by the presence of peat. Clear signs of sub-aerial pedogenesis frequently characterise these types of alluvial deposits.

1.2.2. - *Deltaic deposits*

All the deposits associated with an estuary, mainly identified according to geomorphological indicators, are defined as deltaic, especially if there is evidence of the mouth of the old watercourses in the lagoon.

Having developed in a coastal transition environment, deltaic bodies often have common or very similar characteristics to those in the adjacent alluvial and coastal environmental units, so that distinguishing them is sometimes problematic.

Within-lagoon deltaic bodies of limited extent were identified by their generally lobed forms and variably irregular surroundings. Further inland, these deposits mix with fluvial ones, of which they are the natural continuation; seawards, they are interfingered with beach deposits. Geomorphological considerations became essential to distinguish between alluvial and deltaic sediments, mainly in all cases where palaeontological indicators did not clearly reveal the transition between the two types of environment. For this purpose, the presence and setting of ramified distribution channels were considered (sometimes developing near small, narrow, sandy-silty bodies from which small crevasse splays occasionally originate) and marshy basins.

From a lithological viewpoint, the deltaic deposits are highly diversified. Sand and silty and/or clayey sand are often deposited close to distribution channels and accumulate in natural banks, after their transport by high-energy water currents. They may therefore reveal traction structures. Silt and sandy and/or clayey silt, sometimes containing organic matter, make up the deltaic flood plain areas, sometimes containing cross- or parallel bedding. Clay and silty and/or sandy clay, often organic and sometimes showing signs of bioturbation, were deposited by settling in distal areas with respect to the channels, where the energy of the currents is very low. They are thin-bedded and contain silty or more rarely sandy laminations. Peat, frequently mixed with clayey-silty sediments (organic soil), is found near marshy deposits which developed in depressed areas of convergence and collection of river floodwaters (interdistribution basins) and in the adjacent lagoon environment.

1.2.3. - *Littoral deposits*

With reference to the definitions of RICCI LUCCHI (1978), the Venetian lagoonal area is considered as a lagoon-barrier-beach system, in which the beach environment is identified with a complex coast, characterised by an offshore beach and associated with an emerging sandy belt (lido, littoral), which make up a discontinuous barrier between the open sea and the protected zone (lagoon) behind. It was therefore considered suitable to distinguish between beach deposits (including exposed, intertidal and submarine beach deposits) and lagoonal deposits inside the littoral environment.

In the study area, starting from the Pleistocene, similar conditions arose many times, in response to transgressive marine events after deglaciations.

Many traces of old beach ridges and lagoonal palaeochannels were identified during geomorphological surveys, revealing in a preliminary way areas characterised by beach deposits and larger sectors in which lagoonal *facies* prevail.

The boundaries between the two units identified inside the beach environment were defined with precision by sedimentological/stratigraphic and palaeontological analyses.

The beach deposits, which develop near the littoral belts, more or less reworked by wind, are made up of well-sorted sand, silty sand and very sandy silt. At times, cross-laminations appear, and graded granulometric layers are frequent. Small silty-clayey bodies, sometimes containing organic matter, are found between the beach ridges or successive dune alignments.

Compared with the beach deposits, the lagoonal units are characterised by generally finer, highly differentiated lithologies. Silt and clayey and/or sandy silt prevail; more silty sand is found near the lagoon mouths, in shallows and in channels subjected to high-energy currents. Their presence here may also be due to reworking of beach sediments.

Clay and silty and/or sandy clay, often organic, are found in areas where poor water circulation favours settling and the tendency towards marsh formation. Peat deposits are also found in similar conditions, generally along the inner margin of the lagoon. Pelitic sediments are very frequently finely bedded or bioturbated.

Excellent indicators of saltmarsh in the lagoon sequences are oxidised horizons containing concretions, silty-clayey aggregates and vegetal relics, which often preserve their original position of growth.

1.2.4.- *Shelf deposits*

This sections describes shallow deposits, generally composed of fine sediments, identified on sedimentologic-stratigraphic bases. Palaeontological analyses of samples were also carried out.

2. - REFERENCE STRATIGRAPHICAL UNITS

The Geological Map aims at representing outcropping and sub-outcropping stratigraphic-depositional units in their three spatial dimensions, defining their distribution, reciprocal relations and lithological characteristics and the *facies* that distinguish them.

In the 1990s, guidelines for the geological mapping of Quaternary deposits in continental and marine areas indicated that they should be classified as allostratigraphic units (SERVIZIO GEOLOGICO NAZIONALE, 1999) or stratified bodies defined and identified according to the discontinuities which limit them (NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE, 1993), although the publication *Quaderno 1, series III* of the Italian SERVIZIO GEOLOGICO NAZIONALE (1992) had already called them *Unconformity Bounded Stratigraphic Units* (UBSU) (CATALANO *et alii*, 1996).

In the Chioggia-Malamocco Sheet, following the recommendations of a recent document on continental Quaternary surveying published by the SERVIZIO GEOLOGICO NAZIONALE (2001) to create the Geological Map of Italy, scale 1:50.000, and the "*Nuove Linee Guida per il rilevamento delle aree marine*, *scala* 1:50.000" (SERVIZIO GEOLOGICO NAZIONALE 2004), reference is made to the UBSU, defined solely according to the presence of two discontinuities with significant and demonstrable boundaries. Therefore, each unit may be extended laterally only if both discontinuities are visible and identifiable.

In the Venetian area, study of Quaternary deposits was made possible by continuous boreholes

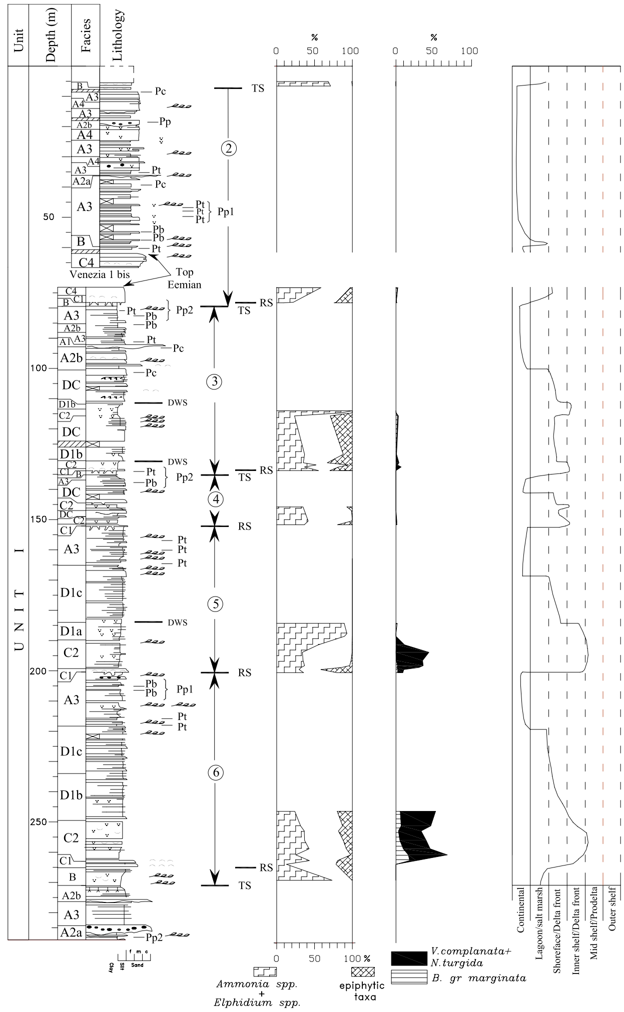

Fig. 72 – *Stratigraphy of upper part of* Venezia 1 - CNR borehole *(from KENT* et alii, *2002, and MASSARI* et alii, *2004). Sequences indicated with Pb, Pt, Pc, Ppl and Pp2 are palaeosoils; Pa represents peat layers.*

Venezia 1 - CNR (the only one using continuous boring to the top of the Pliocene deposits) (Fig. 72) and *Venezia 2 - CNR* (ITALIAN RESEARCH

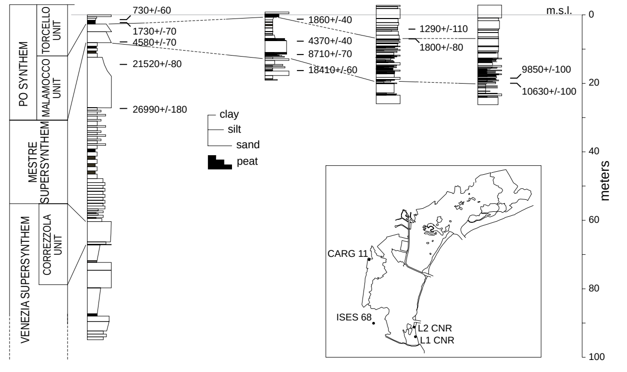

Fig. 73 – *Stratigraphic relations of Venice Supersynthem, Mestre Supersynthem and Po Synthem. Prevailing lithologies of four boreholes and some radiodatings (non-calibrated years BP) are also shown.*

Council, 1971 ; Favero *et alii*, 1973; Serandrei-Barbero, 1975; Favero *et alii*, 1979; Favero & Passega, 1980; Bellet *et alii*, 1982; Müllenders *et alii*, 1996; Massari *et alii*, 2004) (Section II).

To create the Geological Map of the Chioggia-Malamocco Sheet, boreholes mainly explored the first 20-30 m of the subsoiI, i.e., the units belonging to the top deposits of the Last Glacial Maximum (LGM) and the Holocene. A borehole to -94.5 m was also drilled (*CARG 11*), and another, to -100 m, was made available by the ISES Project. The *Venezia 1 - CNR* borehole and two others, drilled respectively near Malamocco and Correzzola, allowed the general stratigraphic setting of the deposits for the Tyrrhenian marine phase in the area covered by the Sheet to be interpreted.

According to the Italian Geological Survey guidelines for geological mapping, scale 1:50.000, the Upper Pleistocene units were attributed to the *Mestre Supersynthem* and partly to the *Venice Supersynthem*, in turn composed of various systems tracts (Fig. 73).

The *Po Synthem*, corresponding to the *Ravenna Allomember (*mapped on Sheet 223 "Ravenna" (Amorosi, 1999), in the Chioggia-Malamocco Sheet), represents Holocene deposits ascribed to the transgressive event after the last glaciation. Two units were identified: the *Torcello Unit,* of post-Roman age, to the top and coinciding with the *Modena Unit* (Sheet 223), and the *Malamocco Unit,* which includes the underlying sediments. The surface separating the two units corresponds to the buried topographic plain of Roman age. Mainly due to the lack of detail of the available stratigraphic data, it was not always possible to identify this discontinuity and then extend it laterally.

The oldest stratigraphic unit in the Chioggia-Malamocco Sheet is the *Venice Supersynthem*, the top part of which is represented by the *Correzzola Unit*, which identifies the Tyrrhenian marine deposits. The *Mestre Supersynthem* follows upwards, including the alluvial units which close with the LGM deposits.

3. - VENICE SUPERSYNTHEM

The non-exposed *Venice Supersynthem* includes post-Messinian units which were deposited from the Pliocene until the Upper Pleistocene. The top sediments of the Tyrrhenian transgression are attributed to the *Correzzola Unit* (CRZ). The lower limit therefore coincides with the Messinian discontinuity, whereas the upper one, which separates it from the overlying *Mestre Supersynthem*, has been located to the transition from the lagoonal deltaic environment unit to the later alluvial deposits.

Data on the sedimentological and depositional environment of the *Venice Supersynthem* are limited to interpretations of analyses of samples from five boreholes: *Correzzola* (Accordi & Socin, 1950), *ISES B - CARG 13* (Carbognin & Tosi, 2003), *CARG 11* (Donnici & Serandrei-Barbero, 2004), *Malamocco* (Calderoni *et alii*, 1998; 2000), *Venezia 1 - CNR* and *Venezia 2 - CNR* (Favero *et alii*, 1973; Serandrei-Barbero, 1975; Favero *et alii*, 1979; Favero & Passega, 1980; Bellet *et alii*, 1982; Müllenders *et alii*, 1996; Massari *et alii*, 2004). In particular, available data only allowed proper study of the upper part of this supersynthem, i.e., the sequence laid down during the Tyrrhenian marine transgression, although its base could not always be defined precisely. In the Chioggia-Malamocco Sheet, this sequence contains neritic *biofacies* at the base and lagoonal ones above.

In particular, study of the *CARG 11* borehole identified a benthic foraminiferal association at approximately -90,1 m from ground level. Twenty taxa were found, including *Uvigerina peregrina*, *Cassidulina laevigata*, *Cibicides refulgens*, *Rosalina brady*, *Bulimina elongata*, *Brizalina spathulata* and *Globocassidulina subglobosa,* which are absent or extremely rare in the lagoonal environment, as well as the prevailing *Ammonia beccarii*. The association is therefore attributable to a neritic marine environment, where the dominance of *A.beccarii* appears to be due to the influence of a fluvial delta. Similar conditions also appear from analysis of fauna present in the sample from -91,6 m, which has a lower number of species (9), but where the dominance of *A.beccarii* persists, together with some neritic forms (e.g., *Discorbis mirus*). From a lithological viewpoint, these deposits are composed of micaceous silty sand, with grain size increasing with decreasing depths, and by thin bedding, sometimes obliterated by bioturbation. Marine bioclasts are particularly abundant at the top of these units.

