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STRATIGRAPHY OF THE CENOZOIC SUBSURFACE SUCCESSION OF THE VENETIAN-FRIULIAN BASIN (NE ITALY): A REVIEW

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Abstract. The present paper reviews and improves the stratigraphy of the Cenozoic subsurface succession of the Venetian-Friulian Basin by means of a foraminiferal study, integrated by calcareous nannofossil analysis in some key stratigraphic intervals, of thirteen ENI wells drilled in the 60-70s and kept reserved since now.

The Venetian Friulian Basin is a complex basin due to the superimposition of three overlapping foreland systems, during the Paleocene to Pleistocene time interval. These systems are related to the evolution of three collisional belts (Southern Alps, Apennines and Dinarides) which experienced structuring phases at different time intervals, with different belt orientation, vergence and topography.

The peculiar location of the basin at the tectonic knot, between the Po Plain Basin and the Adriatic Basin that are the most important Italian sites of gas reservoirs, makes it as an interesting case-study both from a scientific and industrial point of view.

Data of both foraminiferal and nannofossil assemblages were performed using, tentatively, the standard zonations proposed for the tropical-subtropical realm and the Mediterranean region. In the chronostratigraphic intervals where standard events were not recorded, other biohorizons from "regional" zonal schemes were applied. The data obtained allowed to check the applicability of the biohorizons used in the stated schemes to a subsurface succession analysed mainly from cuttings.

Results allowed also to provide a rather precise biostratigraphic correlation of the thirteen studied wells which is a fundamental step to better describe the geometry of the sedimentary infill and to reconstruct the synoptic chronostratigraphic frame providing the timing of the sedimentary events and the main sedimentary or erosional hiatuses. Based on this chronostratigraphic scheme, the Cenozoic subsurface succession of the Venetian -Friulian Basin is subdivided into five depositional sequences (*S1-S5*) bounded by four major unconformities (*U1-U4*) and by their correlative conformity surfaces, regionally recognised throughout the basin.

Riassunto. Lo studio biostratigrafico dei foraminiferi e, per alcuni intervalli stratigrafici, dei nannofossili calcarei di 13 pozzi ENI perforati negli anni '60-70 e ubicati nel Bacino Veneto-Friulano, ha permesso di proporre una revisione stratigrafica della successione cenozoica di sottosuolo del settore più orientale della Pianura Padana.

Il bacino Veneto Friulano rappresenta un caso di studio interessante per indagare l'evoluzione dei bacini di avanfossa, sia in termini di risposta flessurale alla strutturazione della catena che di riempimento sedimentario. Nell'intervallo compreso tra il Paleocene ed il Pleistocene, registra infatti l'evoluzione di tre avanfosse che si succedono nel tempo, legate alla strutturazione di tre catene con diversa orientazione e vergenza: le Dinaridi a Est, le Alpi Meridionali a Nord e l'Appennino a Sud-Ovest.

Il lavoro rappresenta un primo contributo di un progetto di ricerca tra Università di Pavia ed ENI, che ha reso possibile lo studio di materiale sino ad ora riservato. Lo studio biostratigrafico (oltre 400 campioni) è stato condotto attraverso l'applicazione, ove possibile, degli schemi biostratigrafici standard per le basse-medie latitudini e per l'area mediterranea, e ove necessario, attraverso l'utilizzo di schemi regionali. I dati ottenuti hanno permesso di verificare l'applicabilità di questi schemi. In particolare, si sono evidenziati gli eventi più riproducibili in successioni di sottosuolo, prevalentemente analizzate attraverso "cutting" e con forti problemi di conservazione legati sia alla profondità di seppellimento che al contesto deposizionale.

La dettagliata analisi biostratigrafica ha permesso inoltre di correlare in modo rigoroso le unità di sottosuolo, ricostruendo la geometria del riempimento sedimentario. Si propone infine un quadro cronostratigrafico che evidenzia i tempi del riempimento, le stasi di sedimentazione ed i principali eventi erosivi. Sulla base del quadro cronostratigrafico ottenuto si è potuto riconoscere nella successione sedimentaria cenozoica del Bacino Veneto-Friulano cinque sequenze deposizionali (*S1-S5*) separate da quattro maggiori discontinuità (*U1-U4*) e dalle corrispondenti superfici di concordanza, riconosciute regionalmente nel bacino.

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Introduction

Foreland basins represent the major depositional site for accumulation of detritus dismantled from collisional belts and, consequently, one of the main sites for accumulation of clastic sediments in the world. For this reason they are also one of the major targets for hydrocarbon exploration.

In the Italian area, the main target for hydrocarbon research has been since many years the Po Plain-Adriatic foreland basin, where most of the gas reservoirs has been discovered so far (Casero 2004). It is a complex basin bounding the whole Italian peninsula, linked to the combined and partly overlapping flexural effects of the Southern Alps, Northern Apennine and Dinaric collisional belts. With this respect it can be schematically divided in two main parts: the Po Plain Basin forming the foreland basin of both Southern Alps and Northern Apennine belts, and the Adriatic Basin linked to the Central-Southern Apennines and Dinaric collisional systems. The tectonic knot that links these two basins is provided by the Venetian-Friulian Basin (VFB) located at the northern end of the Adriatic Sea and at the eastern end of the Po Plain Basin (Fig. 1).

This peculiar location was one of the reasons that pushed to a renovated interest on that part of the Po Plain-Adriatic hydrocarbon province, and gave way to a joint research program between ENI and Pavia University. In the frame of this research, an extensive review of wells' stratigraphy, mostly not revised after drilling (in the 60-70s) and kept reserved until now, was performed.

The primary aim of this work is to present micropaleontological data, mainly on foraminifera, locally integrated by calcareous nannofossils, from the subsurface Cenozoic succession of the VFB, whose lithostratigraphy (Dondi & D'Andrea 1986) has been defined exclusively on drilling wells.

The revised stratigraphy is a starting key point to improve the chronostratigraphic constraints necessary to reconstruct in detail the depositional evolution of the basin, during the Late Paleocene to Pleistocene time interval.

Geological framework

During its Cenozoic history, the VFB represented the foreland basin, at different times and with different tectonic directions, for each of the three thrust-fold belts surrounding it, i.e the Dinarides, the Eastern Southern Alps and the Northern Apennines (Fantoni et al. 2002 and references therein, Fig. 1).

The starting point of the Cenozoic evolution of the VFB was provided by the paleogeography inherited from the Mesozoic extensional evolution. Its basic features were a wide and pretty flat Mesozoic carbonate platform (Friulian Carbonate Platform, Fig. 1) abruptly passing southwestward, by means of a sinuous and steep margin, to a deep sea trough which was the southward prolongation of the Mesozoic Belluno Basin of Eastern Southern Alps (Cati et al. 1987; Fantoni et al. 2002).

The VFB history as foreland basin began in the Paleocene-Middle Eocene time interval, due to the collisional tectonics developed in the external Dinaric thrust-fold belt. It caused the WSW migration of the NNW-SSE trending belt-foreland system coupled with inversion tectonics of the eastern margin of the Friulian carbonate platform, which was down-tilted eastward.

From a depositional point of view in the southern portion of the basin, the Paleocene-Lower Oligocene succession was characterised mainly by hemipelagic deposits (Scaglia Rossa; lower portion of the Gallare group=Scaglia Cinerea). Towards northwest, the Scaglia Rossa and Vena d'Oro Marl were replaced by turbidite sediments (Belluno Flysch, Jesolo Flysch and Possagno Marl), since middle Ypresian, whereas towards northeast, shallow marine limestones (Nummulitic Limestone) deposited on the Mesozoic Platform, were onlapped by terrigenous deep-water turbidite sediments (Cormons Flysch, Venturini 2002). Since late Priabonian, the whole northern area of the VFB was affected by an important subaerial erosional phase (Tunis & Venturini 1987, 1992).

During the Chattian-Langhian pp. time span, the VFB recorded only the effects of a relatively far tectonics active in the Alpine region, as suggested by the weak NNE-ward tilting and thickening of the coeval sediment prism (Fantoni et al. 2002). The Upper Oligocene-Lower Miocene succession consists of mixed terrigenous-carbonatic platform sediments (Cavanella group), developed on the whole Venetian-Friulian area. It also covered part of the present-day Southalpine chain, as in the Belluno area to the north, part of the Carnic Prealps and some Dinaric anticlines to the east (Cargnacco structure, Venturini 2002) as far as the Northern Adriatic offshore to the south. Only in the south-westernmost sector, hemipelagic sedimentation (middle portion of the Gallare group) persisted during the Late Oligocene to Early Miocene.

