GEOLOGIE EN MIJNBOUW© VOLUME 57 (4), p. 559-576 1978

TURBIDITE DISPERSAL IN A MIOCENE DEEP-SEA PLAIN: THE MARNOSO-ARENACEA OF THE NORTHERN APENNINES

F. RICCI LUCCHI[1]

ABSTRACT

Ricci Lucchi, F. (1978). Turbidite dispersal in a Miocene deep-sea plain: the Marnoso-arenacea of the northern Apennines. *In:* A. J. van Loon (ed.): Key-notes of the MEGS-II (Amsterdam, 1978). Geol. Mijnbouw, 57, p. 559-576.

Deposition in a typical 'flysch trough' (Marnoso-arenacea or Inner Basin of the Periadriatic Apennines) was interpreted in terms of the depositional system (slope-deep-sea fan-deep-sea plain). The basin fill is wedge-shaped and shows vertical and lateral grading; in its proximal portion, it forms a progradational turbidite 'suite' with upward increase in grain size, sand content and bed thickness indicating a transition from deep-sea plain via outer-fan to inner-fan environment. The outcropping part of the plain is 175 km long. Detailed studies of lateral variations of single beds show that:(1) sandy lobes from outer fans prograded into the plain over a distance of 25-50 km; (2) 30-40% of basin plain turbidites are more than 40 cm thick, and 15 out of 100 can be correlated axially over a distance of more than 125 km; (3) these single, huge turbidites (called Contessa-like beds) were introduced from different, lateral and axial sources but their dôminant dispersal was axial.

INTRODUCTION

The main tectonic phase of the Northern Apennines occurred in the Middle Miocene (Tortonian). It controlled the evolution of turbidite or flysch troughs which progressively shifted northeastward toward the Adriatic area, *i.e.* the interior of the African continental margin subject to compression (see SESTINI, 1970). Flysch units were deposited from Early to Late Miocene in the Periadriatic domain (RICCI LUCCHI, 1975-a); they were incorporated into the Apennines chain in various stages (Upper Miocene, Pliocene, Pleistocene) and now form its outer or Adriatic side.

Two main areas and stages of turbidite deposition can be recognized in the Miocene of the Periadriatic Apennines (Fig. 1): (a) the Umbrian Basin or Inner Basin, filled by the Marnoso-arenacea Formation (Langhian-Tortonian), and (b) the Foredeep, which was subdivided into minor basins to the North and a major basin filled by the Laga Formation (Tortonian-Messinian) to the South.

In the Northern Periadriatic area, the Umbrian Basin and the Foredeep merged (Emilia-Romagna region) as the axis of deposition, parallel to the tectonic strike, gradually migrated from SW to NE. In the Umbria and Marche regions, South of the Marecchia Line (see dashed line marking the Northern boundary of the basin plain in figure 1), growing structures of Apenninic trend (so-called Mesozoic Ridge) formed submarine sills separating not only the Umbrian Basin from the Foredeep but also minor turbidite basins within the Foredeep (RICCI LUCCHI, 1975-a).

The Marnoso-arenacea is a huge sedimentary body made of sandstones and mudstones (volume of about 28.000 km^3), consisting of a Northern foundered segment (buried by Ligurian or 'eugeosynclinal' tectonic units and recent sediments of the Po Plain), and a Southern outcropping segment separated by the Sillaro Line (see asterisk in Fig. 1). The outcropping part, or Marnoso-arenacea s.s., stretches for about 200 km parallel to the tectonic strike as a wedge tapering southeastward (Fig. 1). Its southwestern boundary is tectonic (overthrust of the Tuscan Modino-Cervarola sequence), the northeastern one is stratigraphic (with younger sediments in Romagna, and with older pelagic deposits in Umbria-Marche).

The maximum thickness of the Marnoso-arenacea is about 3,500 m; the rate of sedimentation averaged 15-45 cm/1,000 year (it increased with time: 75 cm/1,000 year in the Tortonian). The vertical trend of the sedimentation rate is match-

[1] Istituto di Geologia e Paleontologia, Universitá di Bologna, BOLOGNA, Italy.

ed by an upward increase of sediment grain size, sand content and layer thickness reflecting relative shallowing and offlap of proximal turbidites and slope deposits on basin centre turbidites. This evolutionary trend fits a progradational model of turbidite sedimentation (RICCI LUCCHI, 1975-b). Hemipelagic sediments including chaotic bodies cap the turbidite suite (except in Umbria, where they underlie or bound it laterally).

The main source areas of clastic supply were located along the Southern side of the emerged Alps judging from petrographic composition (CIPRIANI & MALESANI, 1963; RICCI LUCCHI, 1969, 1975-a) and subsurface stratigraphy (see AGIP wells in RICCI LUCCHI, 1975-a). Submarine channels cutting the Padan slope with North-South trend funneled sediment to the Piacenza area (subsurface sections show gravel bodies embedded in mudstones with an open-marine fauna) and built deep-sea fans which extended southeastward along the axis of the basin (Fig. 1). The feeding channels or canyons tended to migrate eastward with time. Other sources contributing no more than 2-3% of the total supply can be differentiated from the major ones both compositionally (RICCI LUCCHI, 1969-a; RICCI LUCCHI & PIALLI, 1973; GANDOLFI & ZUFFA, in prep.) and geometrically (through palaeocurrent analysis and correlation of individual deposits). These minor sources were activated at different times and points along the SW and SE sides of the basin, in a belt of 'intrageosynclinal' deformation involving older apenninic and alpine units. Only in some cases are stable depositional systems related to minor sources.