The benthic foraminiferal association changes at -63,6 m and -60,5 m, inside a deposit with granulometry fining upwards, overlying a peaty level with a clear erosional contact. Indeed, ten species are generally found, characterised by *A. beccarii* prevailing and typically lagoonal taxa (*Valvulineria perlucida*, *Haynesina paucilocula*, *Cribrononion granosum*, *Cribrononion translucens*), as well as sporadic individuals of *Fissurina lucida*, *Buccella frigida*, *Cribrononion advenum*, *Elphidium complanatum* and *Elphidium macellum.* These associations are indicative of a paralic environment with medium confinement, in which sedimentation conditions favoured the initial accumulation of medium-coarse sand rich in shell debris, gradually replaced by silty, finer sand with small-scale ripples.

In the *ISES B* (*CARG 13*) survey, the sandy deposits between approximately -76 m and -86.5 m from ground level appear as inner front delta sediments. In particular, an abundant marine malacofauna was found at -80 m (*Cyclope neritea*, *Cardiidae*) and foraminifers belonging to taxa characterising high-energy coastal environments at -76 m (Miliolides, *Ammonia beccarii, Elphidium* spp.). These findings perfectly match the grain size of the sediments, which are composed of fine silty sand between approximately -86.5 m and -80 m and micaceous medium-coarse sand with pelitic clasts between -80 m and -76 m.

In spite of the small number of analysed boreholes, a series of selected stratigraphies of wells drilled for water supplies was examined, in which fossiliferous deposits attributed to this unit were identified. Lateral correlations were also attempted, allowing definition of the various depths at which the top of these marine deposits are found. They generally appear between -80 m and -50 m on the Chioggia-Malamocco Sheet.

3.1. - Correzzola unit

The *Correzzola Unit* (CRZ) is composed of marine deposits of the last Tyrrhenian transgressive event, the top of which is found at between -80 m and -50 m on the Chioggia-Malamocco Sheet. It was studied with data from surveys to define the supersynthem to which it belongs (see previous section).

In the *CARG 11* survey, the CRZ coincides with the sequence containing benthic foraminifers at depths between about -66 m and -60 m, and lies on alluvial deposits with a clearcut erosional contact. However, identifying the CRZ in the *ISES B* (*CARG 13*) survey was more difficult, because, unlike the case of other CARG boreholes extending to -100 m in the Venetian area, a single transgressive event was identified between -86.5 m and -76 m, represented by deposits of a within-lagoon deltaic front. The *Correzzola Unit* sub-outcrops in the trench, approximately 50 m deep, at the mouth of the Malamocco inlet.

4. - MESTRE SUPERSYNTHEM

The *Mestre Supersynthem* (MT) lies on the *Venice Supersynthem* and is represented by alluvial plain deposits of sand, silt and clay, sometimes with evident signs of pedogenesis. The generally sandy coarser sediments are mainly found near old ridges; finer ones, often rich in organic matter, appear in floodplains.

The silt and clay generally have tabular, bedded structure, and contain peat layers, sometimes clearly correlable over long distances and characterised by the presence of seeds, opercula of freshwater gastropods, and shells of the genera *Valvata* and *Vallonia*. Sand follows preferentially sinuous directions, defining extinct watercourses.

Four main stages of climatic warming within the *Mestre Supersynthem* between 40,000 and 19,000 years BP were identified in the *Venezia 1 – CNR, Venezia 1 bis - CNR* (Müllenders *et alii*, 1996) and *CARG 5* (ex *BH2*) (Tosi *et alii*, 2005) boreholes by means of pollen analysis. The two oldest stages are difficult to attribute, but the two more recent ones go back to the Tursac and Laugerie interstages. Calderoni *et alii* (1998) also identified four main sedimentary cycles in this supersynthem.

The top deposits of the *Mestre Supersynthem*, dated to about 18,000 years BP, show evident signs of pedogenesis due to prolonged subaerial exposure. The boundary surface separating them from the later Holocene units is erosional.

Although variable lithologies appear, overconsolidated clay, locally known as *caranto*, is frequently found at the top and is regarded as a palaeosoil (Gatto & Previatello, 1974; Tosi, 1993; 1994a; 1994b; 1994c; Bonardi & Tosi, 1994b; 1995a; 1997; 1999; 2000a; 2000b; 2001; Bonardi *et alii*, 1997; Brambati *et alii*, 2003; Mozzi *et alii*, 2003). It varies in thickness between a few centimetres and 2 m, and is generally composed of clayey silt or very compact silty clay. It is pale yellowish-grey in colour, with ochre pressure marks, and contains carbonatic nodules a few millimetres in diameter. This layer and the layers immediately underlying it accumulated between 20,000 and 18,000 years BP. Recent studies locate pedogenesis and overconsolidation in the stage corresponding to the stratigraphic gap or reduced sedimentary flow that took place between 14,500 years BP and the onset of the Holocene transgression (Mozzi *et alii*, 2003).

Although the *caranto* is an excellent guideline level identifying the boundary between Pleistocene and Holocene deposits, it has more or less large, localised lateral discontinuities, represented by coeval *facies* made up of sandy deposits (probably deriving from fluvial ridges) and clay of lacustrine and palustrine origin, where pedogenesis may have been hindered by particular textural and depositional characteristics and only erosion could occur, probably during the post-glacial transgres-

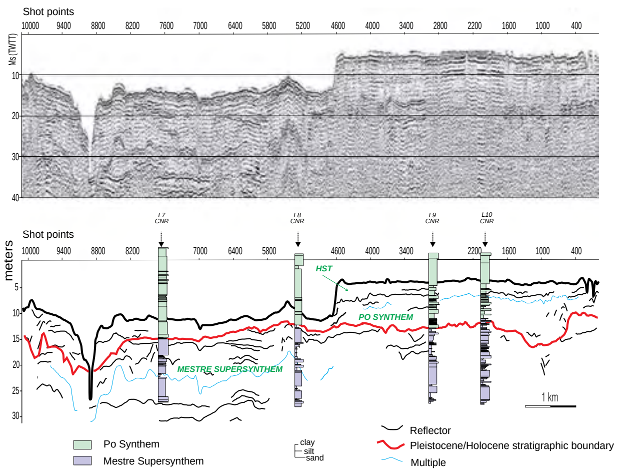

Fig. 74 – *Seismic cross-section acquired in a lagoon channel connecting mouth of Malamocco with Lido.*

sive stage. Interfingering with marine-lagoonal sediments reveals palaeo-riverbeds or filled channels. Recent studies on the subsoil of the city of Venice have described the formation of a vegetal cover and occasional sedimentary flows in this interval, which locally interrupted pedogenesis (SERANDREI-BARBERO *et alii*, 2005b).

High resolution seismic surveys in the lagoon and offshore have provided important information on the *Mestre Supersynthem*, and a series of extended structures, laterally well correlated and showing the presence of erosional unconformities and peat layers, probably reflecting the presence of gas, have been identified.

Fig. 74 shows a portion of a seismic profile acquired in the lagoon along a channel running parallel to the southern beach of the Lido, where the erosional limit separating the *Mestre Supersynthem* from the overlying *Po Synthem* is particularly evident.

On the Chioggia-Malamocco Sheet, alluvial deposits attributed to the *Mestre Supersynthem* only outcrop in the lagoon channels, where the depth is compatible with Pleistocene depth.

5. - PO SYNTHEM

The *Po Synthem*, abbreviated on the Geological Map to POI, is composed of Holocene deposits. The boundary separating it from the underlying *Mestre Supersynthem* is an erosional unconformity. There is a stratigraphic gap, varying in time, between the Pleistocene and Holocene deposition: the bottom of the synthem has different ages in the various sectors of the Venetian area: it is older in the southern coastal sector (10-11,000 years BP) and dated to 5-7,000 years BP in the north-western sector.

The variable arrangement of the base of the *Po Synthem* reflects the morphology of the Pleistocene plain during the LGM. It is thickest along the present-day southern littoral of Sottomarina (20-22 m), falls towards the Lido littoral, where it is only 8-10 m thick, and becomes still thinner both towards the margin of the lagoon (about 2 m) and offshore, where the *Mestre Supersynthem* outcrops starting from the isobath -23-25 m.

The *Po Synthem* is the best represented stratigraphic unit and its top corresponds to the present-day depositional surface. Where possible, the synthem is divided into two units, the *Malamocco Unit* (of pre-Roman and Roman age) and the *Torcello Unit* (of post-Roman age), shown on the Geological Map as POI9 and POI10, respectively.

5.1. - MALAMOCCO UNIT

The *Malamocco Unit* (POI9) is the lower portion, and therefore the oldest part, of the *Po Synthem*.

Its basal deposits are made up of transgressive marine sediments in the central-eastern sector of the Sheet and alluvial-deltaic sediments to the west. The former reflect the progressive landward migration of a coastal barrier, behind which a lagoon formed. They therefore include sandy-silty beach deposits, at the base of which there is often a thin layer rich in bioclasts and marine biosomes in a poor detritic matrix and silty-clayey lagoonal sediments, sometimes organic, of the back-barrier. The beach deposits generally overlie the back-barrier deposits, from which they are separated by a time-transgressive boundary surface, dipping weakly east. In some cases, however, the transgressive barrier sediments overlie the Pleistocene alluvial units with an erosional contact.

Under the back-barrier deposits, thin layers of reworked sandy silt are found locally, with chaotic structure and containing Pleistocene clay breccias, interpreted as "overflow" as they probably originated as a result of fluvial channel fill after deglaciation or marine transgression.

Near the mainland margin of the lagoon, the back-barrier deposits are interfingered with those of an alluvial-deltaic environment, the sequence of which often begins with thin "overflow" layers similar to those described above.

Transgressive deposits are buried under others belonging to the prograding system of the highstand systems tract (Fig. 75).

Transgressive and prograding beach ridges

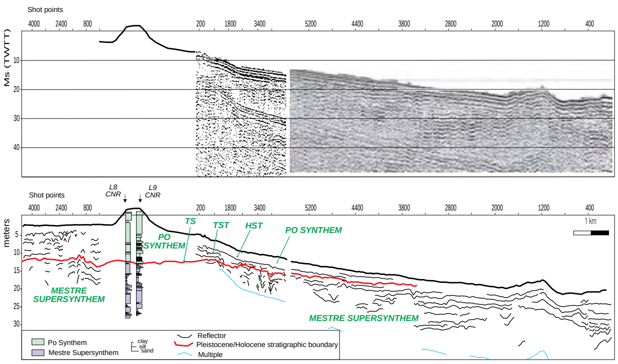

Fig. 75 – *High resolution seismic cross-sections integrated by data from two boreholes, of coastal area.*

give rise to a sandy-silty body thinning to the NW, the geometry of which is particularly complex in the sector near the present-day littoral, where the disposition and reciprocal relations with the various *facies* reveal migration of the coastline, initially inland and then towards the sea.

Behind the beach deposits are silty-clayey lagoonal back-barrier sediments, sometimes organic, which are interfingered with the deltaic units and which often contain peat in areas adjacent to the inner margin of the lagoon, then becoming marshy *facies*.

Seawards, within the sandy body composed of transgressive and prograding barrier deposits, is a wedge-shaped unit mainly composed of silty shelf transition sediments, which completely replace the former deposits seawards.

The *Malamocco Unit* outcrops in the lagoon channels and behind the Pellestrina littoral, where traces of two large beach ridges have been identified. The inner one indicates a long period of stasis of the coastline during the peak of the marine ingression (5-6,000 years BP), and the outer one to the east corresponds to a stasis of coastal progradation about 4,500 years BP (Section IX-1.1).

The base of the *Malamocco Unit* corresponds to that of the *Po Synthem*, whereas the top dates back to late Roman times. The top deposits often show clear signs of pedogenesis, indicating conditions of prolonged subaerial exposure.

5.2. - Torcello unit

The *Torcello Unit* (POI10) corresponds to the top part and more recent to the *Po Synthem* and is attributed to post-Roman deposition, from the V to VI centuries AD.

The characteristics of the basal deposits of this unit reveal climatic deterioration between the IV and VI centuries AD, which led to a considerable increase in precipitation, with more frequent flooding (Veggiani, 1994) and probably also a rise in sea level, which caused partial submersion of the lagoon area. This event is often recorded by lagoonal deposits overlying anthropogenic levels of Roman age. In the absence of such evidence, the unit was identified according to other elements, like those found during the mapping of the corresponding *Modena Unit (Sheet 223 "Ravenna")* (Amorosi, 1999). On the mainland, the lower limit of the *Torcello Unit* does sometimes coincide with fluvial erosional surfaces which can be correlated laterally with yellowish-brown and reddish-brown soils, showing partial or total decarbonation of surface layers and accumulations of carbonates in the deepest parts.

Thanks to study of many geo-archaeological levels found in the Venetian area and its surroundings, and to results obtained by interpreting available chronostratigraphic data, this unit could be mapped in many areas of the Chioggia–Malamocco Sheet (see also Amorosi, 1999; Regione Emilia Romagna, 1999).

The *Torcello Unit* is composed of sand, silt, clay, and alluvial, deltaic, beach and lagoonal peat, although the deposition of fine sediments in a shelf environment is now believed to have been scarce from the late Roman period onwards.

The distribution of the various *facies* that make up this unit generally reflect sedimentation conditions very similar to present-day ones.

The considerable availability of data from manual drilling on the mainland and from boreholes in the lagoon allowed the reconstruction of the geometry, distribution and stratigraphic setting of these deposits in greater detail than for the other units mapped on the Sheet. In order to interpret the characteristics of the subsoil classified as part of the *Torcello Unit* and mapping of relative deposits, historical sources provided particularly useful information, since they provided valid support to the reconstruction of variability in time of the sedimentation environments.