Since Serravallian time, the flexural effects of the Eastern Southern Alps collisional system strongly affected the VFB. It was mainly due to the intense shortening phase experienced by the frontal part of the belt during the Middle-Late Miocene (Serravallian-Messinian) with a NNW-SSE direction of tectonic transport (e.g. Castellarin & Cantelli 2000 with references therein). This event rapidly created new accommodation space that was infilled by clastic sediments (upper portion of the Gallare group, San Donà Marl, Vittorio Veneto Sandstone, and Montello Conglomerate), forming a southward thinning wedge, the northernmost part of

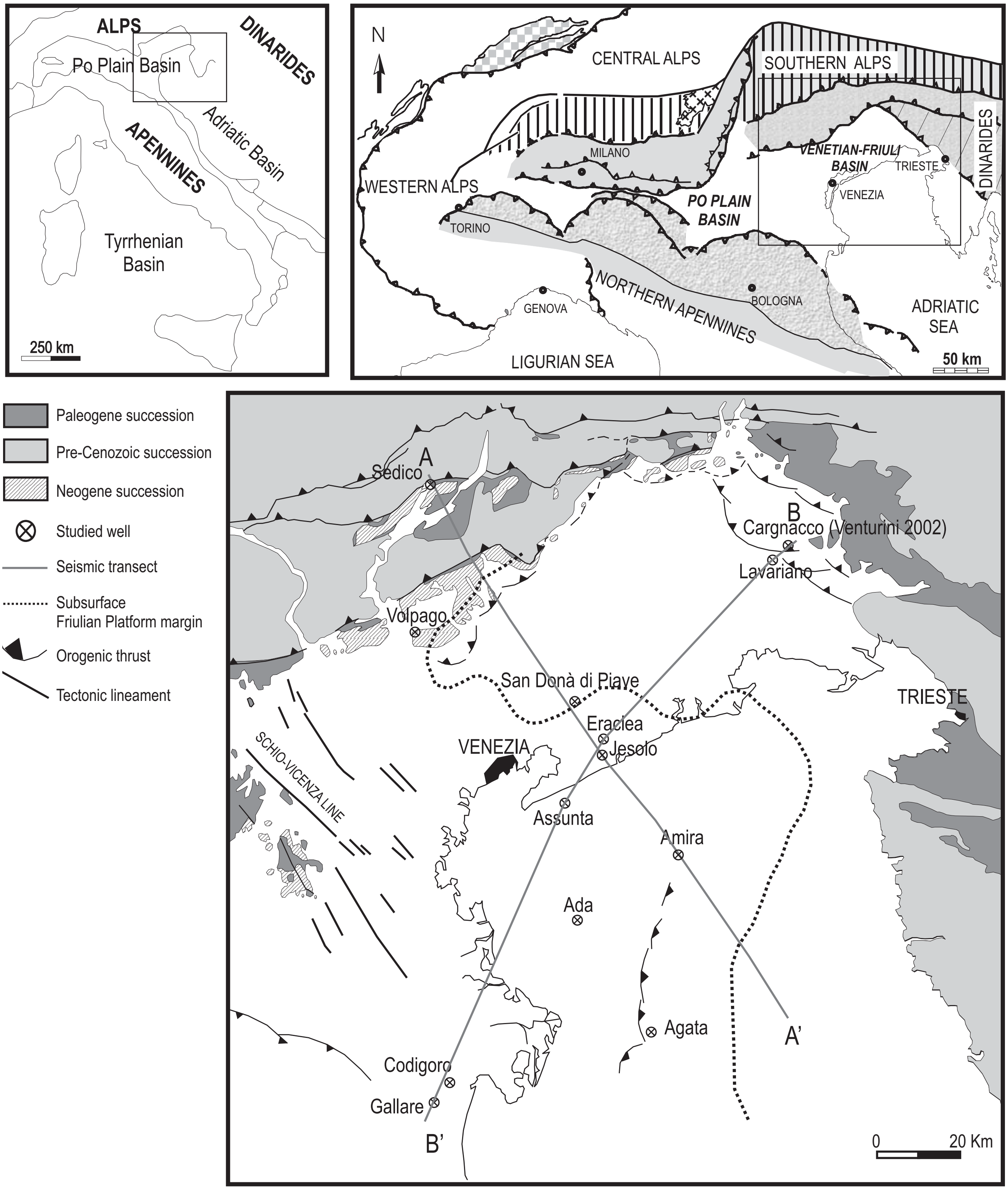

Fig. 1 - Synthetic geological map of the Venetian-Friulian area and location of the studied wells with respect to the NNW-SSE trending section AÀ and the NE-SW trending section BB' (reported in figure 2). The dotted line marks the margin of the subsurface Mesozoic Friulian Carbonate Platform.

which is currently exposed in the Venetian foothill region (Massari et al. 1986 Mellere et al. 2000) as a consequence of a Pliocene-Quaternary tectonic activity. In the south-westernmost sector of the basin, upper neritic marly sediments of the Gallare group persisted till the late Messinian, when evaporitic (Gessoso Solfifera) to fan delta deposits (Boreca Conglomerate) accumulated.

This overall pattern was abruptly modified during the late Messinian by the extreme lowering of the sea level linked to the Mediterranean salinity crisis (Roveri et al. 2003 with ref.). During this event, the whole basin experienced a sub-aerial erosion which produced a basin-scale unconformity surface. Afterwards, the latter was rapidly sealed by open to marginal marine Pliocene sediments (Conegliano unit, Eraclea Sandstone and Santerno group) recording the abrupt sea-level rise at the end of the crisis. The irregular surface produced by the intra-Messinian erosion strictly controlled the highly variable thickness and paleo-water depth of the Pliocene sediments all over the basin. This, in turn, makes somewhat difficult to recognize the probable flexural effects of tectonics active in the surrounding belts on the basin lithosphere, and particularly in the Northern Apennines during late Messinian and Pliocene times.

Tectonic effects become again easier to investigate in the Pleistocene, as the rough basin topography returned to be relatively smooth due to the infilling of Messinian incisions by Pliocene successions, and the deposition of mainly sandy marine sediments (Asti group) deposited in the whole basin. Nevertheless, at the moment, this effect sounds weak and somewhat questionable at least for the Middle-Late Pleistocene.

Sampling strategy and well location

Thirteen hydrocarbon wells (courtesy of ENI) were selected along two key seismic profiles, oriented NNW-SSE and NE-SW i.e. roughly orthogonal to the Southalpine and the Dinaric – Northern Apennine tectonic trends, in order to analyse their Cenozoic succession for a bio-chronostratigraphic reconstruction (Figs. 1-2). The wells examined along the NNW-SSE transect (AÀ) are Sedico, Volpago, San Donà di Piave, Eraclea, Jesolo, Amira and Agata (simplified after Barbieri et al. 2002), whereas the wells examined along the NE-SW transect (BB') are Lavariano, Assunta, Ada, Codigoro and Gallare (simplified after Pieri & Groppi 1981). In order to complete the investigated framework, literature data have also been used for the Cargnacco well (Venturini 2002).

Four hundred forty samples for the foraminifera and 110 for the nannofossil contents were studied; most of them were cuttings, only 20 samples were collected from wall cores of the Ada well (upper potion of the Gallare group and Cavanella and Santerno groups).

Analytical methods

Foraminiferal biostratigraphic analyses were performed to improve the chronostratigraphic constraints of the Cenozoic subsurface succession in the Venetian-Friulian area. The analysis of the calcareous nannofossil content was mainly used to integrate the foraminiferal data and improve the biostratigraphic resolution across two key intervals, the Paleocene-Eocene and the uppermost Chattian-lower Serravallian.

Foraminiferal laboratory techniques were based on standard washing methodology through three sieves (425, 180, 75 microns). Each fraction was analysed under a stereo-microscope through the quantitative counting of 150 specimens. Species abundance was indicated as follow: rr (very rare) = 1-3 specimens, r (rare) = 4-6, r/f (rare to frequent) = 7-8, f (frequent) = 9-15, ff (very frequent) = 16-30, c (common) = 31-50, cc (very common) = > 50. Preservation, caving and reworking were carefully evaluated.

Taxonomic attributions are after Toumarkine & Luterbacher (1985), Bolli & Saunders (1985), Spezzaferri (1994), Olsson et al. (1999) for planktonic foramifera and Agip Atlas (1982) for benthic species.

For the study of nannofossil content, simple smear slides (Bown & Young 1998) were made from the same samples used for the foraminiferal study and were analysed under a polarising light microscope at 1250X magnification. The total and species abundance of calcareous nannofossil were estimated semi-quantitatively counting in each sample, all the nannofossil specimens occurring in 400 random fields of view, corresponding approximately to an area of 6 mm^2. The data were expressed as number of specimens/mm^2.

Results

Biostratigraphy

Data of both the foraminiferal and nannofossil assemblages were performed using, tentatively, the standard zonations proposed for tropical-subtropical latitudes and the Mediterranean region. In the intervals where standard events were not recorded, other biohorizons from “regional” zonal schemes were applied (Agip 1982; Mancin et al. 2003; Catanzariti et al. 1997; 2002). The data obtained allowed to check the applicability of the biohorizons used in the stated schemes to a subsurface succession analysed mainly from cuttings. However, the position of some recorded biostratigraphic events must be considered with caution, because both foraminiferal and calcareous nannofossil occurrences could be biased for the following reasons:

– samples (cuttings) collected at low to very low resolution, occasionally 100 m apart, from and over 20,000 m-thick succession. That resulted in detecting few species in low abundance and in preventing to established accurate ranges (mainly shorter then true species distribution), as most of the first and last occurrences of various taxa remain undetected.

– Facies related to depositional environments which are not favourable to the occurrence and preservation of both planktonic foraminifera and calcareous nannofossils, such as deltaic and rhodalgal platform sediments.

– Caving and reworking, which could displace the first and last occurrence events (FO and LO).

– Moreover, although the used of the last occurrence events could have minimised the effect of caving in cuttings from a subsurface succession unfortunately zonal and subzonal boundaries in the standard schemes are mainly defined by first occurences.

For these reasons, bioevents were recorded as lowest (LO) and highest (HO) occurrences of a species, rather than its first and last occurrence (FO and LO).

The detailed foraminiferal and nannofossil biostratigraphic data for each well can be downloaded from the http://manhattan.unipv.it/sedgeo/Research.htm web site as well as from the data repository of the journal (http://users.unimi.it/rips/). Foraminiferal and calcareous nannofossil range charts are available on request to the corresponding author.

Foraminifera. The adopted biostratigraphic subdivision for the Cenozoic succession was based on the most recent schemes proposed by various authors; a synthesis of the utilised schemes is reported in Fig. 3.

Preservation and total abundance of foraminiferal assemblages were strongly controlled by lithology, sedimentary facies and burial depth. In the deep carbonate hemipelagic mudstones of the Scaglia Rossa Formation, planktonic foraminifera are rare to frequent and quite diverse, *vice versa* benthic taxa are very rare to absent. Preservation is good with a scarce degree of crushing and breakage. Caving displaced particularly the upper Eocene assemblages and the Plio-Pleistocene taxa.

In the overlying marly hemipelagic mudstones of the Gallare group and in the coeval turbidite sediments of the Belluno and Jesolo flysches, planktonic and benthic foraminifera become abundant and well diversified. Preservation is quite good, with a moderate degree of crushing. Foraminiferal abundance markedly diminishes in the upper portion of the Jesolo Flysch and in the sandy marls of the Possagno Formation, which yield very rare planktonic foraminifera and shallow-water benthic species.