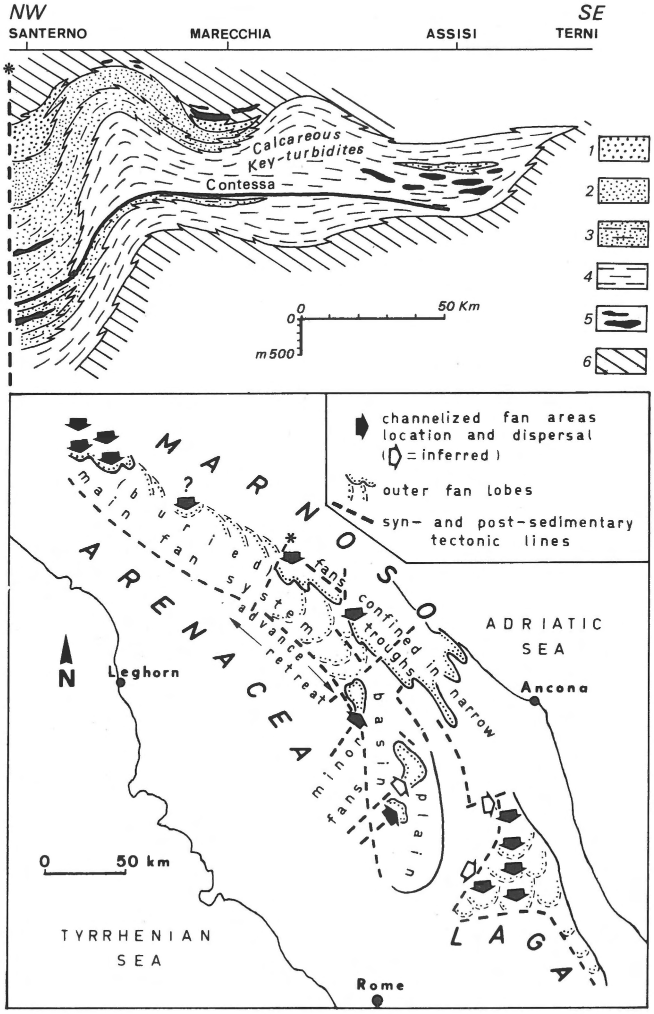

Fig. 1
Longitudinal cross-section of Marnoso-arenacea Formation and outline of basin with entry points of terrigenous clastics.
Legend: 1: channelized deposits of inner deep-sea fan; 2: outer-fan deposits; 3: deep-sea plain deposits with interfingering outer-fan lobes; 4: deep-sea plain association; 5: megaslumpings and olistostromes; 6: hemipelagic slope mudstones.

DEPOSITIONAL SETTING

In modern oceans, bathyal and abyssal plains (= deep-sea plains) form the largest, deepest and flattest areas of turbidite deposition. They are linked to shelf and coastal zones by submarine canyons, valleys and gullies cutting continental slopes and building submarine fans at their toes. A similar depositional model, expressed by distinctive lithofacies associations, can be applied to stratigraphic sections of ancient turbidite basins, particularly in the Apennines (MUTTI & RICCI LUCCHI, 1972, 1975, 1978). Of course, corrections and adjustments are needed when taking into account different tectonic and physiographic settings.

In summary, the model includes an environment of sedimentary transport and by-pass (slope-canyon) and two major environments of deposition: they are, in order of decreasing depth and distance from the shoreline, the *deep-sea plain* (*basin plain*) and the *deep-sea fan* (Fig. 16). The plain has no gradient (or a very low one) and is generally reached by turbidity currents of large volume but low concentration of sediment (mostly fine sand and mud). Due to the high momentum acquired on marginal slopes, the flows are essentially driven by inertia. The fan is a positive topographic feature gently sloping into the plain: it is subdivided into a peripheral area devoid of sizeable channels[2] (*outer fan*) and an innermost channelized and more elevated area (*inner fan*). The inner fan is occupied by a more or less stable system of distributary channels branching out from an apical fan valley. Sand and coarser materials are both trapped within the channels (especially upon their abandonment) in the inner fan, and accumulated in lenticular to tabular bodies (depositional lobes) in the outer fan. The outer fan lobes are inferred to be aligned with the mouths of inner-fan channels. Mud and thin-bedded, fine turbidite sand are deposited in the inter-channel

[2] *Channel* is used here for a relatively large, deep and stable element of a depositional system. In modern submarine settings, its lower size limit depends upon the resolution power of instrumental records. In terms of depth, 2 metres should approach this limit, and are taken as reference for defining channels in ancient turbidite and related sediments.