The *Torcello Unit* outcrops both in the lagoon and on the mainland (Section 5). It is generally relatively thin, 2-3 m, and has limited lateral variations.

6. - STRATIGRAPHIC CORRELATIONS AND EVOLUTIONARY MODEL

On the Chioggia-Malamocco Sheet, two deep boreholes drilled continuously (*ISES B - CARG 13* at Correzzola, and *CARG 11* in Valle Averto, reaching -100 and 95.4 m respectively) identified marine deposits attributed to the Tyrrhenian transgressive event, established as belonging to the *Correzzola Unit*.

As the sites where data are available are located far from each other, the silty-sandy, shell-rich levels given in some lithological descriptions of wells drilled for water supplies could not be correlated, although they identified the top of the *Correzzola Unit*, found at depths varying between -80 and -50 m.

The *CARG 11* core reached the Eemian interglacial (corresponding to the 5.5 marine isotopic stage, dated to 125,000 years BP) at -90 m, represented here by Tyrrhenian deposits composed of inner shelf *biofacie*s. Conversely, a lagoonal *biofacies* was found around -63 m, which correlates with an interstadial at the 5.3 marine isotopic stage (MASSARI *et alii*, 2004). The *CARG 11* core thus completely sampled the Upper Pleistocene sediments, made up of continental alluvial deposits laid down during the last glacial/interglacial cycle. Not all the isotopic stages from 5.5 to 2 are represented in the borehole data. At approximately -42 m, traces of pedogenesis mark the stratigraphic gap going back to between 60,000 and 40,000 years BP, already reported by BORTOLAMI *et alii* (1977) in the Venice subsoil at a depth of about 40 m. In the overlying layers, the succession of continental sediments, characterised by the widespread occurrence of peat, seeds, opercula of freshwater gastropods and shells belonging to the genera *Valvata* and *Vallonia*, was deposited during the four interstages, between 36,000 and 19,000 years BP, which occurred in the Venetian area (MÜLLENDERS *et alii*, 1996; BERTOLDI & CANALI in TOSI *et alii*, 2005) during the generally arid, fully glacial climate of the Würmian. Above the deposits of the most recent interstage (Laugerie), the LGM sequence is interrupted by the stratigraphic gap, which is very variable, as already reported in the Venetian area (BORTOLAMI *et alii,* 1977; TOSI, 1994a, SERANDREI-BARBERO *et alii*, 2001, 2002). Near the lagoon margin of the Valle Averto, the continental floods of the LGM were reached and covered by transgressive Holocene deposits around 5,000 years BP – more precisely, 4,580±70 years BP in the *CARG 11* borehole (DONNICI & SERANDREI-BARBERO, 2004) and 5,040±40 years BP in the *ISES 7* borehole located in the drainage basin.

Between -86.45 m and -76 m, the *ISES B* borehole revealed deltaic front deposits characterised by highly active sedimentation and composed of sand containing littoral bio-indicators, sometimes mixed with freshwater gastropod shells. These deposits are attributed to a prograding stage belonging to an Eemian oscillation. They are followed by sterile alluvial deposits, often containing carbon-

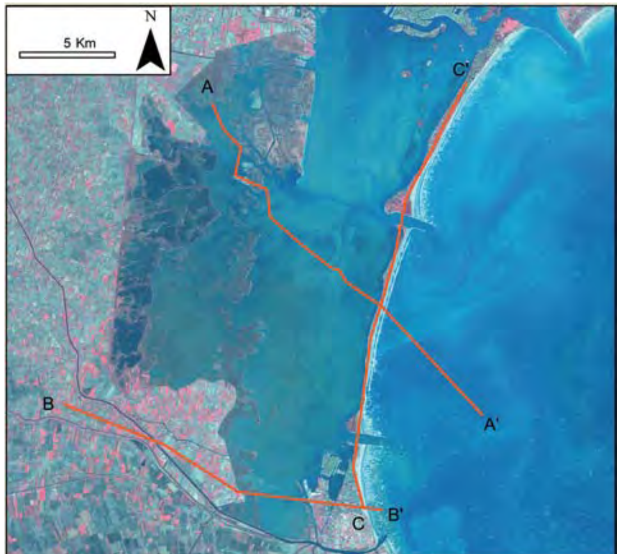

Fig. 76 – *Locations of geological cross-sections.*

ate concretions or mollusc shells from freshwater environment.

Thanks to the considerable amount of data available, it was possible to study the stratigraphic setting of the Holocene deposits in the Chioggia-Malamocco Sheet in great detail. Three geological sections, two of which run WNW-ESE and the other S-N, parallel to the coast (Fig. 76), show the stratigraphy of the *Po Synthem* (Figs. 77, 78, 79). These deposits lie on the Late Pleistocene alluvial ones corresponding to the final stage of the *Lowstand Systems Tract* (LST) related to the LGM. They are separated by a significant discontinuity which deepens eastwards, except for the north-eastern sector of the Sheet, where a large morphological high with its apex near the Bocca del Lido is present (Fig. 79).

Fluvial lacustrine sediments, mainly silty-clayey and sometimes rich in organic matter, are found towards the mainland at the base of the Holocene

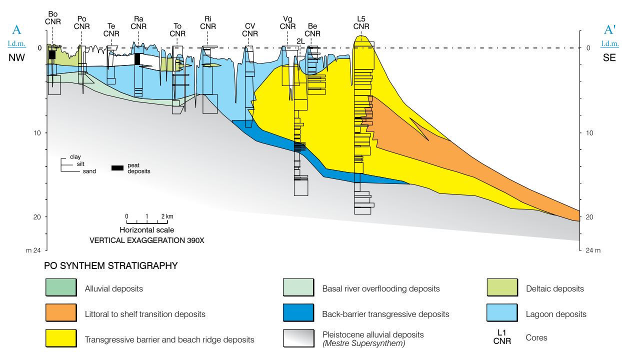

Fig. 77 – *Stratigraphy of Po Synthem along a cross-section running WNW-ESE towards southern basin of lagoon (location shown in Fig. 76).*

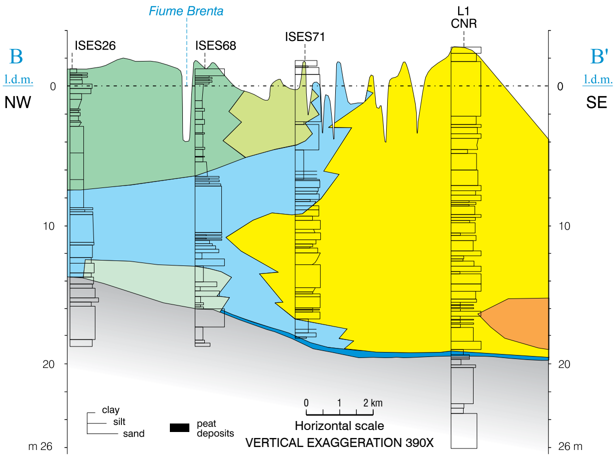

Fig. 78 – *Stratigraphy of Po Synthem along a cross-section running WNW-ESE along southern margin of lagoon (location shown in Fig. 76; see legend to Fig. 77).*

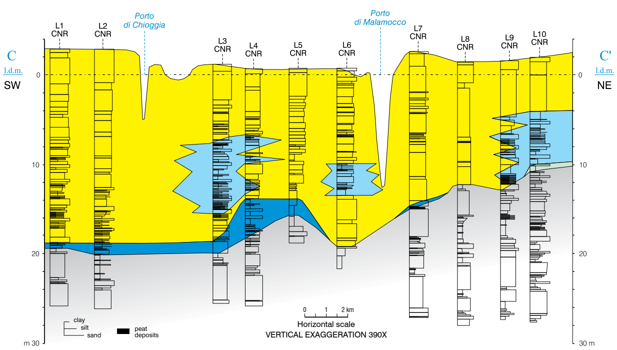

Fig. 79 – *Stratigraphy of Po Synthem, running S-N along coast from Sottomarina to port of Lido (location is shown in Fig. 76; see also legend to Fig. 77).*

sequence. They were deposited during channel filling caused by deglaciation and the subsequent rise in sea level. Seawards, they are generally replaced by fine transgressive marine *facies*. These units, which mark the onset of Holocene sedimentation, locally reach thicknesses of 3 m. The frequent presence of particular sedimentary structures, such as erosion pockets and chaotic layers containing soil breccias removed from the top of the underlying Pleistocene continental units, indicate extensive reworking (Gatto & Previatello, 1974; Tosi, 1994c).

The central-eastern sector of the area contains sandy-silty units of a littoral beach environment, representative of transgressive barrier *facies* at the base and a prograding beach ridge to the top. They lie on the above-described marine sediments with a clearcut contact or, locally, directly on the *Mestre Supersynthem*. This littoral sequence is interrupted to the east by a wedge-shaped body composed of a granulometrically finer pro-delta *facies*, the thickness of which gradually falls seawards. Lagoonal horizons are sometimes also found in beach deposits, and probably formed in small, low-lying areas between one beach ridge and the next.

Westwards, the transgressive barrier sediments are in contact with the silty-clayey lagoon back-barrier sediments, which lie discontinuously over the Holocene fluvial- lacustrine deposits or over Late Pleistocenic continental if Holocene fluvial lagoon deposits are lacking.

The back-barrier and transgressive barrier deposits and the lower part of the pro-delta wedge deposits represent the *Transgressive Systems Tract* (TST). Those representing the subsequent progradational stage, which started about 6,500 years BP, identified with the *Highstand Systems Tract* (HST), continue upwards. The accumulation of the latter was favoured by considerable fluvial clastic flows, combined with a great reduction in the rate of sea level rise.

Behind the prograding beach ridges, a large lagoon developed, with deposits which are often heteropic, with alluvial and freshwater marsh *facies* in an inner position. They represent deltaic bodies which originated from old courses of the river Brenta flowing directly into the lagoon.

IX - CARTOGRAPHY

The Geological Map of the Chioggia-Malamocco Sheet was created by collecting, analysing, processing and interpreting the considerable amount of data on the Lagoon of Venice, its drainage basin, and the immediately adjacent marine areas. Some of these data had been collected previously and others were acquired during the CARG project. For mapping purposes, geological, geomorphological, sedimentological, mineralogical, palaeontological and geophysical studies were conducted throughout the study area.

The surveys, which are complementary, may be summarised as follows:

- Collection, verification and interpretation of existing geognostic data (boreholes, manual drillings, soil survey sections, soil analysis) provided by the Veneto Region, Province of Venice, Information Service of the Venice Water Authority, Environmental Sector of the Province of Padova, and ARPAV (Environmental Protecton Agency of the Veneto Region), all integrated with extracts from existing bibliographic and cartographic sources (geological, geomorphological, historical, etc.), as well as information from published and/or unpublished studies carried out at ISMAR-CNR as part of other research projects;
- Analysis and interpretation of altimetric data on emerging land and bathymetry of the lagoon and the high Adriatic as regards morphological study. For this purpose, the Altimetric Map of the area, provided by the Province of Venice, was also consulted;
- Examination of many aerial photographs from several aerial surveys, taken between 1955 and 1999, to identify the main morphological features of the area and to distinguish textural variations in the terrain, thereby facilitating mapping of the lithological boundaries of the units to be mapped;
- Direct field surveys;
- Implementation of new borings, drillings, exploration trenches and samples within the CARG Project;
- Sedimentological and stratigraphical study of outcropping and sub-outcropping deposits sampled during surveys, mentioned previously or performed as part of other research projects. In particular, for the purposes of creating the surface map, only mainland sediments to a depth of 1.5 m were examined, except for the first 40-50 cm (when considered appropriate), generally representing the horizon of worked soil characterised by mixed textures or anthropic backfill. In the lagoon and offshore, in view of the difficulty of taking samples with simple manual tools, mapped deposits were studied from sediments sometimes no deeper than 1 m;
- Interpretation of results of laboratory analysis (micropalaeontological, mineralogical, dating) on sampled material;
- High resolution seismic surveys in the lagoon and offshore, with the support of the Department of Lithosphere Geophysics of the Natural Oceanography and Experimental Geophysics Institute of Trieste (OGS) and interpretation of relative results.

Following the recommendations of the Italian Geological Service (now APAT), the surface map, scale 1:50.000, was created by overall interpretation of maps produced during surveys and processing, which were initially to a scale of 1:10.000 and were then reduced to 1:25.000.

Initially, a legend was created to represent and classify the various types of deposits and to highlight the main geomorphological features of the area, while respecting CARG regulations for Quaternary cartography. Some changes were subsequently made to this legend on the basis of updating suggested by APAT and in response to new needs which gradually emerged during the generation of the Geological Map.

The various sedimentary bodies were classified as *Unconformity Bounded Stratigraphic Units* (UBSU) and thus grouped into supersynthems, synthems and subsynthems (see section VII-3). Stratigraphic units were defined according to age, depositional environment, sedimentary textures, and the discontinuities marking them (RIZZETTO *et alii*, 2005).

As regards the age of the deposits, as already noted in section IV, Holocene units (*Po Synthem*, divided in turn into the *Torcello Unit* and *Malamocco Unit*) and Upper Pleistocene units (*Mestre Supersynthem* and *Correzzola Unit*) were identified.