In the shallow carbonate platform sediments of the Cavanella group, planktonic foraminifera are very rare to absent and benthic taxa are rare to frequent but well preserved. Caving is important, displacing particularly the Plio-Pleistocene taxa.

In the overlying hemipelagic sediments of the upper portion of the Gallare group, the San Donà Marl and in the silty-clayey mudstones of the Santerno group, foraminifera are abundant, well diversified and preserved. Sometimes, planktonic foraminiferal assemblages result characterised by long-ranging species, preventing biostratigraphic resolution.

Finally, in the shallow marine sands of the Asti group, planktonic foraminifera become very rare to absent and benthic assemblages result characterised by littoral species; preservation is very good.

Primary bioevents, which identify zonal and subzonal boundaries, together with some auxiliary

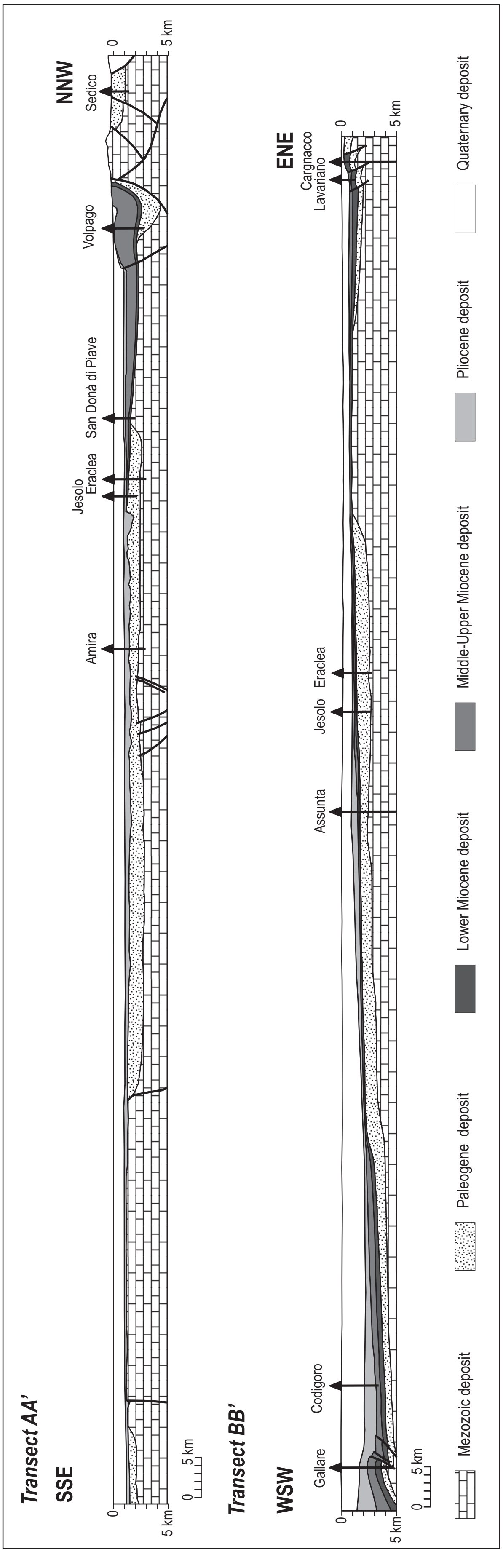

Fig. 2 - Interpreted geological profiles oriented according to the Southalpine (AÀ) and Dinaric (BB') direction of tectonic transport; the location of the studied wells is also reported. Transect AÀ is after Barbieri et al. (2002), transect BB' is after Pieri & Groppi (1981).

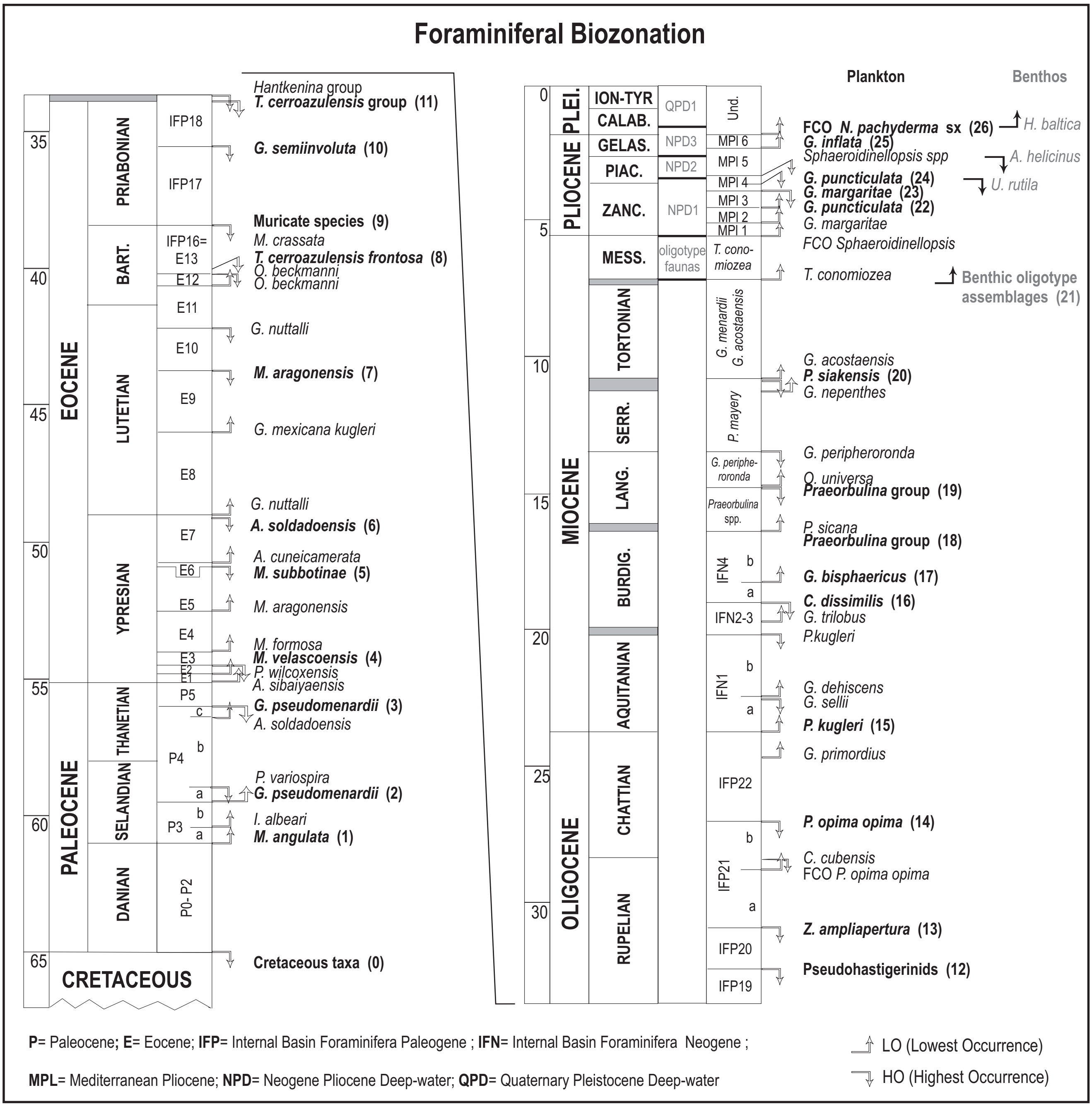

Fig. 3 - Adopted planktonic foraminiferal biostratigraphic zonal schemes, from bottom to top: a) Berggren et al. (1995) revised by Berggren & Pearson (2005) for the Paleogene (P and E zones). This scheme was partially modified by Mancin et al. (2003) for some middle Eocene-lower Miocene bioevents (IFP-IFN zones); b) Iaccarino (1985), modified by Foresi et al. (1998) and by Sprovieri et al. (2002) for Middle-Upper Miocene Mediterranean region; c) Sprovieri (1992) for the Pliocene-Lower Pleistocene Mediterranean region (MPL zones). Recorded planktonic foraminiferal bioevents are in bold; d) Benthic foraminiferal biozonation (NPD-QPD, in grey) after Agip (1982).

bioevents are listened in Figs. 4 and 5. The numbers mark the most reproducible biohorizons used to correlate the different studied wells. A brief discussion on the applicability and reproducibility of the listed bioevents is reported below. Their description goes on from the oldest to the youngest and is organised into four key time slices: Paleocene-Eocene, Oligocene-Early Miocene, Middle-Late Miocene and Pliocene-Pleistocene.

Paleocene-Eocene

– The oldest sample collected (Sedico well, Fig. 5) contain *Morozovella angulata* (1 in Figs. 3-5), whose LO defines the lower boundary of the P3 Zone. Only in the Amira well, reworked Cretaceous taxa are recorded up to the Scaglia Rossa/Gallare group boundary.

– LO of *Globanomalina pseudomenardii* (2), lower boundary of the P4 Zone, detected in the Sedico well. In Eraclea, Assunta and Ada wells this species occurs sporadically.

– HO of *G. pseudomenardii* (3), lower boundary of the P5 Zone, detected in the Sedico and Ada wells. In the Eraclea and Assunta wells, this biohorizon was traced tentatively.

– Early Eocene marker species, such as *Acarinina sibaiyaensis, Pseudohastigerina wilcoxensis* and *Morozovella velascoensis*, are very rare to absent and discontinuously distributed, make impossible to recognise the LO and HO datum levels. *Acarinina sibaiyaensis,* LO of which defines the lower boundary of the E1 Zone, is always missing. This is probably due to samples collected at low to very low resolution not suitable to detect short-ranging species. The LO of *P. wilcoxensis,* which defines the lower boundary of the E2 Zone, detected in the Sedico, Eraclea and Ada wells, is recorded diachronously in the wells studied probably because displaced by caving and/or for poor preservation.