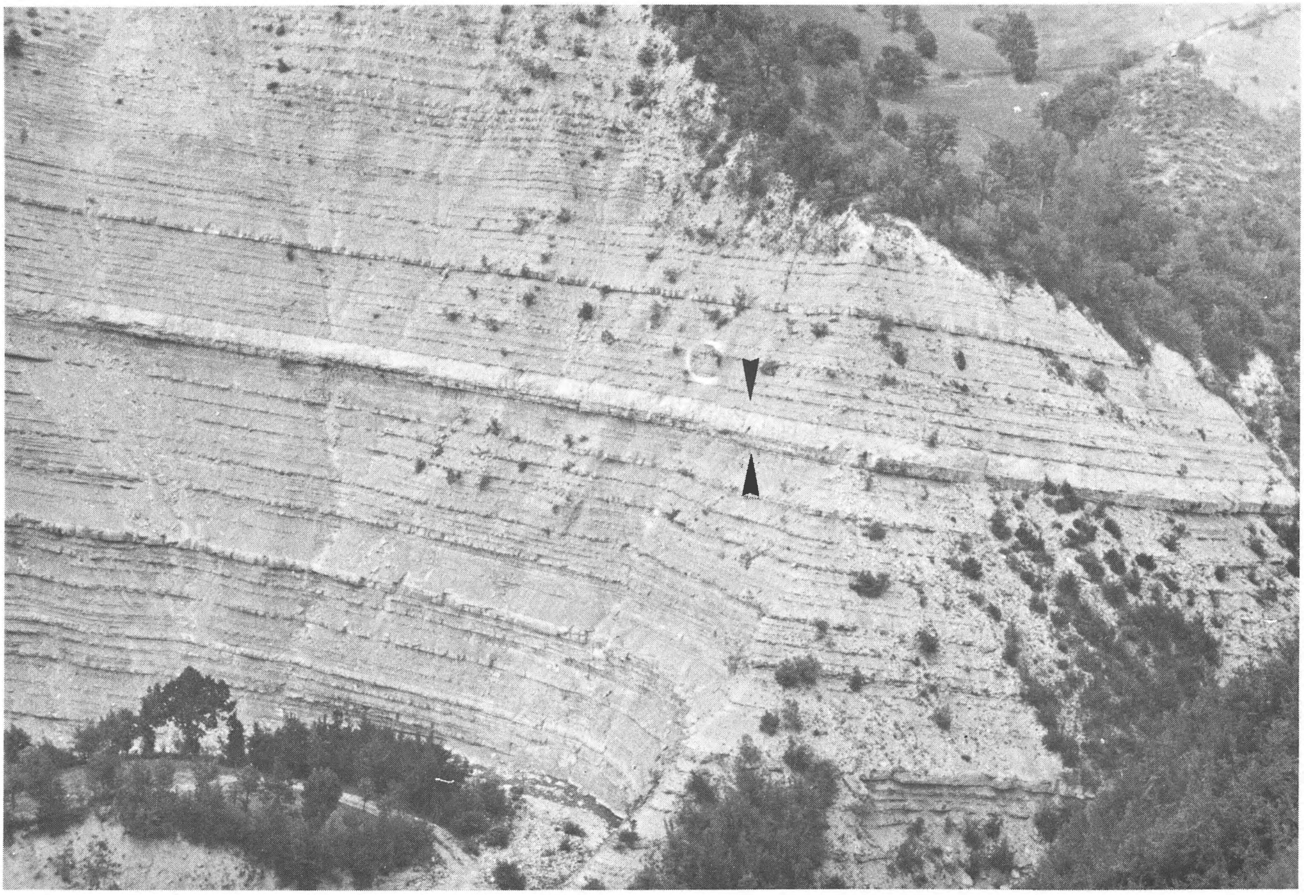

Fig. 2
Panoramic view of deep-sea plain turbidites; arrows frame a Contessa-like layer (bioclastic turbidite or 'colombina').
Savio valley, Romagna Apennines.

area of the inner fan (as a result of overbanking) and in interlobe to fringe areas of the outer fan (as a result of lateral expansion and loss of energy of the flows).

The plain and fan are flanked by the *basin slope* cut by channels or canyons; no stable accumulations of coarse clastics are found on it, but only variable thicknesses of hemipelagic muds. The slope is characterized by instability and slumping or sliding of blocks, slices and chaotic masses.

The basin-plain association of facies forms the bulk of the Marnoso-arenacea. It is mainly represented in Umbria, but extends to the whole length of the formation at several stratigraphic levels (mostly during the Serravallian). The extent of the plain was intermittently reduced by deposition of sandstone lobes advancing from Northwestern fans over distances of 30-50 km (Fig. 1), by uplifting and tilting of some areas forming intrabasinal highs and slopes, and by accumulation of large chaotic masses. Basin-plain deposits are less tectonized than more marginal deep-water sediments, and form spectacular outcrops in terms of size and quality (Fig. 2). In these respects, and also because the stratigraphic relationships with adjacent facies are better preserved in comparison with other flysch basins, the Marnoso-arenacea offers the best opportunities for the study of this class of deep-water deposits.

As far as the absolute depth of the plain is concerned, it has been roughly estimated in the range 1,000 - 3,000 m on the basis of geometrical considerations (e.g., inferred distance of source area versus minimum gradient needed by gravity transport), absence of skeletal benthic remains, and ichnofacies (*Nereites* association: SEILACHER, 1967).

THE DISPERSAL PROBLEM

In their first stage, studies of turbidite basins were mainly concerned with the long-debated item of deep versus shallow-water deposition and provenance of the detritus (kind and location of source areas, marginal repositories, triggering mechanisms of resedimentation, lateral versus longitudinal input, etc.).

As far as provenance and dispersal are concerned, two main approaches were used: analysis of sandstone composition, and analysis of palaeocurrents. The geometrical criterion, widely employed in nearshore, deltaic and continental facies, was more neglected in turbidites partly because of difficulties in-