Examination of the final cartographic product clearly shows that most of the outcropping and sub-outcropping deposits belong to the *Po Synthem*, as they are of Holocene age. The *Torcello Unit* and *Malamocco Unit* were mapped separately, where the discontinuity surface that separates them could be identified and extended laterally. Elsewhere, when data useful for identifying these boundaries were scanty or discontinuous, sediments were attributed to the *Po Synthem* in an undifferentiated way.

Outcropping Pleistocene deposits belonging to the *Mestre Supersynthem* were only found in the lagoon basin, both near the trenches at the inlets to the lagoon itself, and near the deepest channels. Interpretations were made possible by combined interpretation of geognostic surveys and seismic profiles. Sediments of the Tyrrhenian transgressive event outcrop in the trench at the Bocca di Malamocco, where the top of the *Correzzola Unit* was identified at a depth of about 50 m by means of borehole data (CALDERONI *et alii*, 1998, 2000) and VHR seismic profiles. However, the outcrop was too small to allow mapping on scales of 1:25.000 and 1:50.000.

The particular nature and conformation of the area made it necessary to distinguish and represent depositional environments in detail. Mapped sediments were therefore attributed to alluvial, deltaic, lagoon, beach, and shelf systems. Anthropogenic deposits were also identified (infill reclamation, anthropically reworked sediments). As regards shelf deposits outcropping in the northern Adriatic, the boundary between them and the beach deposits was located approximately at the -10 m isobath, where an evident lithological variation is found, with a sharp transition from silty sand to much finer silty sediments. The recommendations of ALBANI *et alii* (1998) were applied.

From a lithological perspective, due to the uninterrupted compositional variability of the deposits, four grain size classes were chosen: sand, silt, clay, and peat. Deposits of intermediate composition were grouped in one of these categories according to their prevailing granulometric class. Isolated outcrops lithologically different from surrounding ones were not considered, both because they were not reliable and because, if real, they would have involved the identification of units which could not be mapped to the scale required by the survey.

As regards the geomorphological setting, features contributing to the identification of these deposits, useful for indicating the various *facies* and attributing the various units to a certain depositional system, are mapped. It was considered suitable to indicate traces of palaeo-riverbeds, particularly pronounced ridges (to identify the direction of development of the main fluvial depositional bodies, in the absence of evidence of channels, or where they are particularly discontinuous, and to explain the extensive and well-defined deposits of sand and sandy silt), traces of lagoon palaeochannels and old coastal belts. The positions of the main old lagoon mouths are also shown, since they are important in understanding the geological evolution of the area. Other minor elements identified during the survey, although useful for palaeo-environmental interpretation of deposits, were voluntarily omitted, in order to facilitate the interpretation of the Geological Map.

The various types of processed data are mapped with a combination of symbols and colours. The age of each stratigraphic unit is shown in a pre-defined background colour. Various degrees of shading are used to show low-ranking units belonging to the same period. Differing nuances of each shade are used to show depositional environments.

The textural properties of sediments are indicated with differently coloured symbols, according to the genetic processes responsible for their formation. Geomorphological features are shown with suitable simplified symbols and highlighted in different colours to indicate prevailing origin.

The resulting end-product shows the distribution, reciprocal relations, lithological characteristics and *facies* of the stratigraphic units outcropping or sub-outcropping in the area. Background topographic information allows deposits to be easily located.

1. - GEOLOGICAL MAP OF CHIOGGIA-MALAMOCCO SHEETS

The Chioggia-Malamocco Sheet includes the southern part of the Lagoon of Venice, the adjoining portion of its drainage basin, beach ridges separating the lagoon from the sea, the littoral strips of Lido, Pellestrina and Sottomarina, and the narrow belt of the northern Adriatic adjacent to it.

The mainland sector is mainly composed of farming land, some of which lies below sea level, especially the part behind the lagoon margin. Here, pumping equipment and drainage channels ensure the removal of excess water, so that normal farming can take place.

The area is crossed by two important watercourses, the Brenta and the Bacchiglione. The Brenta flows NW-SE as far as the southern margin of the lagoon, and then runs parallel with it to the east. At the port of Brondolo, located slightly further south of the south-eastern boundary of the Chioggia Sheet, it then debouches into the Adriatic. The Bacchiglione, further south, runs WNW-ESE, and then joins the Brenta south of the lagoonal basin.

Most of the plain covered by the Chioggia Sheet belongs to the terminal portion of the Holocene depositional system, bordered to the south by the Holocene system of the Adige.

The identification of many abandoned watercourses gave useful support to knowledge of the events responsible for the geological and geomorphological evolution of the area. The considerable variability of these courses, together with frequent changes in the texture of their deposits, both on the surface and at depth, reveal a complex alluvial environment, which developed in very changeable conditions in the course of time. This is also revealed by the large crevasse splays found throughout the area.

Relict palaeo-riverbeds, very abundant almost everywhere, only become less frequent to the north-west. They are generally very sinuous, ramified, thin and discontinuous, so that their preferential flow directions could only be identified locally. Instead, the fluvial ridges, which developed uninterruptedly throughout the area and are separated by evident depressed zones, allow easier identification of the ancient directions of river flow. Analysis of their distribution revealed two main systems, developing respectively north and south of the Bacchiglione and both running towards the lagoon margin. The former, more northerly, is characterised by a series of courses mainly running NW-SE and WNW-ESE; the latter, less extensive, runs W-E.

The old hydrographic elements north of the Bacchiglione correspond to the Late Holocene courses of the Brenta, connected by a transition running NE of Padova through Vigodarzere and Ponte di Brenta. Those to the south correspond to extinct courses of the Adige and Po (BONDESAN & MENEGHEL, 2004). Previous studies (CASTIGLIONI, 1978) suggest that, south of the lagoon, traces remain of the oldest northern course of the Po, which passes from west to east near Agna, Cona, Conca d'Albero and Civè towards Chioggia. A palaeo-bed of the Adige, running W-E near Candiana and Villa del Bosco, merged with this ancient course of the Po near Conca d'Albero. Despite archaeological remains dating back to the Bronze Age on this old ridge of the Po (BASSAN *et alii*, 1994), archaeological and historical data confirm that this watercourse remained active until Roman times (CASTIGLIONI, 1978; BASSAN *et alii*, 1994) (Fig. 80).

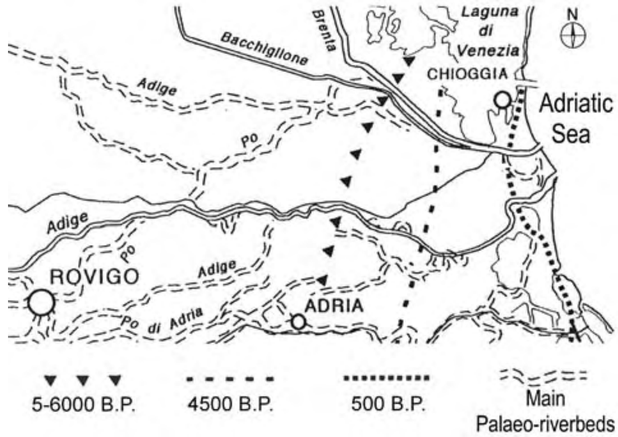

Fig. 80 – *Variations in coastline during Holocene and traces of main palaeo-riverbeds (from* BONDESAN et alii, *2001, modified).*

The ridges identified in the area partly coincide also with the more recent or present-day flow direction of the Brenta. This is generally due to artificial channelling, mainly to prevent the river from continually flooding and to protect the lagoon.

As early as the year 1143, the Brenta was diverted and made to flow along the Naviglio Brenta towards the city of Venice. Although it was thus forced to abandon its most southerly branches, this work caused the adjacent S. Ilario area to become marshy.

To halt the damage caused by floods in 1327, the mouth of the Brenta was moved slightly further south, at Volpego, towards the island of S. Marco di Bocca Lama, situated at the northern margin of the Sheet.

In 1457, the Brenta was again diverted from Dolo towards Sambruson and thence to Lugo, along the Brenta Secca, and finally entered the Grand Canal through the Lugo Canal.

In order to move the river away from Venice once and for all, in 1488 the excavation of Taglio Brenta Nuova (or Brentone) was decreed. Work

Fig. 81 – *Territory of "Brenta Delta Reclamation": detail from Geological Map of Chioggia-Malamocco Sheet.*

was finished in 1495, and the new cut was opened in 1507. This made the Brenta flow south, passing Corte as far as Conche, and then enter the Bacchiglione (whose course corresponded to the present-day course of the Montalbano Canal) and debouch into the lagoon of Chioggia. In 1540, the common mouth of the Brenta-Bacchiglione system was displaced from the lagoon seawards, near Brondolo, while further changes were made to its terminal stretch.

The excavation of the Taglio Nuovissimo dates back to 1610, and ran from Mira to Brondolo along much of the border of the lagoon. In 1840, the water was made to flow into lagoon of Chioggia: in less than 50 years, this created a deltaic apparatus which, it has been calculated, would have led to the disappearance of over 30 km^2 of the lagoon, reaching to within 3 km of the harbour mouth of Chioggia (Zunica, 1974). Today, the corresponding area, mainly reclaimed, is known as the "Brenta Delta Reclamation" (Fig. 81).

From 1858, the Brenta was made to flow into the Cunetta di Stra, corresponding to its present-day course, but its mouth was finally diverted from the lagoonal basin in 1896 by artificial channelling.

From the above, it seems clear that some of the sediments outcropping near the drainage basin closest to the lagoon margin are due to deposition in the directions of flow documented by historical sources.

However, the temporal collocation of the oldest river courses, and therefore of their relative deposits, is problematic. Radiocarbon dating shows that the Brenta, flowing near Camin, Saonara and S. Angelo, was active in the first half of the 1st millennium BC and between the V and IX centuries BC. In the period 968-544 BC, sedimentation resumed in the flood plain opposite the end of the Arzergrande ridge, near which archaeological findings indicate the presence of a large river, presumably the Brenta, in Imperial Roman times (I-II centuries AD) (Bondesan & Meneghel, 2004). Similarly, there is evidence of Iron Age human settlements on the ridge connecting Sant'Angelo, Boion and Lova, suggesting the existence of an active watercourse flowing from the Paduan hinterland in the 1st millennium BC (Bondesan & Meneghel, 2004). A sample from the left bank of the Brenta, taken at -1.9 m from ground level in the Sant'Angelo-Campolongo-Corte direction and belonging to a sandy fluvial body, was dated at 3,740±40 years BP (cal 2,280-2,030 BC; 4,230-3,980 BP), confirming that a river flowed there already in the 2nd millennium BC.

The problem of establishing the age of alluvial deposits therefore not only derives from lack of knowledge of the period of activity of the oldest watercourses, but also from the complex stratigraphic relationships existing between the various *facies,* due to the frequent oscillations of watercourses and sometimes to the reactivation of extinct ones.

In the south-western sector of the Sheet, peat samples from various areas at depths of between -0.60 m and -1.2 m from ground level date back to the Iron Age. It is therefore very probable that the outcropping deposits in these sites are pre-Roman. However, available data do not allow us to trace the boundary separating them from post-Roman sites, which is one reason why we were unable to map them as part of the *Malamocco Unit.* As a re-

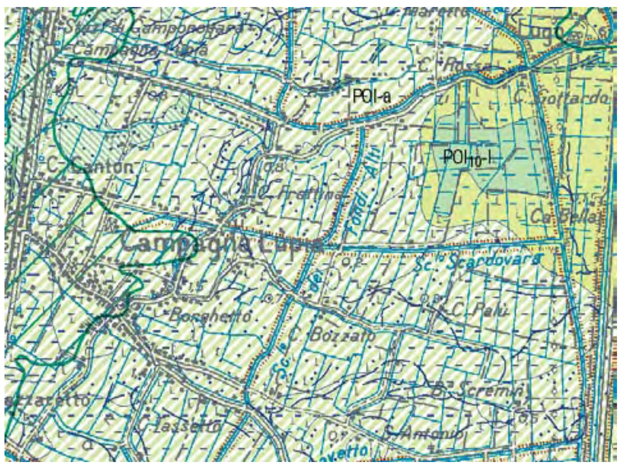

Fig. 82 – *Detail of Geological Map of Chioggia–Malamocco Sheet: lagoon deposits on mainland NE of Campagna Lupia.*

Fig. 83 – *Deltaic deposits in northern sector of Geological Map of Chioggia-Malamocco Sheet.*

sult, here, as in other mainland sectors, most of the outcropping units are attributed to the *Po Synthem*. Instead, all the deposits definitely associated with the depositional activities of present-day rivers, or in any case watercourses active from Medieval times onwards, are assigned to the *Torcello Unit*, are located on the respective ridges, and are generally composed of silty and sandy sediments.

Throughout this portion of the drainage basin, the complete lack of evidence of a lagoonal environment are set against the abundance of fluvial traces, although the area is adjacent to the lagoon. Indeed, until about 500 years ago, the line of demarcation separating it from the mainland was located further east than it is now, due to the depositional activity of the Brenta branches which entered it, giving rise to deltaic apparatuses. Only with the diversion of the river did the previous freshwater environments start to regress, favouring expansion of the lagoon basin inland. This process was interrupted when the border of the lagoon was completed by banking in 1791, which stopped it from being able to invade the flood plain further inland.

Relicts of old lagoon deposits still remain NE of Campagna Lupia, where *valli di pesca* (extensive fish-farms) existed in the past (Fig. 82).