– *M. velascoensis* (LO=4 in Figs.3-5), in spite of its easily recognisable morphology, is usually very rare to absent and discontinuously distributed. Therefore it is quite difficult to place the E2/E3 zonal boundary. *M. formosa* and *M. aragonensis* are very rare to rare in their initial ranges. However, in four wells (Sedico, Eraclea, Ada and Assunta) their lowest occurrences are recorded diachronously probably because displaced by caving, so that the E3/E4 and E4/E5 zonal boundaries could be not traced.

– HO of *Morozovella subbotinae* (5), lower boundary of the E6 Zone, detected in the Sedico, Eraclea Assunta and Ada wells. The marker species was recorded in most of the studied wells but it is very rare and discontinuous in its final range. Therefore, in subsurface sections with samples collected at low to very low resolution, caving and reworking can be quite difficult to discriminate.

– HO of *Acarinina soldadoensis* (6) was recorded in all the studied wells. This event, which slightly pre-dates (at 49.3 Ma, Berggren & Pearson 2005) the HO of *Guembelitrioides nuttalli* (at 49.0 Ma) in the tropical realm, recorded in all the studied wells has been used to approximate the lower boundary of the E8 Zone, because the marker species *G. nuttalli* is always missing. The LO of *Globigerinatheka mexicana kugleri*, lower boundary of the E9 Zone, was recorded only in the Sedico well. In the other wells the genus *Globigerinatheka* resulted always displaced by caving preventing from recognising its lowest occurrence, so that the zonal boundary was not traced.

– HO of *Morozovella aragonensis* (7), lower boundary of the E10 Zone, recorded in the Volpago, Assunta and Ada wells. In the other wells this event was tentatively placed as the marker species was usually very rare and discontinuous in its final range.

– HO of *Turborotalia cerroazulensis frontosa* (8). This event (= Last occurrence of *Subbottina frontosa*, at 39.3 Ma, Berggren et al. 1995), which just post-dates the HO of *Orbulinoides beckmanni* (at 40.0 Ma, Berggren & Pearson 2005) in the tropical realm, being recorded in most of the studied wells, has been used to approximate the lower boundary of the E13 Zone. The marker species *O. beckmanni*, in fact, probably for samples collected with low resolution, occurs only sporadically preventing the identification of its lowest and highest occurrences.

– HO of muricate taxa (9), lower boundary of the IFP17 Zone. This event, easily detectable for the sharp decrease in abundance and abrupt disappearance of the muricate taxa, still frequent in the underlying levels, was recorded in most of the wells (Volpago, Eraclea, Amira, Gallare, Ada and Assunta wells). Moreover, the HO of *Morozovella crassata*, which defines the lower boundary of the E14 Zone (Berggren & Pearson 2005), occurs at a level very close to the extinction of the genera *Acarinina* and *Truncorotaloides* (at 38.0 Ma, Wade 2004), so that the IFP16 Zone of Mancin et al. (2003) well correlates with the E13 Zone of Berggren & Pearson (2005).

– HO of *Globigerinatheka semiinvoluta* (10), lower boundary of the IFP18 Zone, recorded in the Volpago, Eraclea, Agata, Gallare, Ada and Assunta wells.

– HO of *Turborotalia cerroazulensis* lineage (11), lower boundary of the IFP19 Zone, detected in the Gallare, Ada and Assunta wells. In the other wells (Volpago, Eraclea and Jesolo) this event was not recorded because has been removed by a strong erosional phase affected part of the upper Priabonian sediments.

Oligocene-Early Miocene

Oligocene marker species, such as pseudohastigerinids with size <125 μm, *Zeaglobigerina ampliapertura, Chiloguembelina cubensis* and *Paragloborotalia opima opima*, are very rare to absent and discontinuously distributed preventing from accurately placing the zonal boundaries.

– HO of *Pseudohastigerina* spp. (12), lower boundary of the IFP20 Zone, recognized in the Ada well. In the other wells, (Gallare, Assunta and Agata), pseudohastigerinids disappear together with the *T. cerroazulensis* lineage probably for the samples collected to low resolution and/or for the strong condensation and selective dissolution, which could have removed these small-size taxa.

– HO of *Zeaglobigerina ampliapertura* (13), lower boundary of the IFP21 Zone. This species occurs very rarely and discontinuously, so that only in the Ada and Agata wells this bioevent was recorded.

– *C. cubensis* is always missing probably for lack of preservation.

– HO of *Paragloborotalia opima opima* (14), lower boundary of the IFP22 Zone, recorded in Gallare, Ada, Assunta and Agata wells.

– Also most of the Early Miocene marker species, such as *Paragloborotalia kugleri*, *Globoquadrina dehiscens*, *Globigerinoides altiaperturus, Globigerinoides trilobus, Globigerinatella insueta* and *Catapsydrax dissimilis* are very rare to absent and discontinuously distributed in the studied wells, preventing from recognising their first and last occurrences. Particularly, very rare *Paragloborotalia kugleri* occurs sporadically, *G. dehiscens*, *G. altiaperturus* and *G. insueta* are missing. *C. dissimilis* is usually very rare and discontinuously recorded in the wells probably because it occurs in sedimentary facies (shallow water carbonate platform sediments) less suitable to the development and preservation of deep-water planktonic taxa.

Middle Miocene-Late Miocene

Most of the Middle-Late Miocene Mediterranean zonal marker, such as *Globorotalia peripheroronda* and *Paragloborotalia partimlabiata* are missing in the studied wells; moreover, in the standard Mediterranean Zonation (Sprovieri et al. 2002) the primary events, used to define zonal or subzonal boundaries, are mainly first occurrences that result often displaced by caving.

– LO (18) and HO (19) of the *Praeorbulina* lineage were not recorded; only very rare specimens of this group, usually poorly preserved, sporadically occur in the carbonate platform sediments of the Cavanella group. *Orbulina* spp. and *Globigerinoides* spp. are usually displaced by caving preventing in recognising their lowest occurrences. *Neogloboquadrina acostaensis, Paragloborotalia siakensis* and *Globorotalia menardii* group occur sporadically. For these reasons, only some zonal boundaries were tentatively placed.

Plio-Pleistocene

The oldest sample collected from the transgressive Pliocene sediments (Amira, Agata, Assunta and Ada wells) contain *Globorotalia puncticulata*, whose LO (22) defines the lower boundary of the MPL3 Zone. In the other wells (San Donà, Eraclea and Jesolo), the planktonic foraminiferal marker species are missing, therefore the Agip benthic assemblage zones were utilised.

– HO of *Globorotalia margaritae* (23), lower boundary of the MPL4a Subzone. This bioevent was recorded only in the Agata and Ada wells.

– HO of *Globorotalia puncticulata* (24), lower boundary of the MPL4b Subzone. This bioevent was recorded in the Amira, Agata and Ada wells. In the Gallare well, *G. puncticulata* is already missing from the first sample collected in the Pliocene Porto Corsini Formation upwards.

– only in the Gallare well the HO of *Globorotalia bononiensis* (lower boundary of the MPL5b Subzone) was recorded only. In the other wells this species is rare to absent preventing to place the subzonal boundary.

– LO of *Globorotalia inflata* (25), lower boundary of the MPL6 Zone. This bioevent was recorded in the Amira, Agata, Ada, and Gallare wells.

The lower Pleistocene interval was tentatively distinguished on the basis of the benthic assemblage composition according to the benthic Agip scheme.

Calcareous nannofossils. The biostratigraphic study of the Paleocene-Eocene nannofossil assemblages was performed using, tentatively, the standard 'global' Zonation of Martini (1971), partially modified by Perch-Nielsen (1985), Berggren et al. (1995) and, for some Eocene biohorizons, by Catanzariti et al. (1997, 2002). The scheme proposed by Fornaciari & Rio (1996) for the Mediterranean region was applied to the uppermost Oligocene-lower Miocene interval.

A total of 110 samples were analysed in six wells (Sedico, Eraclea, Assunta, Ada, Amira, Gallare), 10 of which were devoid of calcareous nannofossils. The nannofossil abundance as well the species diversity are mainly low, particularly in the cuttings derived from the Scaglia Rossa Formation. The low total abundance of calcareous nannofossils is considered to be dependent on preservation related to lithology and burial depth, with the marlstones of the Gallare group containing the best preserved and abundant nannofloras. Etching and overgrowth of specimens seem to confirm a strong diagenetic imprint on assemblages. The biostratigraphic events easily detected and more reproducible in the studied wells are discussed below.

– LO of *Fasciculithus tympaniformis*. This event, which defines the lower boundary of the NP5 Zone, was recorded in the Assunta and Sedico wells. Above its appearance, this species is common and continuously distributed up to the Paleocene/Eocene boundary.

– LO of *Heliolithus kleinpellii*. This event, representing the lower boundary of the NP6 Zone, was recorded in the Sedico and Eraclea wells. However, the species is very rare and unevenly distributed throughout.

– LO of *Discoaster multiradiatus.* The lower boundary of the NP9 Zone was traced in all the studied wells. *Discoaster multiradiatus* is well preserved and common in the NP9 zonal assemblages.

The NP9/NP10 boundary is difficult to recognize. As a matter of fact in the literature, the base of the NP10 Zone was defined by the LO of *Tribrachiatus contortus* or alternatively by the LO of *Discoaster dyastipus*. *T. contortus* was never recorded in the studied sample, whereas *D. dyastipus* is difficult to recognise in heavily altered samples. Only in the Assunta well, few specimens of *D. dyastipus* were observed. The HCO (highest common occurrence) of *Fasciculithus tympaniformis*, which disappears near the top of the NP9 Zone (Perch-Nielsen 1985 with ref.), was recognised in the Sedico well.

– The Early Eocene *Discoaster* zonal markers, such as *D. lodoensis* and *D. sublodoensis,* are very rare and discontinuously distributed. Moreover, they are frequently only poorly preserved and could not clearly identified.