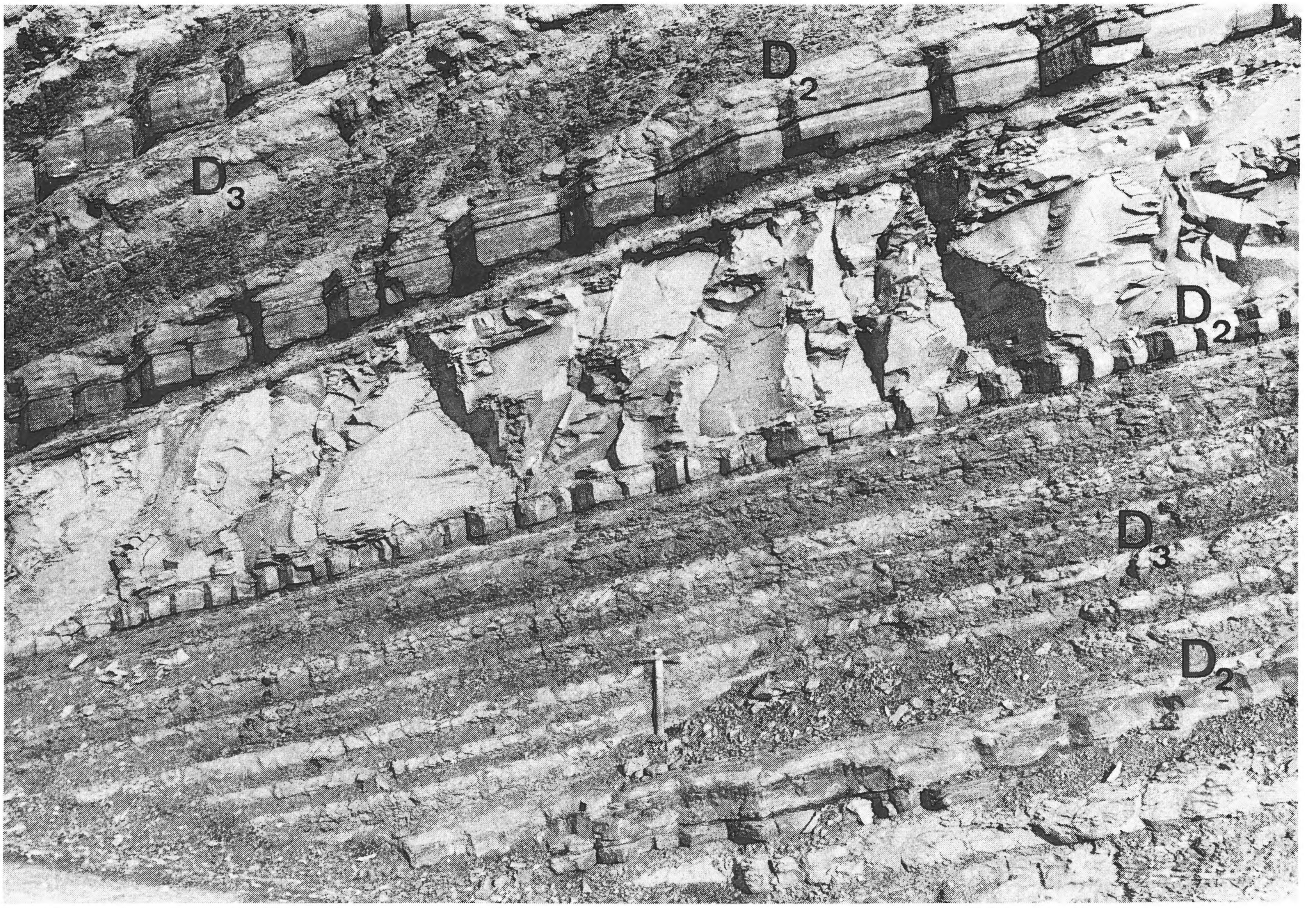

Fig. 3
Typical facies of the deep-sea plain association. Pelitic-sandy turbidites of facies D_2 occur in the thin-bedded variety (below hammer) and the thick-bedded or Contessa-like variety. Pelitic turbidites of facies D_3 alternate with hemipelagites (beds of lighter colour). The light D_2 layer is a calcareous 'colombina' with a north-westward palaeocurrent direction.

herent to flysch formations (limited outcrops, severe tectonization) and partly because of scarce accessibility to modern deep-water environments and lack of suitable models. Based on the bedding pattern at outcrop scale and hydraulic simulation, the most accepted view of a turbidite layer was a regular, extensive, fan-shaped sheet (BOUMA, 1962; KUENEN, 1964). ENOS (1969) confuted this model by analysing the lateral continuity of beds in the Chloridorme Formation: the physical continuity of this large body is not matched by individual layers. They cannot be traced downcurrent for more than a few kilometres and show strong and irregular thickness variations.

The geometrical approach in the study of turbidites was re-evaluated in the seventies after a major advance in knowledge of physiography and sediment distribution in modern oceans. Attention was focused on size, shape, internal organization, lateral variability, bedding surfaces etc. of sedimentary bodies in favourable exposures of Circum-mediterranean chains (MUTTI, 1969, 1974; RICCI LUCCHI, 1969-b). A better picture of dispersal patterns was obtained by integrating these data with composition and palaeocurrents (see, for example, RICCI LUCCHI, 1975-c, for the Umbrian Basin).

As said above, the largest part of the Marnoso-arenacea body is constituted by basin-plain sediments; their general or average characters will be described first, then the major geometrical units will be emphasized. They are represented by: (1) individual turbidite layers[3] of great thickness (more than 40 cm, up to 16 m) and basinwide extent (they are defined as Contessa-like deposits); (2) composite or multilayer sandstone bodies formed by bundles of thick to massive sandstone or sandstone-mudstone layers with a high sand/pelite ratio interfingering downcurrent with more pelitic turbidites; (3) deformed and chaotic bodies of intra- and/or extrabasinal materials emplaced by large-scale slumping and sliding (megaslumpings).

Interpretation and discussion of the described features will follow with regard to the dispersal problem.

[3] The term *layer* is given the meaning of single depositional event. The most common turbidite layer is a lithological couplet, consisting of a lower sandy portion (sandstone *bed*) and an upper pelitic portion (mudstone, shale or pelite *bed*). A turbidite of uniform lithology can be qualified either as a layer or a bed.

THE DEEP-SEA PLAIN FACIES-ASSOCIATION

Examples of ancient deep-sea plain sediments were illustrated by MUTTI & RICCI LUCCHI (1972, 1978) from Cretaceous to Miocene formations of the Apennines, the Eocene Hecho Group of the Southern Pyrenees, etc. (see also MUTTI, 1977; RICCI LUCCHI, 1975-a, b; PAREA & RICCI LUCCHI, 1975; JOHNS & MUTTI, in press). Some aspects of these deposits (e.g., lateral continuity of layers, vertical sequence, palaeocurrents, distinction between hemipelagic and turbiditic portions, depth of deposition) were dealt with by HESSE (1965, 1974, 1975), PAREA (1975), SCHOLLE (1971), and SAGRI (1972, 1974) mostly in the helminthoid flysch of the Alps and the Apennines.

The main characters of the Marnoso-arenacea basin-plain deposits are summarized below.

General

(1) Turbidites form 80-90% of the total volume, hemipelagites the remaining part (Fig. 4); vertical alternation of the two deposits occurs with remarkable regularity in comparison with the deep-sea fan environment and gives the basic rhythm or depositional theme of the deep-sea plain association (see Fig. 3).

(2) Turbidites have a low to nil sand content (sand/pelite ratio 0-1) represented by fine-grained, well-laminated sandstone; distinction can be made between sand-bearing turbidites (sandstone-mudstone couplets) and pelitic or muddy turbidites, corresponding, respectively, to facies D_2 and D_3 of MUTTI & RICCI LUCCHI (1975) (see Table I). They are comparable with the incomplete sequences of BOUMA (1962) and the distal turbidites of WALKER (1967).

(3) In comparison with the outer-fan turbidites, the average thickness of the layer is greater and the sandstone/mudstone ratio is smaller (compare figures 11 and 13 in RICCI LUCCHI, 1975-b).

(4) The statistical thickness distribution of turbidites is not random (RICCI LUCCHI & VALMORI, in press). Two main groups of layers can be made: thin-bedded turbidites, or TBT (MUTTI, 1977), and thick-bedded turbidites, or Contessa-like layers. TBT's are defined as layers thinner than 40 cm for this basin, and are regarded as the normal sedimentary events (ignoring hemipelagic deposition): in fact, they predominate by frequence (55-80%). Contessa-like layers (thicker than 40 cm) represent a higher bulk volume (65-85%, see Fig. 7) but are not frequent, and are qualified as exceptional, or highly catastrophic events.