The whole area of the lagoon behind the boundary is now characterised by saltmarsh, which formed due to marine ingression into peat bogs and freshwater marshland. Here, morphologies and deposits genetically associated mainly with the apparatuses of within-lagoon mouths formed of the extinct courses of the Brenta, for which historical data are available, can still be identified.

From the northern sector of the Sheet, the first deltaic units found in the lagoon are those near Volpego and Lago dei Teneri (Fig. 83), where the terminal stretch of the river was diverted in the 14th century.

Slightly further south, the Giare ridge and the narrow peninsula within which the Lugo Canal flows represent bodies of alluvial and deltaic origin (Fig. 84).

Dating on remains of tree trunks collected at a depth of little more than 1 m at Torson di Sopra and Lago dei Teneri provided ages of 1,140±45 BP and 1,515±85 BP, respectively (Marcello & Spada, 1968). Peat sediments of a freshwater environment at depths of about -1.35 m and -1.95 m near Torson di Sotto were dated to 1,140±80 and 1,730±80 years BP respectively (Pirazzoli *et alii*, 1981). They indicate that the Brenta passing through Stra was active in Roman, Late Roman and High Medieval times. It could then flow into the lagoon along the branches composing the Lugo and Giare fluvial ridges (Bondesan & Meneghel, 2004).

In particular, the marsh peat found at- 0.95 m, near the Lago delle Giare south of the ridge of the same name, is of Late Roman age, whereas the organic sediments sampled at -1.40 m on the narrow peninsula crossed by the Lugo Canal (Fig. 84) are later, being dated to 730±60 years BP (cal 1200-1320 AD, 750-630 BP; 1350-1390 AD, 600-560 BP). These sediments are the substrate of the inner lagoon margin (Donnici & Serandrei-Barbero, 2004), on which lie sediments deposited when the Brenta entered the Lugo Canal. For this reason, it is believed that the saltmarsh, definitely ascertained between -1 m and -0.50 m, is the result of the establishment of a deltaic environment.

Other thick layers of peat, silt and marshy clay

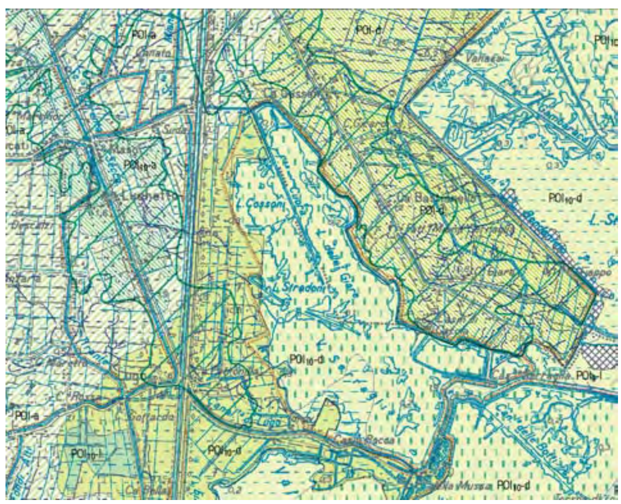

Fig. 84 – *Detail of Geological Map of Chioggia-Malamocco Sheet: Giare ridge and Lugo canal.*

under dated samples indicate that a massive invasion of freshwater probably occurred about 2,500 years ago, due to the migration of the course of the Brenta (Favero & Serandrei-Barbero, 1980). This appears to be confirmed by the results of pollen analysis of a clayey silt from about -2.20 m, slightly deeper than the peat which provided the oldest age mentioned above. This layer may actually be older than the Roman settlement, as no species introduced by man are present (Pirazzoli *et alii*, 1981; Horowitz, 1967).

It seems that Torson di Sotto was already surrounded by marshes and reedbeds in Roman times. Later, during Medieval times, its extension seawards was such that, in the early 14th century, both public and private property - including channels, saltmarsh, peat bogs, mud flats and beaches, where rushes grew in the lagoonal areas of the Alberoni beach, near the present-day port of Malamocco (Favero *et alii*, 1988).

However, it is only after the year 1000 AD that definite information is available regarding the continuation of the Brenta from Stra towards Oriago and Fusina. However, the river was also frequently diverted, especially on the right and particularly from Dolo towards Sambruson, from Mira towards Gambarare and the Giare fluvial ridge, or towards Dogaletto and S. Ilario (Favero *et alii*, 1988).

Extensive deltaic deposits also outcrop in the southern sector of the lagoon. They mainly belong to the wide mouth apparatus which formed in the second half of the 19th century, following the last entry of the Brenta into the southern lagoon. On the mainland, the substrate on which these units lie is characterised locally by organic sediments of a marshy environment, sometimes brackish, at depths varying between -0.80 m and -1.40 m from ground level, and dated to the XI-XIII centuries.

North of the "Brenta Delta Reclamation", it is interesting to note the presence of marshy organic sediments and saltmarsh of deltaic origin. Some samples from this area taken at depths of less than -1 m under the lagoon bottom, are of Late Roman and Medieval age. These deposits lie on a generally peaty continental substrate of Roman age. It is difficult to establish from which course of the Brenta they originated. They may derive from the depositional activity of watercourses, of which traces have been found at the "Brenta Delta Reclamation", upstream from the 16th-century inner lagoon margin, by means of historical cartography (Bondesan & Meneghel, 2004). Due to the lack of precise information about their effective existence and their relative period of activity, this hypothesis cannot be confirmed.

According to the above considerations, it seems evident that most of the deltaic deposits mapped are of post-Roman age.

Due to the lack of necessary chronological data, the deposits at the Giare fluvial ridge (Fig. 84) - as they may correspond to one of the courses of the Brenta which was active in Roman times (Favero, 1989; Bondesan & Meneghel, 2004) - and those further south extending towards Punta Monticello (Fig. 85) were both attributed to the *Po Synthem,* as there is no definite information about the existence of post-Roman courses of the Brenta with mouths in the Valle Ghebo Storto and Valle Morosina. Sediments dated of the latter do appear to be older (Fig. 85). In particular, in the adjacent mainland, there are flow paths coming from the west which are connected to the old course near Arzergrande, which are interrupted at the margin of the lagoon.

From a lithological perspective, all the deltaic deposits which are mapped are characterised by the presence of organic peat, silt and clay. They are often partially buried under a thin cover of lagoon sediments, of negligible importance.

During the drafting of the Geological Map, the need arose to trace the boundary between alluvial and deltaic deposits, the transition between which is generally gradual. At points where it was particularly well-developed, the decision was taken to

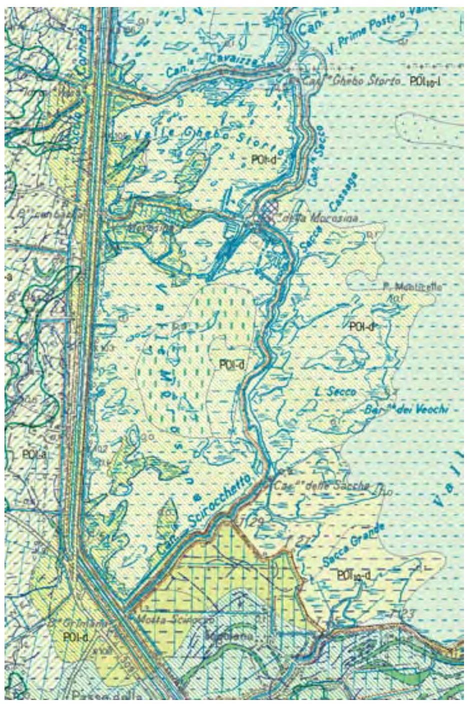

Fig. 85 – *Detail of Geological Map of Chioggia-Malamocco Sheet: deltaic deposits attributed to Po Synthem in south-western sector of lagoon.*

show units outcropping in it in the colour indicating deltaic depositional environments, together with the textural symbol of the sediments in the colour chosen for alluvial environments.

For example, this is the case with the Giare ridge and the fluvial body along the mainland adjacent to the southern margin of the lagoon basin.

The post-glacial transgressive event did not involve the whole lagoonal area at the same time, influenced as it was by the pre-existing morphological conditions of the flood plain on which it lies. In the present-day southern sector, which was originally more depressed than the northern one, the first marine deposits date back about 11,000 years (Bortolami *et alii*, 1984). The Lido and Cavallino littorals further north were not reached by the first ingression until about 7,000 years ago (Tosi, 1994c). Here, the presence of a wide, flat ridge NW of Venice, which extended seawards near the Bocca di Lido and is attributed to a Pleistocene course of the Brenta (Favero *et alii*, 1988; Tosi, 1994c), also influenced the morphology and setting of the beach ridge behind which the first lagoon basin developed. From Jesolo, this ridge probably joined the area near S. Nicolò di Lido, passing slightly inland of the S. Erasmo - Lio Piccolo - Lio Maggiore alignment (Favero, 1985; Favero *et alii*, 1988; Blake *et alii*, 1988). It then continued SW, crossing the southern lagoon near Canale di Val Grande and reached the area near Cavarzere (Favero *et alii*, 1988). This alignment does not actually correspond to the more inner position reached by the coastline at the peak of the transgression, but is behind it: identification of the line of maximum ingression, which some authors attribute to the Mid-Atlantic (Bondesan *et alii*, 1995), is hindered by the lack of stratigraphic data. Studies carried out so far indicate that it passes along the Conche-Cavarzere line, but without reaching Cantarana (Favero & Serandrei-Barbero, 1978; Bondesan *et alii*, 1995; Rizzetto *et alii*, 2002) (Fig. 80; Position X in Fig. 86). The lack of surface evidence of old coastal apparatuses and the gradual transition from deposits of a littoral marine environment to those of a fluvial environment probably indicates that the coastline here was unstable for long enough to allow the development of large beach ridges and that active fluvial clastic supplies caused a gradual regression (Favero & Serandrei-Barbero, 1978; Gatto, 1984; Favero, 1999).

The inner coastal apparatus identified so far corresponds to the alignment that continues parallel with the Canale di Val Grande from the Porto di Malamocco area and then divides, creating two distinct ridges, both characterised by a weak morphological-rilief running NE-SW (Figs. 87, 88). The western one extends towards Punta del Cane, and the other continues towards Motta dell'Aseo, where it approaches the southern margin of the lagoon. Both may indicate the position taken by the littoral about 4,500 years BP (Figs. 80, 86). There is also clear and uninterrupted evidence of this in the large coastal plain further south, between the rivers Brenta and Adige (Favero & Serandrei-Barbero, 1978; 1980).

Another short submerged alignment, running in the same direction, lies slightly further east, near the port of Chioggia. Although chronological data about it is lacking, previous studies date it

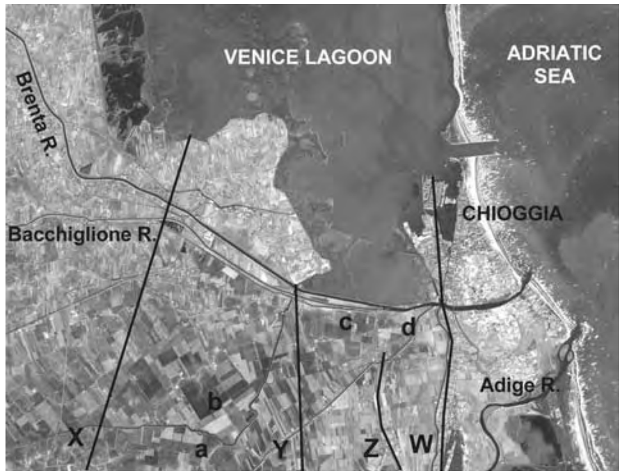

Fig. 86 – *Representation of coastline variations in an ASTER satellite image: (X) 5-6,000 years BP; (Y) 4,500 years BP; (Z) 3,000 years BP; (W) 2,500 years BP (by* Rizzetto et alii, *2003).*

Fig. 87 – *Shaded relief map of bathymetry in a lagoonal sector south of* Canale dei Petroli *[oil tanker route] (a). Two ancient beach ridges are also shown (b,c).*

between 3,000 and 2,500 years BP (Fig. 88).

Due to their direction of development and the textural features of their top sediments, the sandy outcrops south of Chioggia, between the Canale Lombardo and the lagoon of Lusenzo, belong to the northern wing of a deltaic structure with its cusp near Brondolo (BASSAN *et alii* ii, 1994), where the coastline was already located in Roman times (FAVERO, 1999; BONDESAN *et alii*, 2001). It is therefore believed that these deposits belong to the *Malamocco Unit*.

Instead, the lido of Sottomarina began to form in the XVI century, after the common mouth of the Brenta-Bacchiglione system had been excluded from the lagoon. Its growth was due to deposition of solid sediments transported by these two rivers, together with the Adige. Behind the present-day coastline, traces of old beach ridges can still be distinguished, although they are now flattened or characterised by weak reliefs, marking the progressive stages of advance of the beach, although signs of anthropic reworking are also evident.

The ancient coastal structures in the lagoon were identified by geomorphological and sedimentological-stratigraphical studies. These structures are not exposed, but are buried under more recent lagoonal and deltaic deposits. It was decided to map them, as they are on average 1 m thick. Submerged beach ridges were in any case mapped with the appropriate geomorphological symbols.