– LO of *Nannotetrina* sp. The LO of *Nannotetrina fulgens* has been used to define the base of the NP15 Zone but usually the marker species cannot be always distinguished. In heavily overgrown assemblages, as suggested by many authors (e.g. Perch-Nielsen 1985), the appearance of the genus *Nannotetrina* can be used as zonal marker. Within this zone in the Eraclea well, the occurrence of the large size *Chiasmolithus* species, such as *C. grandis* and *G. gigas,* were observed.

– LO of *Reticulofenestra umbilicus* > 14 µm. This event approximates the base of the NP16 Zone (Catanzariti et al. 2002 with ref.) and it is easily detectable also in heavily altered samples. The LO of this species is preceded by the occurrence of specimens morphologically similar to *R. umbilicus* but smaller in size.

– LO of *Dyctiococcites bisectus* (Catanzariti et al. 2002 with ref.) indicates the base of the NP17 Zone. It was easily detected in the Eraclea well.

– LCO (lowest common occurrence) of *Cribrocentrum reticulatum* (Catanzariti et al. 2002 with ref.) approximating the base of the NP18 Zone, was recorded only in the Amira well, but its distribution is marked clearly by an abrupt increase in abundance.

In the Gallare well, several nannofossil events were recorded in the upper Oligocene-middle Miocene interval (uppermost Chattian-lower Serravallian). They are listed below from the oldest to the youngest: HO of *Sphenolithus ciperoensis*, HCO of *D. bisectus*, LO of *Sphenolithus disbelemnos*, LO of *Helicosphaera ampliaperta* and, finally, LCO of *Sphenolithus heteromorphus.*

These events were used by Fornaciari & Rio (1996) to define zonal and subzonal boundaries for the Mediterranean region. In the studied well, the biostratigraphic subdivision proposed by this zonal scheme was recognised except for the MNN1b and the lower boundary of the MNN2a Subzones because both *Sphenolithus delphix* and *Helicosphaera euphratis* were never recorded.

Nannofossil and foraminiferal integrated biostratigraphy allows to improve the biostratigraphic resolution during the Paleocene-Eocene and the Late Oligocene-Middle Miocene intervals. These stratigraphic intervals correspond to the deposition of the hemipelagic sediments of the Scaglia Rossa and Gallare group and turbidite deposits of the Belluno Flysch. The integrated use of both nannofossil and foraminiferal bioevents allowed to well constrain the age of these stratigraphic units and to date the onset of the turbidite sedimentation related to the Dinaric-Mesoalpine orogenetic phases (Castellarin et al. 1992; Castellarin & Cantelli 2000).

Moreover, the recorded foraminiferal and nannofossil integrated biostratigraphy reproduces well the standard zonations previously proposed by the authors (Berggren & Pearson 2005, with ref.). Differences and inconsistencies are exhaustively reported and discussed in appendix. The data collected are reported in Figs. 6 and 7; they synthesize the integrated biostratigraphic correlation of stratigraphic sections studied in the northern sector, close to the thrust belt (Sedico and Eraclea wells, Fig. 6) and in the basinal southern sector (Assunta, Ada and Amira wells, Fig. 7), respectively. The standard planktonic foraminiferal and calcareous nannofossil zonations plotted against chronostratigraphy and magnetostratigraphy used in this study are reported in Fig. 8.

Chronostratigraphy

In Figs. 9-10, the chronostratigraphy of the VFB subsurface succession is summarized along the same transects depicted in Figs. 4 and 5.

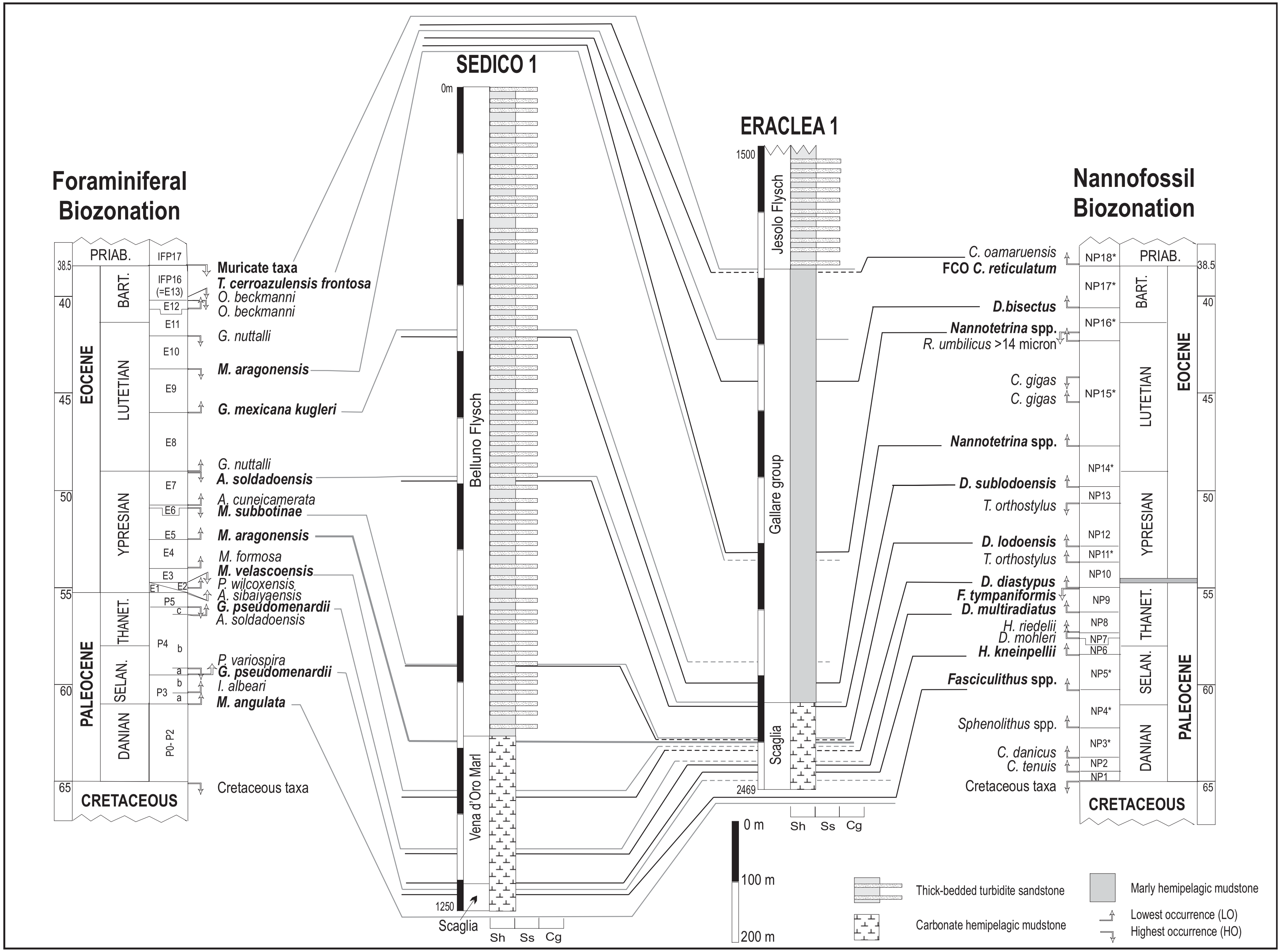

Fig. 6 - Integrated nannofossil and planktonic foraminiferal biostratigraphic correlation between the selected Sedico and Eraclea wells. Grey lines are for planktonic foraminifera, whereas dark lines are for calcareous nannofossils. Dashed lines mark biohorizons whose position is doubtful.