(5) Thin- and thick-bedded turbidites vertically alternate in an

Table I
Typical facies of deep-sea plain turbidites in the Marnoso-arenacea Formation (see Fig. 3)

D_2	D_3
Sandstone-pelite couplet with low sand/pelite ratio (<1) and extremely variable thickness (1 cm to several meters). Grand mean = 40-60 cm (sandstone bed = 20-40 cm); mean of thin beds = 16-18 cm (sandstone = 4-5 cm); mean of thick beds = 120-140 cm (sandstone = 50-60 cm).	*Pelite* (clayey to limy mudstone, shale) corresponding to division e of Bouma sequence. Average thickness = 9-13 cm with low variability (0-40 cm).
Bedding planes: sharply defined, plane-parallel; minor irregularities in sandstone beds due to load casts, ripple marks, local discontinuity. Sandstone-pelite transition is gradual to abrupt (usually ripple-moulded in the latter case).	*Bedding planes:* plane-parallel, recognizable only when hemipelagites and/or sandstones are interbedded (hemipelagic mudstones are characterized by coarser size and lighter colour due to higher $CaCO_3$ content.)
Texture: sandstone bed is constituted by fine to very fine silty sand, medium and medium-coarse sand are exceptional (base of thickest layers). Subtle vertical grading, often localized at sandstone-pelite transition. Sorting is moderate to good, silty-clayey matrix is present (at least 10%). Mica flakes and carbonaceous matter are abundant and selectively concentrated in laminae. Pelite bed is made of sandy silt, clayey silt and silty clay grades (thinner beds are uniform, thicker ones gently graded).	*Texture:* uniform (in thinner beds) or slightly graded (sandy-clayey-silt, clayey silt, silty clay). Sometimes, one or few mm-thick laminae of siltstone at the base. Scattered mica flakes and vegetal debris.
Structures: delicate current marking at the base, frequently associated with burrows. Internally, the sandstone is completely and thinly laminated. Geometry of lamination: plane-parallel, wavy, cross-lamination (ripple drift, climbing ripple), convolute. Each type occurs alone or in various combinations and vertical sequences with the others.	*Structures:* the bed is structureless apart from occasional burrows. When the basal siltstone film is present, wavy laminae and very low-amplitude, often discontinuous ripples are associated with it.
Bouma sequence: incomplete, base-missing types with predominance of T_{c-e} (which is typical of thin layers) over T_{b-e} (more common in thick layers). Upper parallel laminae (d division) are often lacking (abrupt transition to pelite).	*Bouma sequence:* T_e (sandstone-missing).
Transport-deposition mechanism: low-density, or dilute turbidity current exerting traction during deposition of sand.	*Transport-deposition mechanism:* low-density turbidity current (more dilute than in D_2) with decaying turbulence and waning energy.

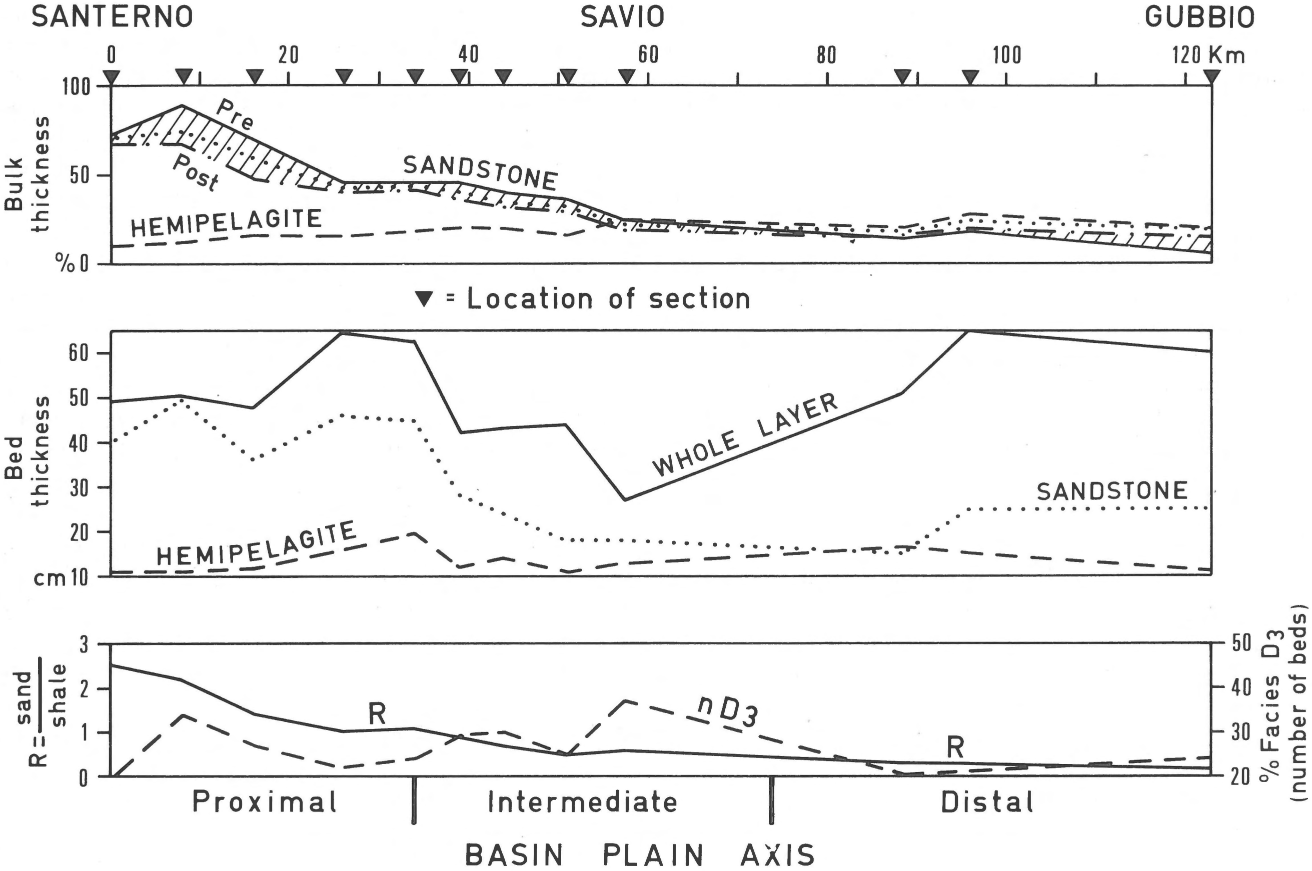

Fig. 4
Downcurrent changes of stratofacies along the axis of the Marnoso-arenacea deep-sea plain. Data from stratigraphic sections of figures 5 and 6.

apparently random, non-cyclical pattern, in contrast with deep-sea fan deposits (MUTTI & RICCI LUCCHI, 1972, 1978; RICCI LUCCHI, 1975-b).