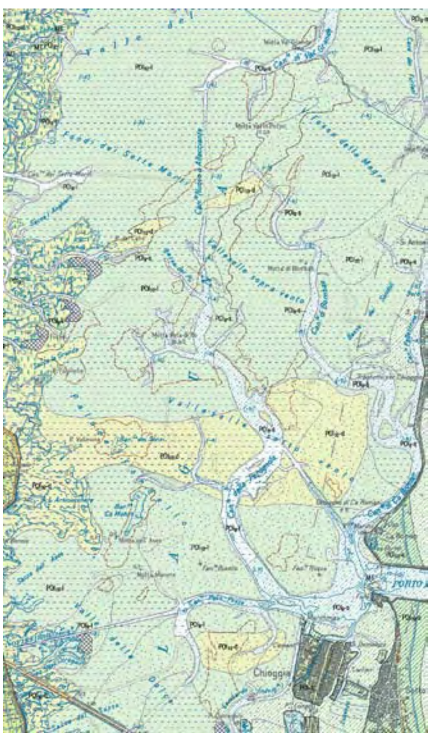

Fig. 88 – *Detail of Chioggia-Malamocco Sheet of Geological Map: traces of ancient littorals in southern basin of lagoon.*

Sandy-silty deposits of a littoral environment are found near the exposed coastal apparatuses at Chioggia and Sottomarina and near the beaches of Malamocco and Pellestrina, despite intense anthropic reworking in the first metre of subsoil.

Elsewhere, in the central-southern lagoon on the Chioggia Sheet, deposits of almost exclusively lagoonal origin are exposed. They are mainly silty, with variable contents of sand and/or clay: finer sediments are found near the border of the inner lagoon, in lateral contact with the deltaic bodies described above. Sand showing signs of a lagoonal environment is found near Chioggia and in the lagoon belt next to the littoral. They are probably the result of reworking and subsequent redeposition of sediments originally belonging to beach deposits.

Mixed infill lithologies are found near small emerging islands, the origin of which has been interpreted as anthropic.

Other anthropic deposits mapped in the northern sector of the Chioggia Sheet correspond to reclaimed areas (artificial islands created over a large area of saltmarsh between 1963 and 1969). The material needed came from the excavation of the Canale dei Petroli which, linking the port of Malamocco to Marghera, was built for the purpose of giving oil tankers access to the Industrial Zone. The reclaimed areas were supposed to have been the site of a third industrial zone, but the project was frozen by the Special Law for Venice of 1973; they have recently been reinstated as natural areas, to encourage water turnover, to restore the saltmarsh, and to counter erosion, mainly caused by their proximity to tanker route.

From a chronological perspective, therefore, nearly all the submerged deposits mapped in the lagoon are attributed to the *Torcello Unit*. Older sediments are exposed in the channels containing lagoon silt and beach sand belonging to the *Malamocco Unit* and alluvial deposits from the *Mestre Supersynthem*. The lagoon silt of the *Malamocco Unit* is mainly found in the ramifications developing towards the inner part of the lagoon. Instead, the beach sand is found in channels near the littoral, which then cross the area in which ancient submerged beach ridges are located. Continental sediments of the *Mestre Supersynthem* are found mainly in the Canale di Malamocco and in channels adjacent to reclaimed areas; elsewhere, only small, sporadic outcrops have been reported.

Recent beach sand occurs on the bed of the northern Adriatic adjacent to the littoral. The sand found at the mouth of the Porto di Chioggia, where marine erosion is more intense, may be older.

2. - SUBSURFACE MAP: THE PO SYNTHEM BASE

This map was produced by interpolating, with a statistical method, the depths of the stratigraphical boundary between the *Mestre Supersynthem* and the *Po Synthem* (section VIII), the latter taken from stratigraphies in the CARG database and from VHR seismic surveys (section III-6.1).

Data distribution generally allowed good overall interpolation, so that a map of the depths of the boundary separating Pleistocene (*Mestre Supersynthem*) and Holocene deposits (*Po Synthem*) could be generated (BRANCOLINI *et alii*, 2005; BRANCOLINI *et alii*, 2006). In areas for which more data were available, a denser interpolation grid was used, yielding greater morphological details, as shown by the smoother trends of the contours.

Available data on the depth of the base of the *Po Synthem* in the north-western area of the Sheet were too scanty to be included in the map. However, the few existing data indicate that the base of the Holocene deposits lies at less than -2 m below sea level and that it sub-outcrops towards the NW.

The general topographical features of this surface preserve those of the Late Pleistocene at the end of the Last Glacial Maximum, although it should be emphasised that they may have undergone partial modification during the transgression and been modelled by differential subsidence.

In the study area, the depth of the boundary varies from -2 m a.s.l. in the NW part of the Sheet (Camponogara and Campolongo) to over -22 m a.s.l. in the Adriatic (SE part of Sheet). In the marine sector, it is located near the point where the *Mestre Supersynthem* outcrops, or where the thickness of the *Po Synthem* is less than 1 m.

In view of the particular heterogeneity of the morphology of the boundary surface, no estimate of its average dip could be made. Overall, however, a structure on several levels was identified, ranging on average from 4 to 6 m, dipping SE.

Quite high gradients in the WNW-ESE direction and estimated at about 3.5‰, are found in the south-west part of the Sheet (near Correzzola), where the base of the *Po Synthem* lies at -4 m to -18 m above sea level.

The general morphological structure of the boundary surface shows several large, clearly defined, lobed ridges, separated by depressions, near the present-day lagoon basin. They extend in three main directions which, from north to south, are: (a) Motte di Volpego – Alberoni; (b) Torson di Sotto – Pellestrina littoral (where two lobes are identified, a northern one directed towards San Pietro in Volta, and a southern one towards San Antonio); further west, near Lugo, a slight cut in this direction can be noted; (c) Valle Pierimpiè – Valle Millecampi – Ca Roman.

The directions of development of these ridges coincide exactly with those of the old river courses running NW-SE, identified in the adjacent drainage basin during geomorphological surveys. They may represent the Holocene courses of the Brenta (BONDESAN & MENEGHEL, 2004), but it is possible that they are older.

Lastly, in this sector of the northern Adriatic, the gradients fall gradually with distance from the littoral.

The subsurface map, is complemented by three geological cross- sections (see section VIII) and three VHR seismic sections. Various reflectors detected within the *Mestre Supersynthem* and *Po Synthem* deposits are shown in the seismic sections, mainly highlighting the stratigraphical boundary. Stratigraphies from the CARG database were used to identify and calibrate them.

A brief description of the seismic sections follows. Profiles CH_18, LI_09 and LI_16 represent a section perpendicular to the coast, located in the lagoonal and marine areas of the Sheet. The base of the *Po Synthem* remains at depths between 12 and 14 m, and is exposed at shot point 2800, with a consequent progressive decrease in the overlying Holocene layers. At shot point 1200 there is a structure, probably composed of cemented sand, which may be a relic form created within the Pleistocene sequence. Profiles CH_42 and CH_43 belong to a section orthogonal to the coast, and run from the inner edge of the lagoon near its border with the land, cross the lagoon, pass through the mouth of Chioggia, and terminate offshore. Profile CH_42, from the southern lagoon, shows regular lagoonal bottom topography; proceeding towards the mouth of Chioggia, there are frequent cuts, the deepest of which falls to 25 m (initial part of profile CH_43). This cut truncates both the shallowest reflectors and the horizon representing the base of the Holocene. At the mouth of the Porto di Chioggia (shot point 3400), the sea bed is characterised by a sedimentary body, the internal features of which indicate that it mainly developed as a result of prevailing progradation.

The reflectors within this wedge-shaped deposit end with downlap configurations on the base of the *Po Synthem,* which lies at constant depths of -17 -20 m, and reaches the surface at shot point 7400. The outermost Pleistocene stratigraphical sequence is composed of horizontal and parallel reflectors, of medium width and regular tendency, except for the large horizon at around -10 m.

Profiles CH_15 and CH_18 were acquired along the lagoon channel behind the Pellestrina and Lido littorals, parallel to them and running mainly NE-SW. The base of the *Po Synthem* has very irregular morphology, with large cuts at Portosecco (CH_15: 6000), crossing the Canale di Malamocco (CH_58: 9000) and towards the Lido (CH_58: 6000), representing Holocene, formerly Pleistocene, palaeo-channels.

The base of *Po Synthem* lies at -17-20 m in the Chioggia sector, and at around -10 m in the Lido sector.

X - MINERALOGICAL CHARACTERISTICS

As already stated in section III-5, study of space-time distributions of the mineral contents of sediments has contributed to further understanding of the palaeogeographical evolution of the Venetian area.

In the past, sediments from the rivers Tagliamento, Livenza, Piave, Brenta, Bacchiglione, Adige and Po all entered the Venetian area and, to a lesser extent, also quantities from spring watercourses, e.g., the Sile.

During the Holocene, the area was one of complex transition, characterised by alluvial plain, lagoonal, littoral and marine environments, the boundaries of which, in the course of millennia, changed, due to first natural and then anthropic causes. Past and present hydrodynamic fluvial, marine and lagoonal processes have caused partial remixing of sediments, leading to great difficulties in distinguishing which sediments came from which watercourses.

With the aim of reconstructing the old river courses and defining the palaeogeographic development of the Venetian territory, both previous data (e.g., GAZZI *et alii*, 1973; JOBSTRAIBIZER & MALESANI, 1973; BARILLARI *et alii*, 1975; BARILLARI, 1978; 1981; HIEKE MERLIN *et alii*, 1979; BONARDI & TOSI, 1994a; 1995a. 1995b) and new data were collected, selected and integrated with results from new studies carried out within the CARG Project.

1. - MINERAL COMPOSITION OF CLAY

The mineralogy of littoral subsurface clay between the mouths of the rivers Brenta-Bacchiglione and Sile was examined within the ambit of multidisciplinary studies on 18 cores, taken at an average depth of 30 m (BONARDI & TOSI, 1994a; 1994b, 1995a; 1995b; 1997; BONARDI *et alii* 1997). A brief summary of the littoral area regarding the Chioggia-Malamocco Sheet is given below.

The average mineral composition of clay belonging to the *Po Synthem* and *Mestre Supersynthem* of the Chioggia, Pellestrina and Lido littoral subsurfaces is shown in Fig. 89. Samples were divided into three groups: two for the *Mestre Supersynthem,* normal consolidated (Pa) and overconsolidated (Pc), belonging to the top level ("*caranto*"), and one (Ol) for the *Po Synthem.*

The three groups have the same general mineral composition, but the average percentage of each mineral differs. The most abundant are calcite, dolomite and quartz, followed by chlorite, illite/mica and plagioclase, with traces of feldspars, smectite, mixed clay minerals, and kaolinite. The average percentage of dolomite increases from the *Mestre Supersynthem* deposits to those of the *Po Synthem*, whereas calcite reaches its maximum average concentration in the *caranto*. Clay miner-

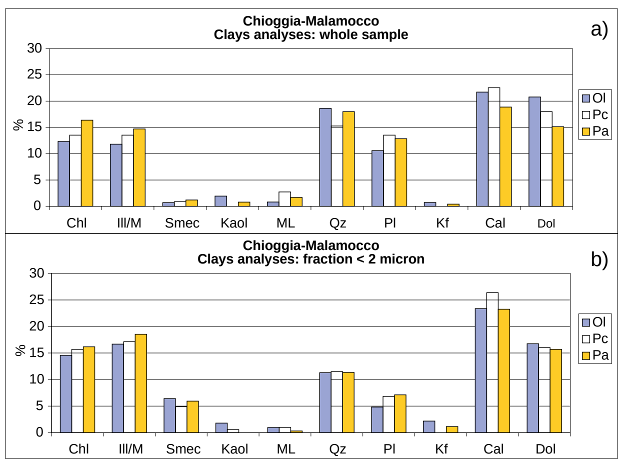

Fig. 89 – *(a) Average mineralogical compositions of three groups of samples (OI ,Pc, Pa). Chl=chlorite, Il/M=illite/mica, SKM=smectite+kaolinite+mixed strata; Qz=quartz, Cal=calcite, Dol=dolomite; (b) Average mineralogical compositions of clay (Ø<2 µm) of three groups of samples (Ol, Pc, Pa). Chl=chlorite, Il/M=illite/mica, Smec=smectite, Qz-=quartz, Pl=plagioclase, Kf=potassium feldspar, Cal=calcite, Dol=dolomite, Kaol=kaolinite, ML=clay minerals and mixed strata.*

als decrease from the *Mestre Supersynthem* to the *Po Synthem*, whereas average percentages of quartz remain almost constant.

In order to identify single clay minerals, clay alone (Ø<2 μm) was analysed (Fig. 89b). The main minerals of this fraction were calcite, illite/mica, dolomite and chlorite, with secondary quartz, smectite and plagioclase, and traces of kaolinite and mixed clay minerals. The quantity of dolomite is similar in the three groups, but calcite peaks in the *caranto* samples. Among clay minerals, chlorite and illite prevail, the latter decreasing from the *Mestre Supersynthem* to the *Po Synthem*, whereas smectite occurs in similar percentages. With respect to whole samples, the clay in all three groups is rich in chlorite and illite.

Fig. 90 shows six SEM photographs of some textural aspects of the clay. Photos (a) and (b) show elliptical lenses of clay within coarse sediments, of lower Holocene age; photo (c) shows phyllosilicates with preferred orientation due to compaction of *caranto*; minerals with a granular texture are silicates (dark grey, medium grey) and carbonates (white); elongated minerals are chlorite (pale) and mica (grey); black areas are pores. Photos (d) and (e) show barite and microcrystalline authigenic pyrite inside fissures, and photo (f) lenses of clay material within coarse sediments, immediately below the *caranto*.