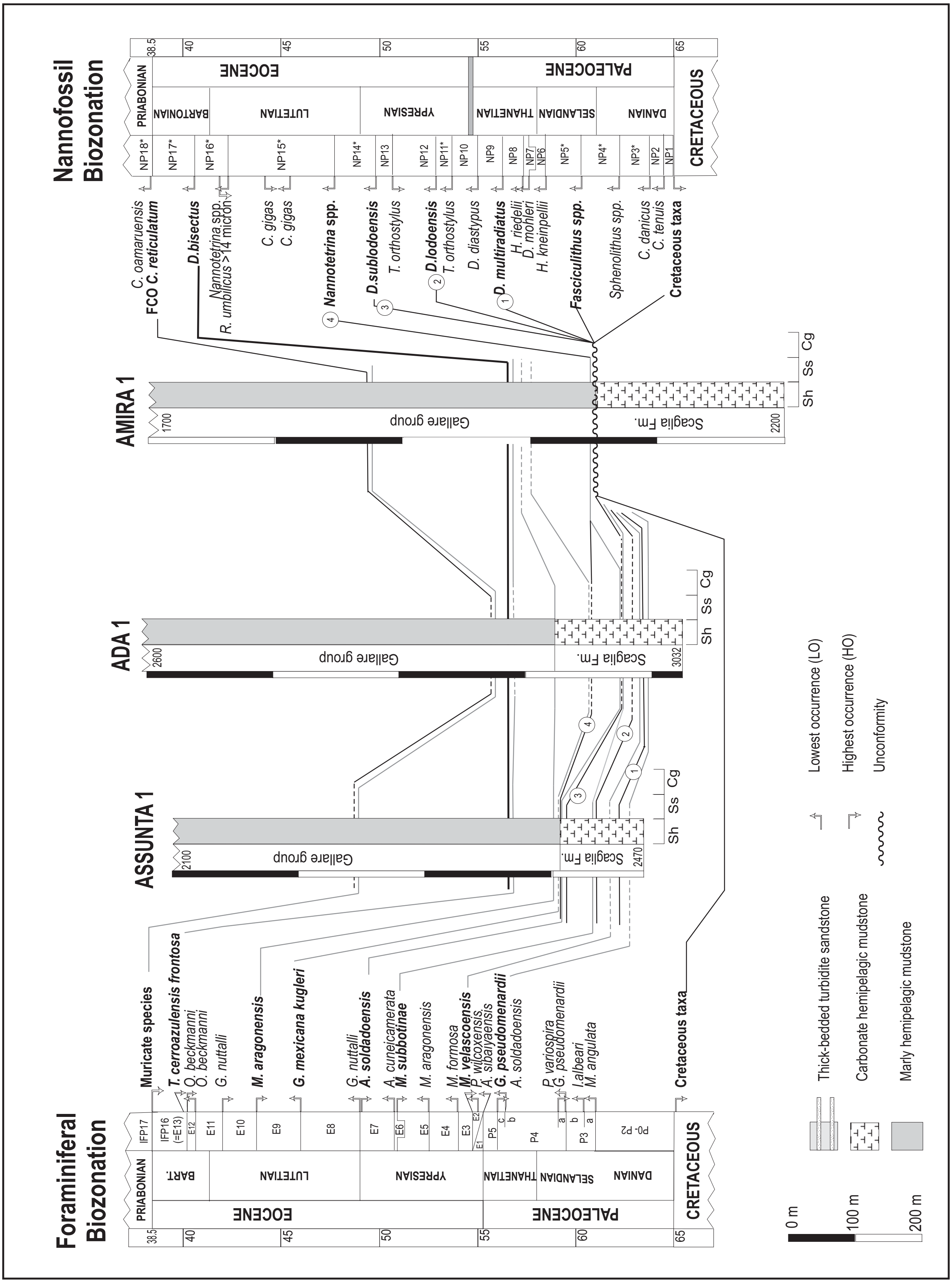

Fig. 7 - Integrated nannofossil and planktonic foraminiferal biostratigraphic correlation among the selected Assunta, Ada and Amira wells. Grey lines are for planktonic foraminifera, whereas dark lines are for calcareous nannofossils. Dashed lines mark biohorizons whose position is doubtful.

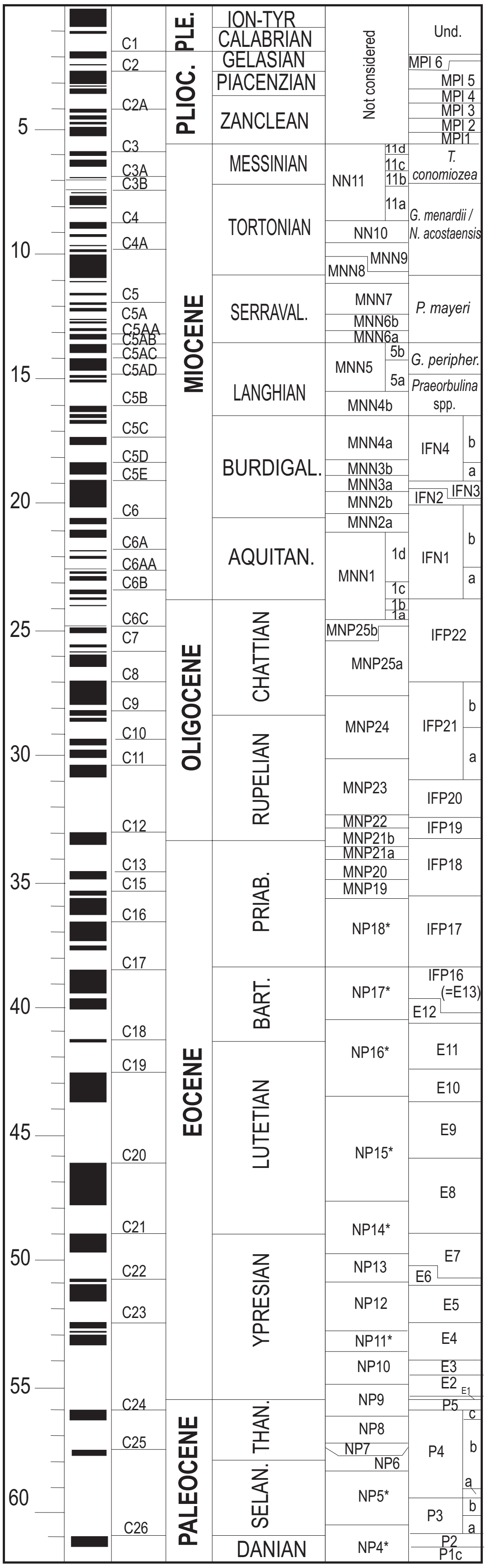

Fig. 8 - Cenozoic standard bio-chronostrastigraphic schemes. Biomagnetochronological calibration is after Gradstein et al. (2004 with ref.). Biozones are: NP, MNP and MNN for calcareous nannofossils; P, E, IFP, IFN, MPL for planktonic foraminifera. See text for major information.

The Scaglia Rossa extends widespread over the basin and it is coeval with the Friulian carbonate platform unit, named Nummulitic Limestone (Venturini 2002), located in the ENE sector of the studied area. The age of the analysed portion of the Scaglia Rossa ranges from the Selandian (foraminifer P3 and nannofossil NP5 Zones) to the Lutetian (foraminifer E9/E10 boundary and top of the nannofossil NP15 Zone). However, its upper boundary results time-transgressive towards the south. In the Sedico well, it lies between the LO of *Globanomalina pseudomenardii* (lower boundary of the foraminifer P4 Zone) and the LO of *Heliolithus kleinpellii* (lower boundary of the nannofossil NP6 Zone). In the Eraclea well, the same boundary is placed between the LO of *Discoaster sublodoensis* (lower boundary of the nannofossil NP14 Zone) and the HO of *Acarinina soldadoensis* (lower boundary of the foraminifer E8 Zone), whereas in the Ada well it is younger and falls close to the HO of *Morozovella aragonensis* at the E9/E10 zonal boundary. In the Sedico well, the Scaglia Rossa is overlain by a grey hemipelagic marly unit (Vena d'Oro Marl, Fantoni et al. 2002) late Selandian-early Ypresian in age, similar to the marlstones of the Gallare group.

In the northern sector, the onset of the Belluno Flysch deposition in the uppermost Ypresian (lower portion of the foraminifer E5 Zone and lower portion of the nannofossil NP11 Zone) interrupted the normal hemipelagic sedimentation. The base of the turbidite units is time-transgressive towards the south and occurred in the Eraclea and Jesolo wells at the Bartonian/Priabonian boundary (close to the highest occurrence of the muricate planktonic foraminiferal taxa). The top of the turbidite units is marked by an erosional unconformity. In detail, the upper boundary of the Jesolo Flysch and Possagno Marl is assigned to the upper Priabonian (foraminifer IFP18 Zone), whereas, in the northeastern sector (Cargnacco well), the erosional hiatus is more extended and the top of the Cormons Flysch is referable to the upper Lutetian (Venturini 2002).

During the middle-late Eocene, the lower portion of the hemipelagic Gallare group heteropically deposited in the southern sector of the Belluno Basin. This latter unit is referable, only in the south-western sector of the basin (Gallare well), to the stratigraphic interval spanning from the Ypresian/Lutetian boundary (close to the HO of *A. soldadoensis*, foraminifer E7/E8 zonal boundary and within the nannofossil NP14 Zone) to the lower Messinian (oligotype benthic assemblages with buliminids and uvigerinids), whereas in most of the studied basin, the Gallare group is overlain, from the upper Oligocene upwards, by the shallow-water limestones of the Cavanella group.

The base of the Cavanella group is time-transgressive towards the south. It has a late Chattian age (Vol-

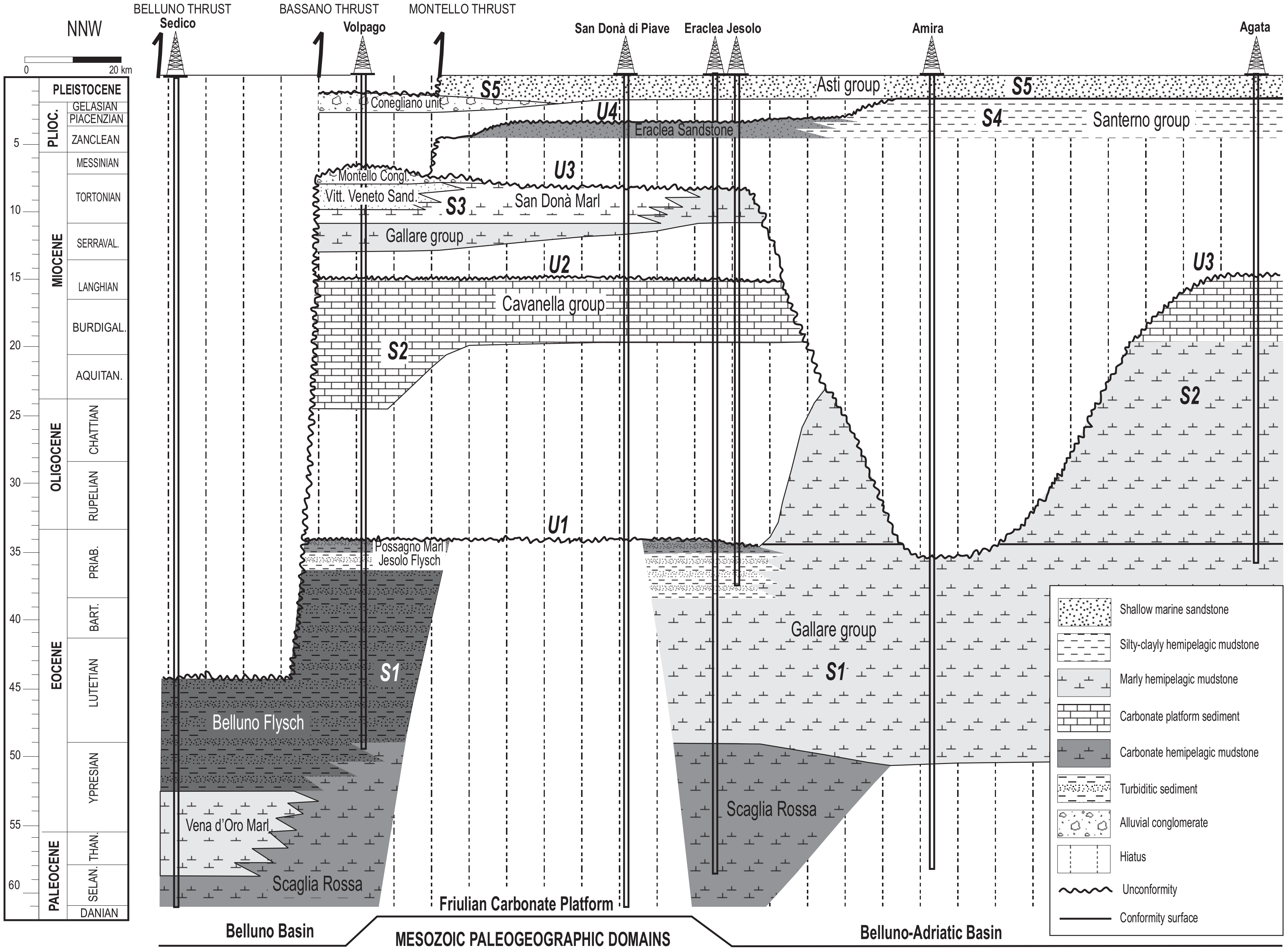

Fig. 9 - Chronostratigraphic scheme of the Cenozoic subsurface succession of the Friulian-Venetian area along the NNW-SSE "southalpine" transect. Depositional sequences (*S1-S5*), major unconformities (*U1-U4*) and correlative conformity surfaces are also reported.