(6) Layers of different composition and palaeocurrent direction are also interbedded with no ordered sequence; compositional changes are not matched by facies changes.

(7) The palaeocurrent pattern is strictly parallel to the basin axis regardless of composition and provenance; two opposite modes of unequal weight are present, the dominant one (toward SE) being related to the main sources of the basin, the secondary one (toward NW) to the minor sources.

(8) The parallelism and continuity of the bedding is impressive at outcrop scale (also in very extensive exposures, see Fig. 2). Lateral thickness changes can only be checked by correlation of detailed sections over long distances (kilometres or tens of kilometres). Analysis of correlated sections (RICCI LUCCHI & VALMORI, in press) shows that about 40% of thicker layers are physically continuous for at least 120 km along the basin axis (Fig. 7) and 25-30 km across it (see an example in Fig. 8). Correlation of TBT's is more difficult (more layers appear in downcurrent sections due to lateral overlap) but in many cases the same degree of continuity can be demonstrated. Downcurrent thickness changes are in the order 0.7-2.0 cm/km; across-current, they are two or three times greater and 25-35% of TBT's tend to disappear within 25-30 km. This suggests an elongated, tongue-like shape. Furthermore, the trend of change is interesting and rather unexpected with respect to conventional models: the average layer (Fig. 4) shows a proximal and a distal thickness maximum (proximal and distal being referred to the layer source) separated by a zone of minimum with fluctuations. Accumulation of sand caused the proximal maximum, accumulation of mud the distal one. The sand/pelite ratio, on the other hand, decreases quite evenly downcurrent (Fig. 4). Inspection of figures 5 and 6 (where only thick layers are reported) reveals other geometric peculiarities: firstly, many layers thicken down-current in the proximal segment of the plain; this trend is more common for pelite beds but is shown also by sandstone beds. Secondly, the pelite bed often keeps or even increases its thickness within the distal plain. These variations are in contrast with the common wedge-shaped model of a turbidite (KUENEN & MIGLIORINI, 1950; BOUMA, 1962). Finally, examination of more detailed cross-sections (not shown here) shows that both sandstone and pelite beds, in spite of their continuity, are affected by irregular thickness changes (within 90% of maximum or average thickness) and local discontinuities (typical is the pinch-out of turbiditic pelite into hemipelagite).

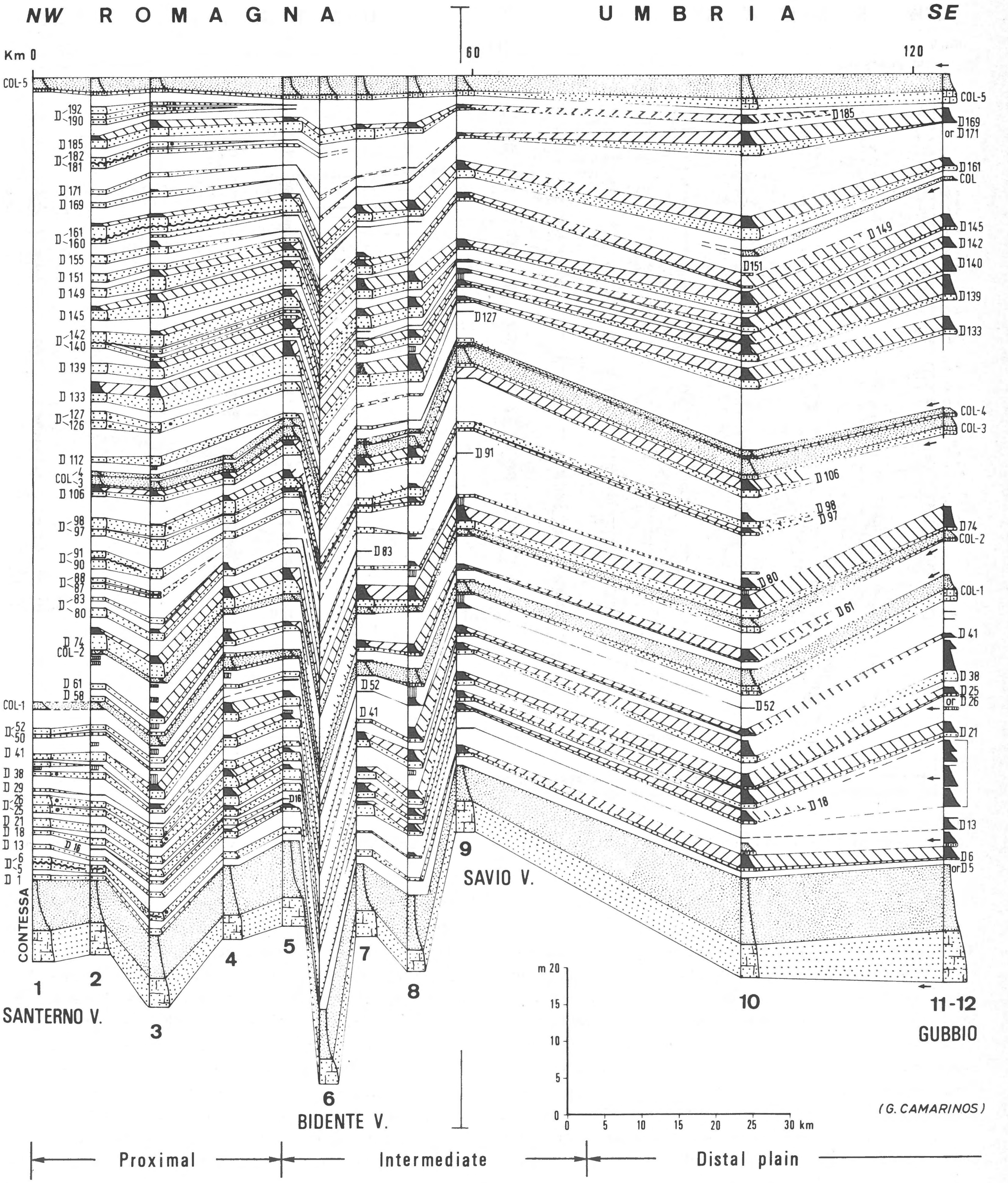

Fig. 5
Longitudinal correlation of individual turbidite layers thicker than 40 cm. Post-Contessa section including five 'colombina' markers (COL-1 to 5). Notice the absence of multilayer sandstone bodies in the proximal segment. Pelitic beds are black (in columns), obliquely hatched or finely dotted (in Contessa and 'colombine' layers). Vertical hatching indicates levels dominated by hemipelagites. Blank areas include thin-bedded turbidites and hemipelagites. A larger dot within the sandstone is for slurry with abundant clay chips. Palaeocurrents from NW to SE except for arrowed layers.