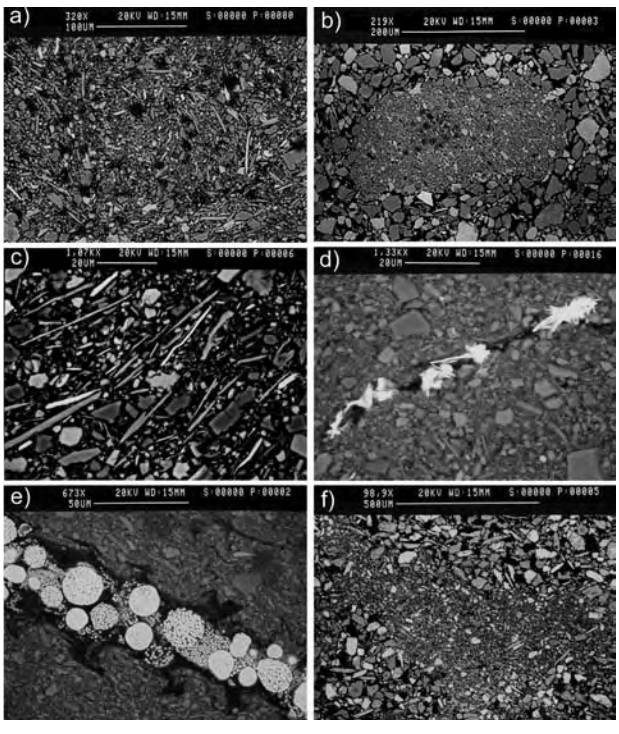

Fig. 90 – *Mineralogical and textural characteristics of clay layer of* Mestre Supersynthem *and* Po Synthem *(from* BONARDI *&* TOSI*, 1994a; 1995b;* BONARDI et alii, *1997;* BONARDI *et alii, 2004).*

2. - MINERALOGICAL COMPOSITION OF SAND

Mineralogical studies of sub-outcropping sandy sediments showed similar mineral compositions, but with clearly differentiated relative percentages, according to location.

Carbonates generally prevail in the north and silicates in the south, confirming the lithological diversity of the Piave, Brenta and Bacchiglione supplies, which are known to come from separate drainage basins.

Dolomite, calcite, quartz, feldspars (potassium feldspar+plagioclase), chlorite and mica are the main minerals, with accessory ankerite, aragonite, kaolinite and hastingsite. Carbonates (dolomite, ankerite, calcite, aragonite) prevail in the north of the Venetian area (60-65%), silicates (quartz+potassium feldspar+plagioclase) are abundant in the south (55-65%), and have similar percentages in the centre. Within the carbonate group, dolomite+ankerite are the most abundant, with maximum values close to 60%; calcite+aragonite are generally less than 25-30%.

The prevalence of sediments from the Piave basin in the north and the Brenta-Bacchiglione system in the south is therefore quite evident. The Piave supplies are rich in carbonates, with dolomite prevailing over calcite, with appreciable quartz and basic vulcanites (GAZZI *et alii*, 1973; JOBSTRAIBIZER& MALESANI, 1973). However, the Brenta sediments have fewer carbonates, with prevailing dolomite and more quartz + feldspars, due to the presence of gneissic and acidic vulcanites in the drainage basin. These lithological characteristics are also responsible for the significant contents of phyllosilicates and clay minerals in sediments carried by the Brenta.

Some zones with "anomalous" percentages are found in various areas of the lagoon. For example, calcite and aragonite distributions show relative enrichment of these carbonates in the southern lagoon, clearly due to the Malamocco and Chioggia tidal inlets, whereas increased phyllosilicates towards the mainland indicate a decrease in energy.

In the marine area, sediments in the area off the Chioggia littoral have mineralogical characteristics close to those of supplies of the Brenta-Bacchiglione system, whereas the deposits of the northern sector of the littoral come from the Piave. As an example, Fig. 91 shows the distribution of quartz in surface sand sediments. The distinction between the two extremes is evident: sediments from the Sile and Piave account for less than 25%; those from the Adige exceed 40%. Instead, the difference between the Brenta and

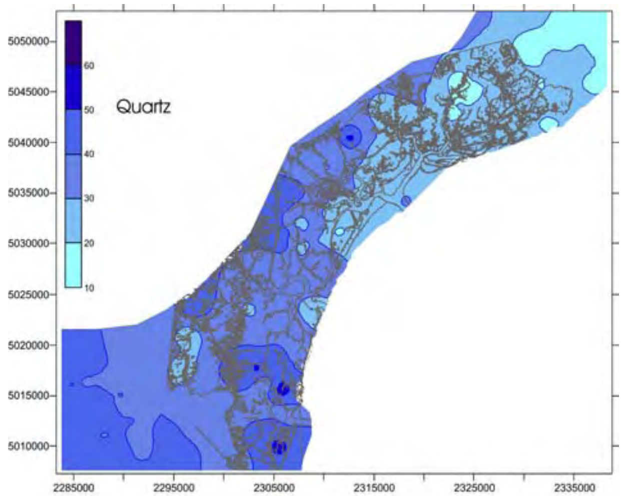

Fig. 91 – *Distribution of quartz in shallow sand sediments.*

Bacchiglione sediments is less marked, with similar percentages (30-35%).

In the southern and western areas of the Chioggia-Malamocco Sheet, the minera compositions of surface sediments often differ from those of deeper ones. This is because, as well as the Brenta and Bacchiglione rivers, branches of the Adige and Po also meandered here.

The percentages of dolomite, calcite and quartz in samples from 10 cores taken along the Sottomarina, Pellestrina and Lido littorals are shown in Fig. 92. The highstand system tract deposits of the *Po Synthem* in the south (Sottomarina, Pellestrina) have different percentages from those of the north (Lido). Calcite and dolomite, respectively around 10 and 15%, are minimal in the south and increase gradually northwards to about 20% and 40%, respectively. The opposite occurs for quartz, which decreases northwards from 45% to 25%. These values indicate the presence of Piave supplies from the north as far as Malamocco, while the deposits are those of the Brenta and Bacchiglione system further south.

Vertical variations in mineral percentages in the Sottomarina and Pellestrina coastal sector occur within the *Po Synthem.* Transgressive sediments reveal Bacchiglione accumulations, being rich in dolomite and to a lesser extent in calcite, but they are more quartz-poor than the overlying ones deriving from the progradation of the coastline and mouth apparatuses of the Brenta. Some levels with up to 40% of quartz and total carbonates of under 20% may indicate depositional events in the Adige system. The *Mestre Supersynthem* deposits, lying below the littorals of the southern lagoon, now show significant areal and vertical mineral variations: about 20% dolomite, 15% calcite and 40% quartz indicate mixing of Brenta, Adige and Po alluvial sediments.

Analysis of two cores from boreholes which reached the *Correzzola Unit* are shown in Fig. 93a: *CARG 11*, located at the border of the lagoon, and *ISES B*, located in the drainage basin, both taken from a depth of about 100 m. The *CARG 11* samples show a shallow level attributable to the Bacchiglione, lying above Adige and Po deposits extending to about -52 m. Below, between -60 m and -80 m, increased carbonates and decreased quartz indicate a different origin, probably from the Bacchiglione and Brenta.

Core *ISES B – CARG 13* shows sediments compatible with those transported by the Adige and Po at the top of the sequence, followed downwards by others with characteristics similar to the those of the Bacchiglione and Brenta to about -20 m; Po and Adige sediments are found again at greater depths.

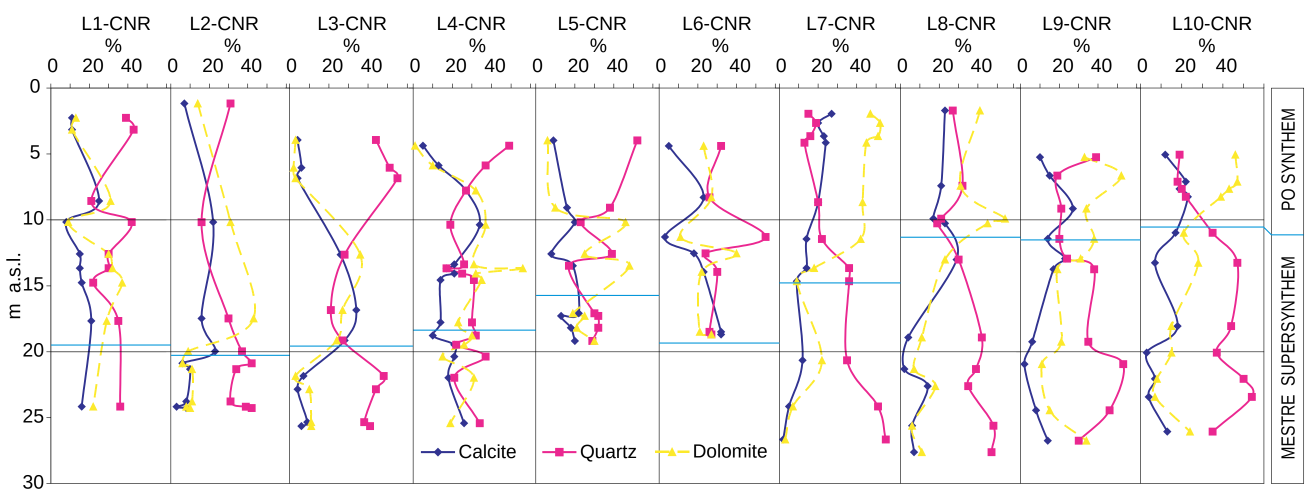

Fig. 92 – *Variations in percentages of quartz and calcite in* Mestre Supersynthem *and* Po Synthem *sand, underlying littoral (cf. Figs. 76 and 79).*

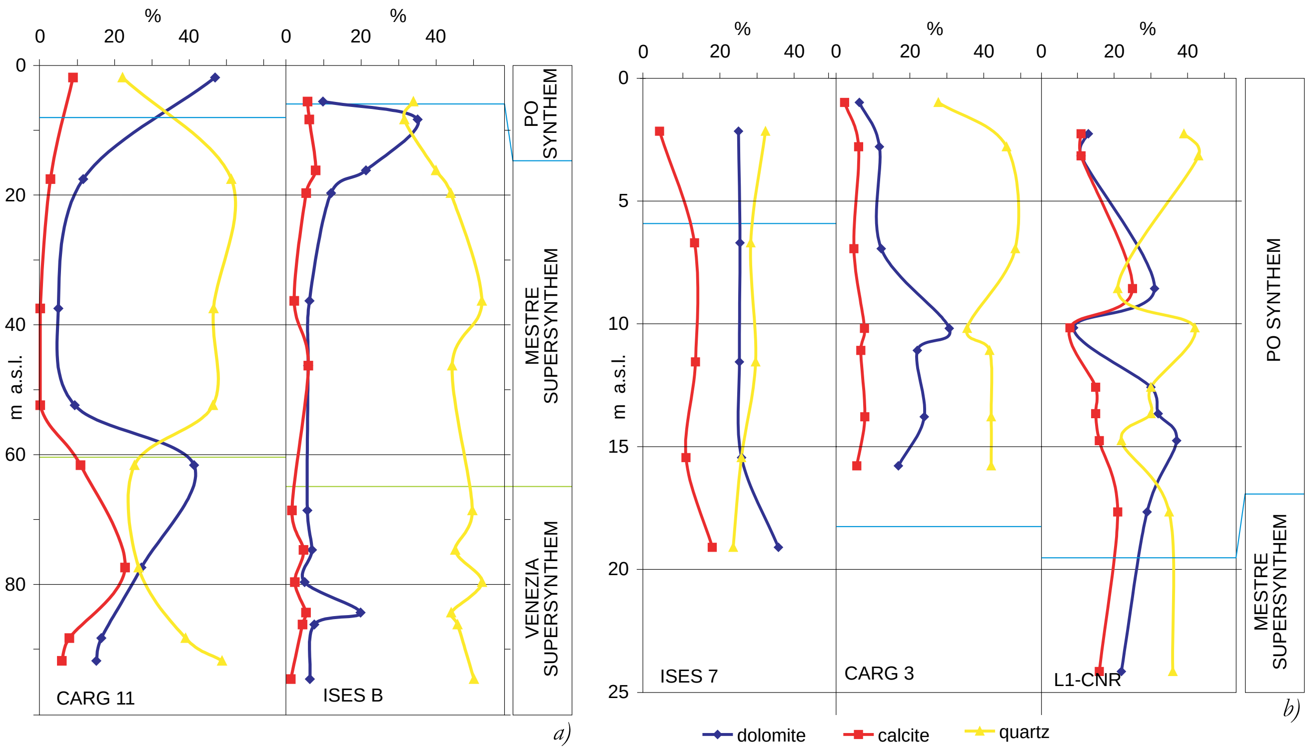

Fig. 93 – *Variations in percentages of quartz and calcite in sand of* Mestre Supersynthem *and* Po Synthem

The analyses shown in Fig. 93 relate to three cores, located respectively in the drainage basin (*ISES 7, ISES 33*) and Sottomarina littoral (*L1-CNR*).

The sandy layers of core *ISES 7*, containing 20-25% dolomite and about 25% quartz, are similar to those of the Brenta deposits, but they do not show vertical variations. Instead, the sandy layers of core *ISES 33*, with levels high in quartz (40%) and under 20% in carbonates, are similar to those of the Adige or the Po. At depths exceeding 10 m, increased dolomite indicates that they are Brenta deposits. Lastly, for core *L1-CNR*, the data shown in Fig. 92 are valid for total carbonates; for dolomite, supplies from the Piave during the marine transgression and then from the Bacchiglione and Brenta are evident.