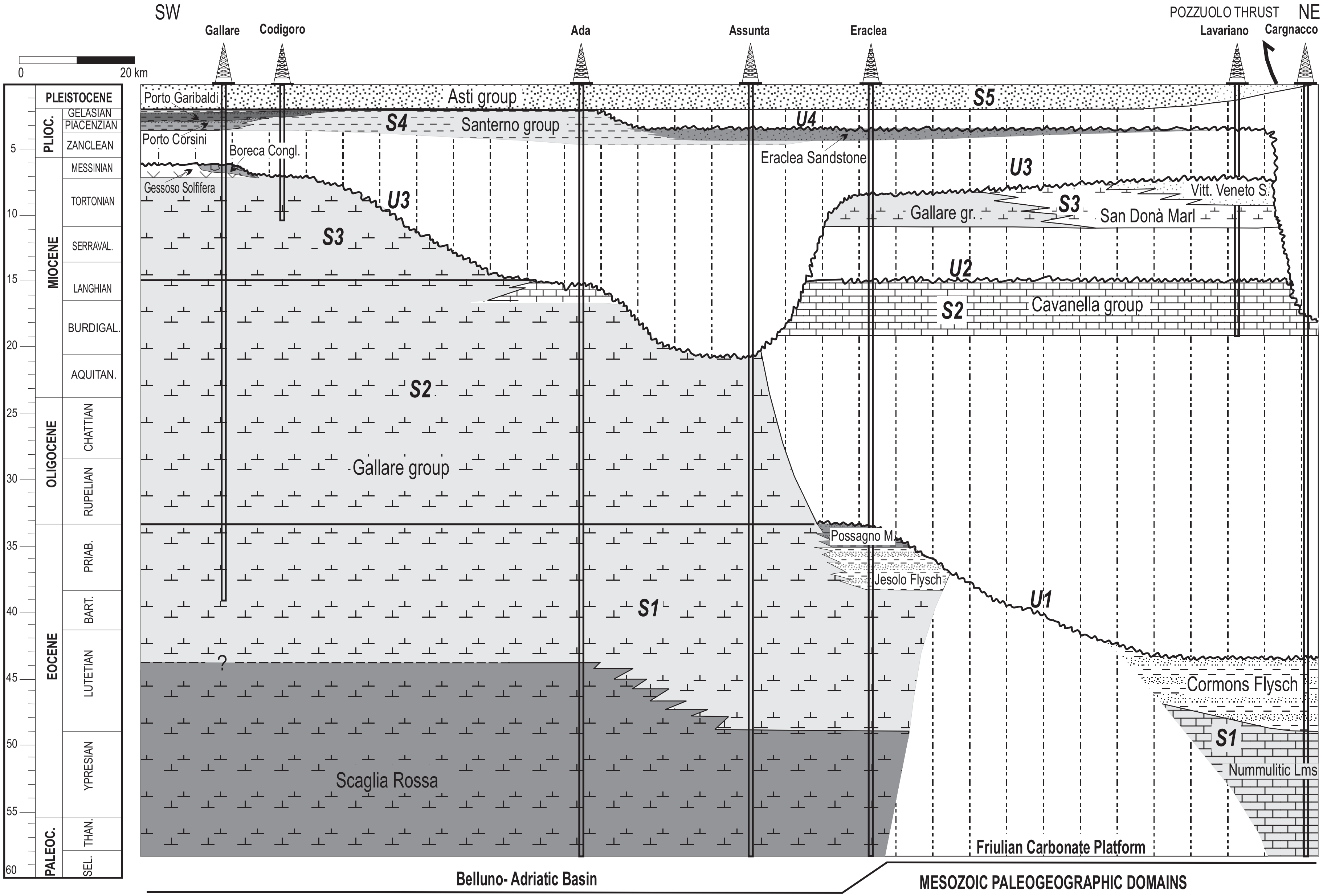

Fig. 10 - Chronostratigraphic scheme of the Cenozoic subsurface succession of the Friulian-Venetian area along the SW-NE “dinaric” transect. Depositional sequences (*S1-S5*), major unconformities (*U1-U4*) and correlative conformity surfaces are also reported. Symbols as in Fig. 9.

pago well, upper portion of the foraminifer IFP22 Zone) in the north-western area of the basin and a Burdigalian (base of the foraminifer IFN4 Zone) to Langhian age (Ada well, base of the *Praeorbulina* spp. Zone) in the other sectors. The top of this unit, is truncated by an unconformity, that appears almost synchronous over the basin and can be dated to the late Langhian (*Praeorbulina* spp. Zone).

Above the unconformity, sedimentation resumed with the deposition of the marly unit of the Gallare group and the San Donà Marl. The onset of the Gallare marly unit above the Cavanella is time-transgressive towards the south since the Serravallian (foraminifer *P. mayeri* Zone) in the north-western sector to the Tortonian (*G. menardii/N. acostaensis* Zone) in the south-eastern sector. The Vittorio Veneto Sandstone, which is Tortonian in age, confined to the northern sector of the basin (Volpago and Lavariano wells), is interfingering with the upper portion of the San Donà Marl.

The overlying Gessoso-Solfifera Formation and the Boreca Conglomerate in the south-western sector (Gallare well) and the Montello Conglomerate in the north-western sector (Volpago well) of the basin are late Tortonian to early Messinian in age.

The Plio-Pleistocene succession starts, in the uppermost Zanclean (foraminifer MPL3 Zone, in the Agata and Ada wells), with the Santerno group showing a base slightly time-transgressive towards both the north and the south-west. Towards the north, it falls within the MPL4a Subzone (Amira well). Towards the southwest (Gallare well), the pelitic sediments of the Santerno group are laterally replaced by the Piacenzian turbidite Porto Corsini and Porto Garibaldi Formations (foraminifer MPL4b-MPL5a Subzones). The top of the Santerno group spans from the upper Pliocene (MPL6, Gallare well) to the lower Pleistocene (benthic foraminifer QPD1 Zone, Ada and Amira wells). In the central sector of the basin (San Donà di Piave, Eraclea, Jesolo and Assunta wells), the pelitic sediments of the Santerno group are replaced by the shallow-water sandstones of the Eraclea Formation, since the middle-late Zanclean.

Finally, the succession ends with the Pleistocene Asti group and with the Holocene deposits. It must be noted that in the Montello area (Volpago well), the upper portion of the Neogene conglomerates are possibly late Pliocene-early Pleistocene in age (Conegliano unit, Viaggi & Venturini 1996).

The studied wells also show four major unconformities of different significance and three of these display a wide lateral extension and can be correlated almost throughout the basin. The detected unconformities (*U1-U4*) allow us to subdivide the Cenozoic succession into five depositional sequences (*S1-S5*). These unconformities, in the depocenter of the basin, pass to their correlative conformity surfaces except the intra- Messinian *U3* unconformity. The recognised depositional sequences, from the older to the younger, are:

Paleocene-Upper Eocene depositional sequence (S1) - The sequence is topped by an erosional unconformity (*U1*) with an associated stratigraphic gap spanning the Middle-Upper Eocene to the Upper Oligocene interval. This unconformity is recorded only in the northern sector of the basin and separates the Paleocene-Eocene flysches from the Cavanella sediments. The top of the *S1* sequence is Lutetian in the north-eastern (Cormons Flysch, Venturini 2002) and Priabonian (Jesolo Flysch and Possagno Marl) in the north-western sectors of the basin.

Upper Oligocene-Middle Miocene depositional sequence (S2) – The second unconformity (*U2*), bounding the *S2* sequence, is observed at the top of the Cavanella group where a gap, encompassing the uppermost Langhian- Tortonian interval, is recorded.

Middle-Upper Miocene depositional sequence (S3) – The third unconformity (*U3*) is related to the intra-Messinian erosional event and topped the *S3* sequence. The gap associated shows different extension throughout the basin reaching the largest stratigraphic interval in the Adriatic offshore, where it ranges from the upper Priabonian to the Lower Pliocene.

Pliocene depositional sequence (S4) - The latter unconformity (*U4*), separating the *S4* from the *S5* sequences, is observed only in the central sector of the basin at the top of the Pliocene succession, where a gap, extending from the uppermost Zanclean to the lower Pleistocene, is recorded.

Pleistocene-Holocene depositional sequence (S5) – The *S5* sequence, Pleistocene-Holocene in age, ends the sedimentary history of the Venetian- Friulian Basin.

Conclusions

The Venetian Friulian Basin (Late Paleocene-Pleistocene) is the result of the superimposition of three overlapping foreland systems, different both in age and direction of tectonic transport; the Dinarides to the East, the Southern Alps to the North and the Apennines to the Southwest.