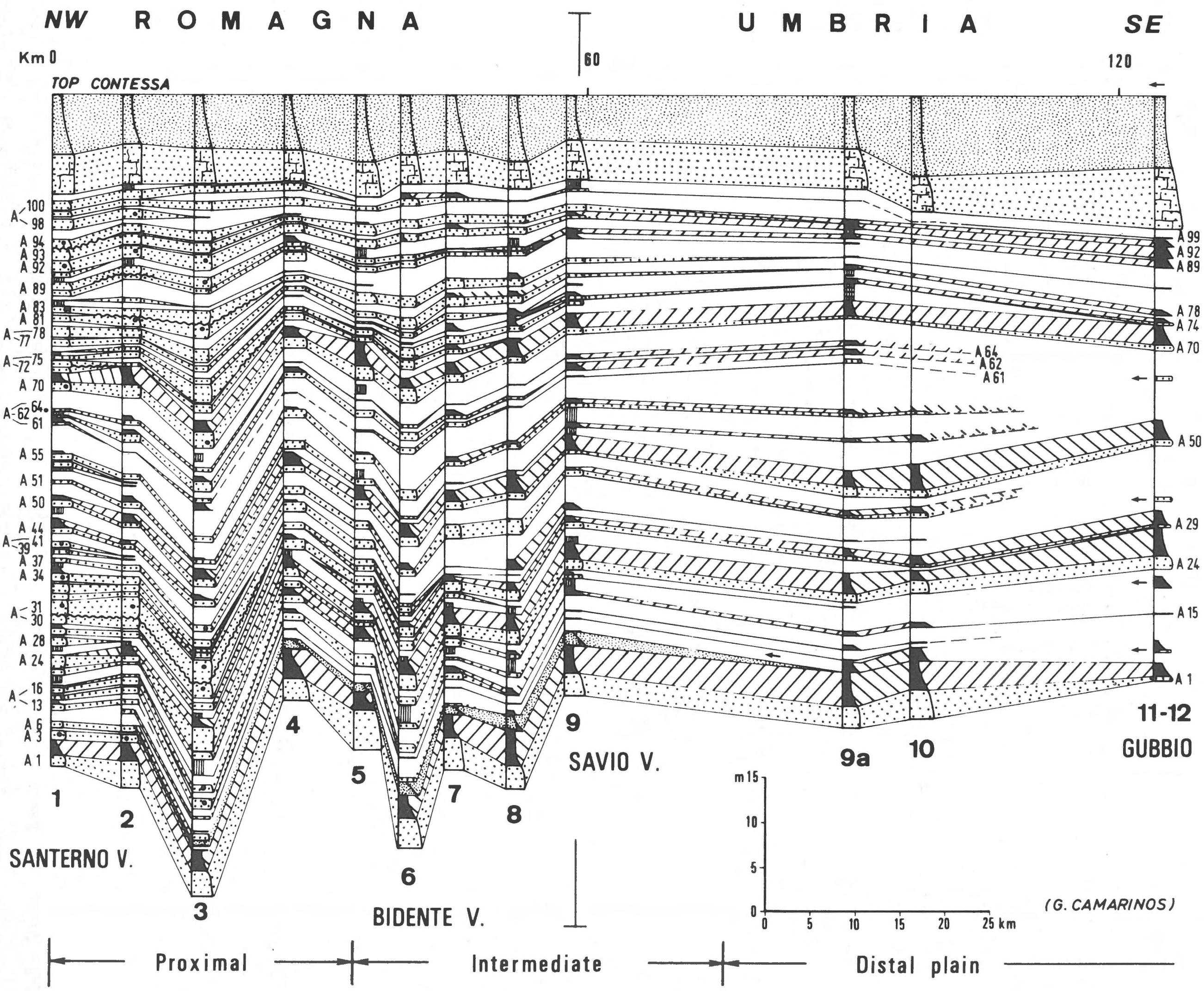

Fig. 6
Longitudinal correlation of individual turbidite layers thicker than 40 cm. Pre-Contessa section showing sandstone bodies in the proximal segment. Refer to figure 5 for symbols.

Contessa-like layers

This qualification derives from the name of the first recognized example of marker bed (RICCI LUCCHI & PIALLI, 1973) and is now used in a purely geometrical sense for thick to very thick layers of basinwide extent with no implications of provenance (Contessa s.s. was supplied by a minor source as shown by its 'anomalous' composition: see RENZI, 1964). This type of deposit is highly characteristic of the Marnoso-arenacea deep-sea plain and probably of many others in alpine geologic settings. It is important in many respects: (1) as a stratigraphic and structural marker (being a turbidite, it provides a perfect time-line); (2) as a multi-purpose palaeogeographic indicator (its size and geometry being influenced by the original length and width of the plain, local bottom topography and palaeocurrent direction); and (3) as a spy of the tectonic control on the sedimentary and geometric evolution of the basin (relation with instability of marginal areas, large-scale collapses of shallow-water sediments, activation of sources and their connection with the deep-sea, etc.).

In essence, Contessa-like layers are tabular or sheet-like bodies (Fig. 8) whose areal changes of texture, sedimentary structures and sand/pelite ratio are subtle and gradual (see PAREA & RICCI LUCCHI, 1975, for sedimentological documentation). Within the layer, whose external shape is mostly determined by deposition of mud, the geometry of the sandstone bed may vary according to the models of figure 9: simplifying, there are two varieties of longitudinal shapes, a tabular or slightly wedging sandstone, and a more lenticular sandstone. The first one is capped by a relatively thick pelite also in the most proximal area, as can be seen in figures 5 and 6. The thickness of the sandstone can be as great as 7 m, of the pelite 9 m; the outcrop area being 3,500 to 4,750 km², the layer volume ranges between a minimum of 1.5 and a maximum of 35 km³.