XI - SUBSIDENCE AND EUSTACY

The reduction in the elevation of the lagoon area with respect to the mean sea level, caused by subsidence and eustacy, has been one of the major environmental problems for the Lagoon of Venice in recent decades.

Although the southern part of the lagoon was only marginally involved by the anthropogenic subsidence caused by groundwater pumping in the Porto Marghera Industrial Zone, a combination of several causes produced serious repercussions in this part of the lagoon. These factors are the following: a greater natural subsidence than that occurred in the city of Venice (Brambati *et alii*, 2003); local groundwater pumping for agricultural and domestic use (Carbognin *et alii*, 1995b); biochemical oxidation of peaty areas located behind the lagoon (Gambolati *et alii*, 2003; Camporese *et alii*, 2005; Gambolati *et alii*, 2005); and salinisation of sediments due to saltwater intrusion in the costal aquifers (Carbognin & Tosi, 2003). To all these causes must be added the general process of eustatic raise in sea level due to the ongoing climatic variations (Carbognin & Taroni, 1996). Although high tides are very well-known in Venice, Chioggia too is suffering from them with increasing frequency and intensity. In addition, erosion of salt marshes and shallows throughout the southern lagoon is significant, together with an increased slope of the seabed near barrier beaches (Carbognin *et alii*, 1995a). The greater risks of flooding, combined with meteorological-marine events of particular intensity, have required large-scale environmental protection and restoration operations in the lagoon.

Study of these phenomena began in the 1970s, by a group of researchers from the CNR in Venice. The main aspects of the problems are described below.

Recent studies on cores from the *Venice 1 – CNR* borehole, drilled at Tronchetto in the 1970s, estimated the average rate of subsidence over the last 2 million years at 0.5 mm/year. This value mainly reflects tectonic events over this period (Kent *et alii*, 2002) - in particular, subduction associated with the Apennine chain (Carminati *et alii*, 2003).

Measurements show that natural subsidence is now very small in the centre of the lagoon (Bortolami *et alii*, 1984; Carbognin, 1992), but increases to a few millimetres per year towards the edges, due to the greater thickness of compressible clay and the more recent deposition of sediments (Carbognin *et alii*, 1995b).

Subsidence of peaty soils is a geochemical process that occurs when these soils are reclaimed for agricultural use. When drainage brings the peat into contact with oxygen in the air, aerobic micro-organisms oxidise the organic matter, causing the loss of carbon in the form of CO_2 released into the atmosphere; the net loss of soil volume causes subsidence. Recent studies show that this process has affected a significant part of the coastal strip near the southern lagoon, with lowering of 1-2 m over the last 50-100 years (Gambolati *et alii*, 2003; Camporese *et alii*, 2005; Gambolati *et alii*, 2005) (Fig. 94). Experimental and modelling results demonstrate that this process can be mitigated by careful management of reclamation, which reduces the depth to the aquifer as much as possible, and by means of particular agricultural practices.

Variations in the chemical characteristics of interstitial water in clay (when, for example, freshwater is replaced by salt water) are known to accelerate natural compaction of sediments, through processes of electrochemical type (Meade, 1964).

Detailed studies show that salt-water intrusion into shallow aquifers involves large areas in the southern lagoon catchment (Carbognin & Tosi, 2003): the freshwater/saltwater interface is found at depths varying between 0 and 10 m (Fig. 95).

Fig. 94 – *A bridge built in 1920s near the southern edge of lagoon at Chioggia, that is now protruding about 1.5 m due to oxidation of surrounding peat soils (from* Tosi et alii*, 2000).*

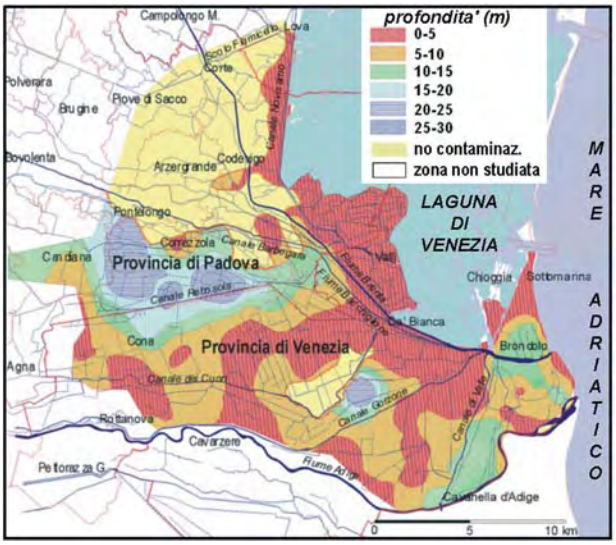

Fig. 95 – *Depth of top of the saltwater contamination in area surrounding southern part of lagoon (from* Carbognin *&* Tosi*, 2003).*

The encroachment of seawater upstream from the river mouths, and the presence of subsurface geological structures enhance the spread of contamination up to 20 km inland (Rizzetto *et alii*, 2003).

1. - MONITORING OF SUBSIDENCE IN THE SOUTHERN PART OF THE LAGOON

Elevation measurements have been carried out in the southern lagoon since the end of the 19th century, when the Italian Military Geographical Institute (IGM) created the first national topographical network. Until 1950, the surveys were carried out only at long intervals, but became more frequent after 1960, when the problem of land subsidence in the Venice area developed. Other regional institutions and research bodies set up new levelling networks, linked to benchmarks considered stable in time.

The results of measurements until the 1990s (see Fig. 96) show that lowering was far from uniform, and was the outcome of many combined factors (Tosi *et alii*, 2000; Carbognin & Tosi, 2003). The area near the Adige river (points 1 and 2) suffered from gas-bearing water extraction from the Po delta between 1940 and 1960; some areas along the edge of the lagoon, characterized by outcropping peat layers and recently reclaimed (basins *a, b, c, d*), sank by up to 1-2 m, due to oxidation of organic soil.

The relative subsidence peak along the lagoon edge (line A-C) was near Porto Marghera (pumped for artesian water until 1970), and an increasing subsidence trend was also recorded in the Valli area (between points B and C). The situation along the littoral appears particularly complex (line C-H), with subsidence peaks due to local water pumping for tourism and agricultural purposes.

Particular attention has been given over the last decade to monitoring the subsidence of this part of the lagoon. The existing levelling network, set up along the lagoon edge, has been updated and improved within the ISES Project, and a monitoring network (*Differential Global Positioning* System) has been set up. In addition, differential SAR interferometry and persistent scatterer interferometry on the ESA ERS-1 and ERS-2 satellites images acquired between 1992 and 2000 (Teatini *et alii*,

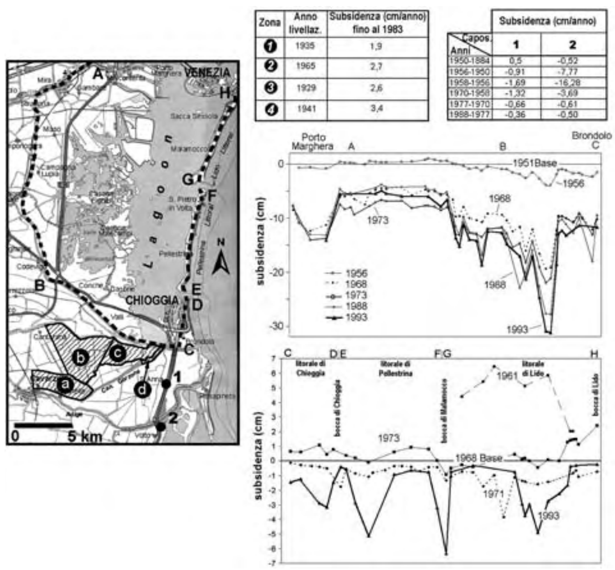

Fig. 96 – *Measurements of land subsidence carried out by IGM, CNR and water reclamation authorities in southern area of the lagoon catchment until 1990s (from* Tosi et alii*, 2000).*

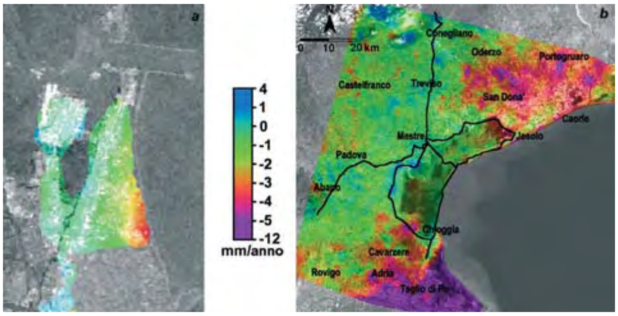

Fig. 97 - *(a) Map of land displacements of Chioggia and Sottomarina, between 1992 and 2000, derived from SAR differential interferometry (from* STROZZI et alii, *2003a); (b) land displacements in Venice area over 1992-2000 time period ,obtained from an integrated monitoring system (*STROZZI et alii*, 2003b).*

2005), have been used to map land movements in the Venice area with high resolution (Fig. 97).

The various subsidence measuring methods currently available were incorporated in an "integrated monitoring system", which, exploiting the peculiar features of each method, allows a reliable and accurate monitoring of the eastern Venice area (STROZZI *et alii*, 2003b, 2005; CARBOGNIN *et alii*, 2005a; Teatini *et alii*, 2005).

Monitoring of the piezometric head in the artesian aquifers has provided a fundamental contribution to the study of subsidence. The data have been collected since the 1970s by a monitoring network established by the CNR-ISMAR. An example of piezometry mapping is shown in Fig. 98.

2. - EUSTACY

Another important aspect concerning with the relative lowering of the Lagoon of Venice and its surroundings is the raise of the mean sea level. As regards the northern Adriatic Sea, the most accurate series available are those recorded at Venice (Punta della Salute) and Trieste tide gauges. The series are long enough to average minor oscillations due to short-term climatic variations.

The average rate of sea level raise over the whole period (1897-1993) is 1.13 mm/year. Comparison of the Trieste and Venice data shows that there is no single trend for the past 100 years for Venice, due to anthropogenic subsidence. After a 20-year period of quiescence, from 1970 to 1990, the data for the last ten years indicate a significant resumption of sea level rise, accompanied by a greater number of episodes of *acqua alta* (high tides) (CARBOGNIN *et alii*, 2004; 2005b).

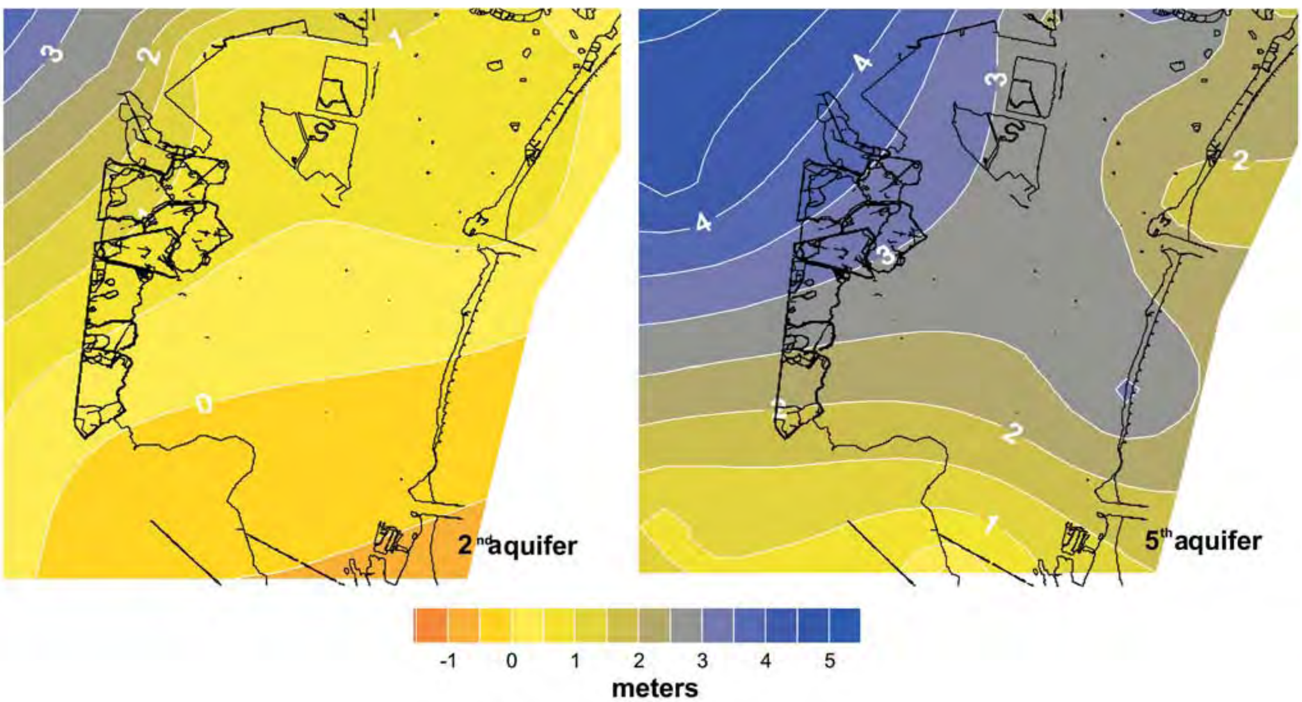

Fig. 98 – *Piezometric maps (m a.s.l.) of second and fifth aquifers, 2003. CNR-ISMAR data from piezometric level monitoring network.*

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