The integrated (foraminifera and calcareous nannofossils) micropaleontological analyses allowed the recognition of several biohorizons in each well succession that made possible, basin-scale biostratigraphic correlations, which, in turn, provide the base for the construction of the here presented synoptic chronostratigraphic scheme. That scheme represents the first published basin wide stratigraphic data-set concerning the subsurface succession of the eastern sector of the Po Plain basin.

This work documents carefully the timing of the sedimentary events occurred in the basin and allows to quantify the time-span contained in the main non depositional and/or erosional hiatuses recorded in the Cenozoic subsurface succession of the VFB. Moreover, it provides a subdivision of the studied succession into five depositional sequences (*S1-S5*) bounded by four major unconformities (*U1-U4*) and by their correlative conformity surfaces documented throughout the basin. In a companion paper, we will discuss the driving processes that guided the sedimentary infilling of a complex foreland basin as the Venetian-Friulian Basin, distinguishing tentatively regional *versus* global forcing.

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Appendix (available in the data repository of the journal: http://users.unimi.it/rips/ **and in the SedGeo Group web site of the Dipartimento di Scienze della Terra of the University of Pavia:** http://manhattan.unipv.it/sedgeo/Research.htm**).**

Detailed chrono-, litho- and biostratigraphy for each well studied (**1.** Sedico, **2.** Volpago A-B, **3.** San Donà di Piave, **4.** Eraclea, **5.** Jesolo, **6.** Amira, **7.** Agata, **8.** Lavariano, **9.** Assunta A-B, **10.** Ada and **11.** Gallare A-B). Calcareous plankton (planktonic foraminifera and nannofossils) bioevents are reported as lowest (LO) and highest (HO) occurrences of a species, rather than first and last occurrence (FO and LO). Foraminiferal bioevents are in bold.

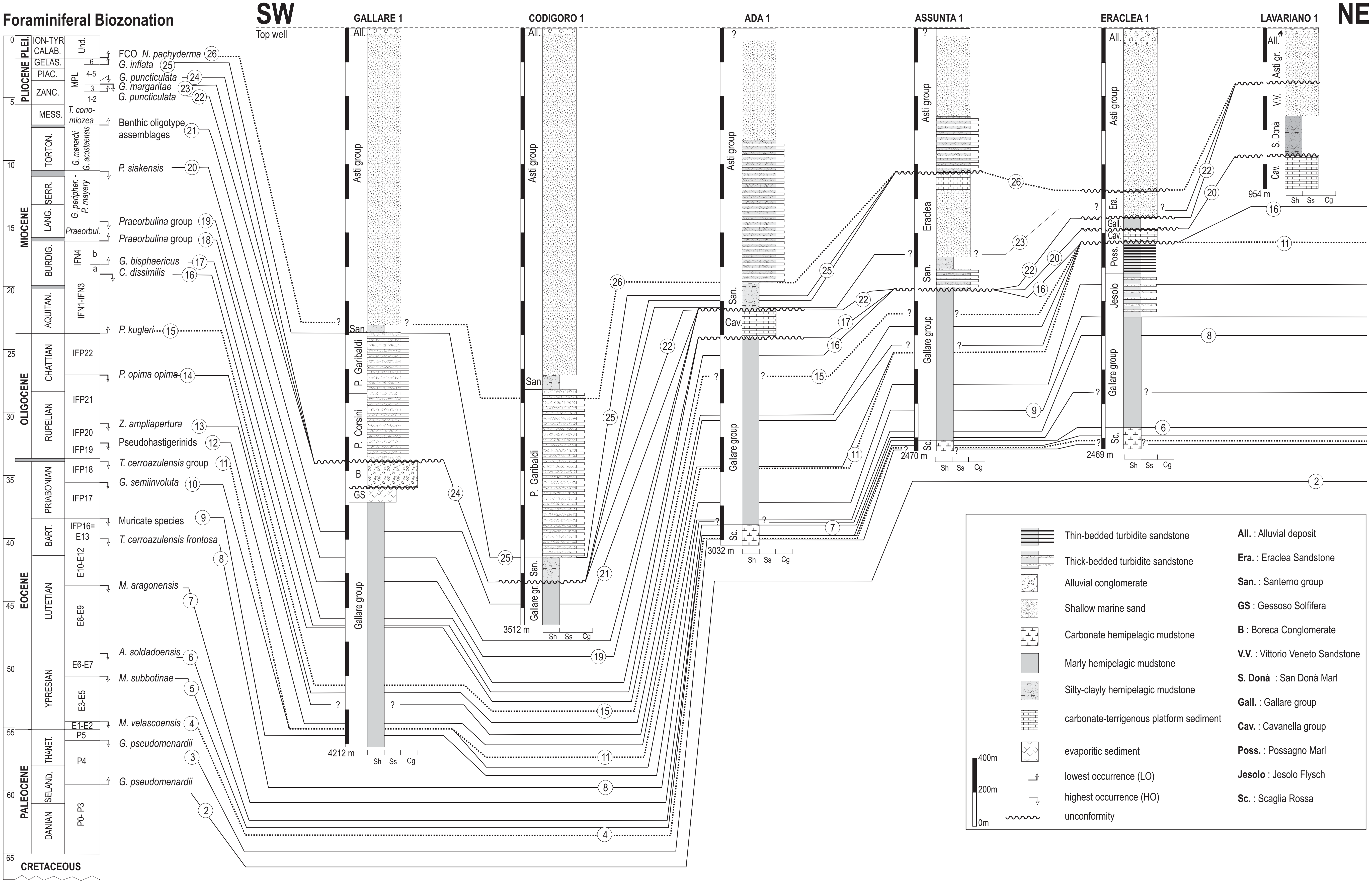

Fig. 4 - Planktonic foraminiferal biostratigraphic correlation of the VFB wells studied along the SW-NE "dinaric" transect, Late Paleocene to the Recent. The numbers denote the most reproducible biohorizons used to correlate the different studied wells.

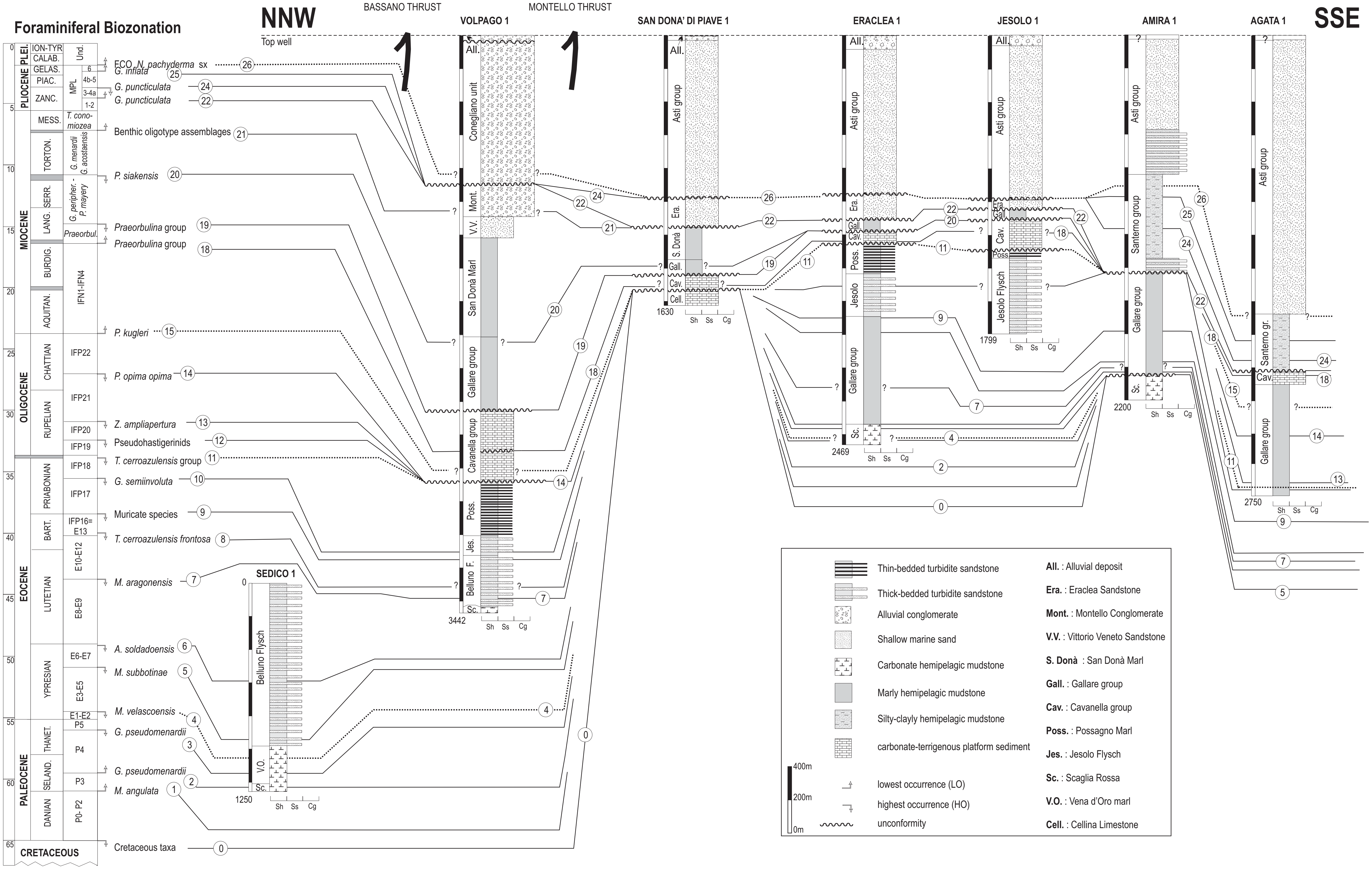

Fig. 5 - Planktonic foraminiferal biostratigraphic correlation of the VFB wells studied along the NNW-SSE "southalpine" transect, Late Cretaceous to the Recent. The numbers denote the most reproducible biohorizons used to correlate the different studied wells.