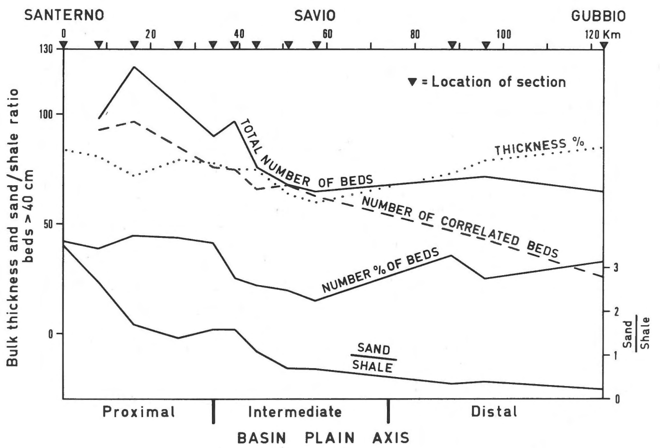

Fig. 7
Diagram showing longitudinal variations of Contessa-like deposits. Main transport direction from NW to SE. Data from sections of figures 5 and 6. Number % of beds is referred to the total number of turbidites in the section.

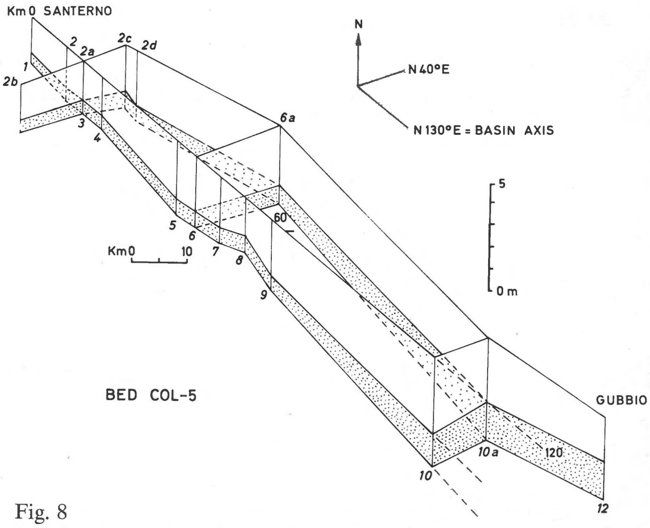

Fig. 8
Fence diagram of a major Contessa-like turbidite. Palaeocurrent from SE to NW. Notice the very low thickness gradients.

These figures are conservative because most layers extend beyond the correlated sections and no corrections for mud compaction were made. If we extrapolate the linear thickness gradients calculated for these layers from end to end of the longitudinal and transverse cross-sections, we get impressive values for their original sizes: length = 120-600 km, width = 50-200 km. The higher figures are undoubtedly exaggerated as the assumed linear gradients are unjustified in the marginal areas of the deposit. In any case, it seems clear that it occupies the whole available area of the basin plain.

In their upcurrent portions, most Contessa-like turbidites display a proximal character, i.e. an erosional base, chaotic intervals and large clay chips within the sandstone, a moderate to high (⩾1) sand/pelite ratio, a coarse basal texture (up to pebble grade), a structureless, graded or faintly laminated lower division, and a higher rate of downcurrent thinning. The layers are here comparable with the proximal turbidites of WALKER (1967) and facies B or C of Mutti and Ricci Lucchi. This implies that the 'distal' features, although typical of basin-plain turbidites, are not to be found in every layer or part of the plain.

Most Contessa-like layers bear a composition and a palaeocurrent direction indicating supply from the main sources and a southeastward dispersal: the sandstone is a quartz-lithic wacke rich in feldspars and mica. Clastic dolomite is present; it should be diagnostic of an alpine origin (CIPRIANI & MALESANI, 1963).

Contessa-like layers derived from minor sources were first correlated and used as stratigraphic markers; they stand out in the field (see Figs. 2 and 3) because of their higher carbonate content with respect to predominating 'alpine' turbidites. Stratigraphically (see Fig. 10), the Contessa layer separates older (pre-Contessa) turbidite markers bearing a variable amount of bioclastics, from younger (post-Contessa) ones composed almost exclusively of bioclastics (carbonate turbidites whose local name is colombine).

Pre-Contessa layers, and the Contessa itself, are fossiliferous quartz-lithic sandstones grading into marly-clayey mudstones; the colombine, present also below the Contessa but largely predominating above, are more or less arenaceous biocalcarenites (65-100% $CaCO_3$) capped by light-colour, calcareous-marly mudstones (Figs. 2 and 3). The coarsest fraction of these bioclastic turbidites is made of shallow-water benthos, while foraminifera constitute the majority of fine sand- and silt-size particles. Almost all organisms are of penecontemporaneous origin. The terrigenous fraction, judging

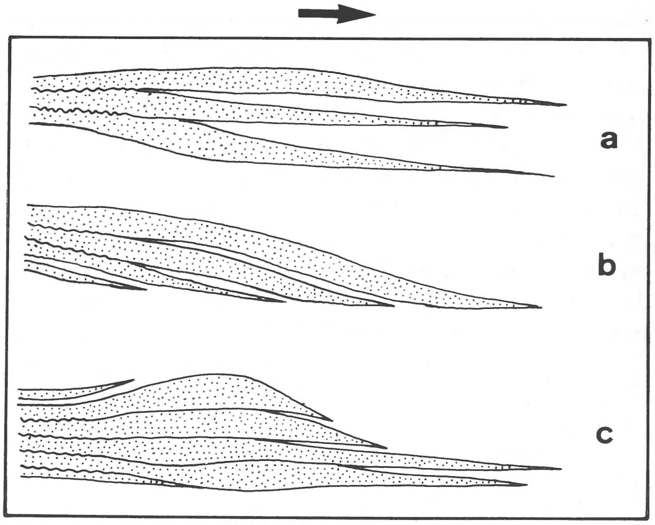

Fig. 9
Longitudinal models of deep-sea plain turbidite layers. Dashed lines indicate thickness of pelite in case of ponding. Case (a) represents only Contessa-like turbidites with no deep-sea fan at their upcurrent end. Other cases refer to both thin- and thick-bedded layers with possible connection - always present in (c) - to a fan body.

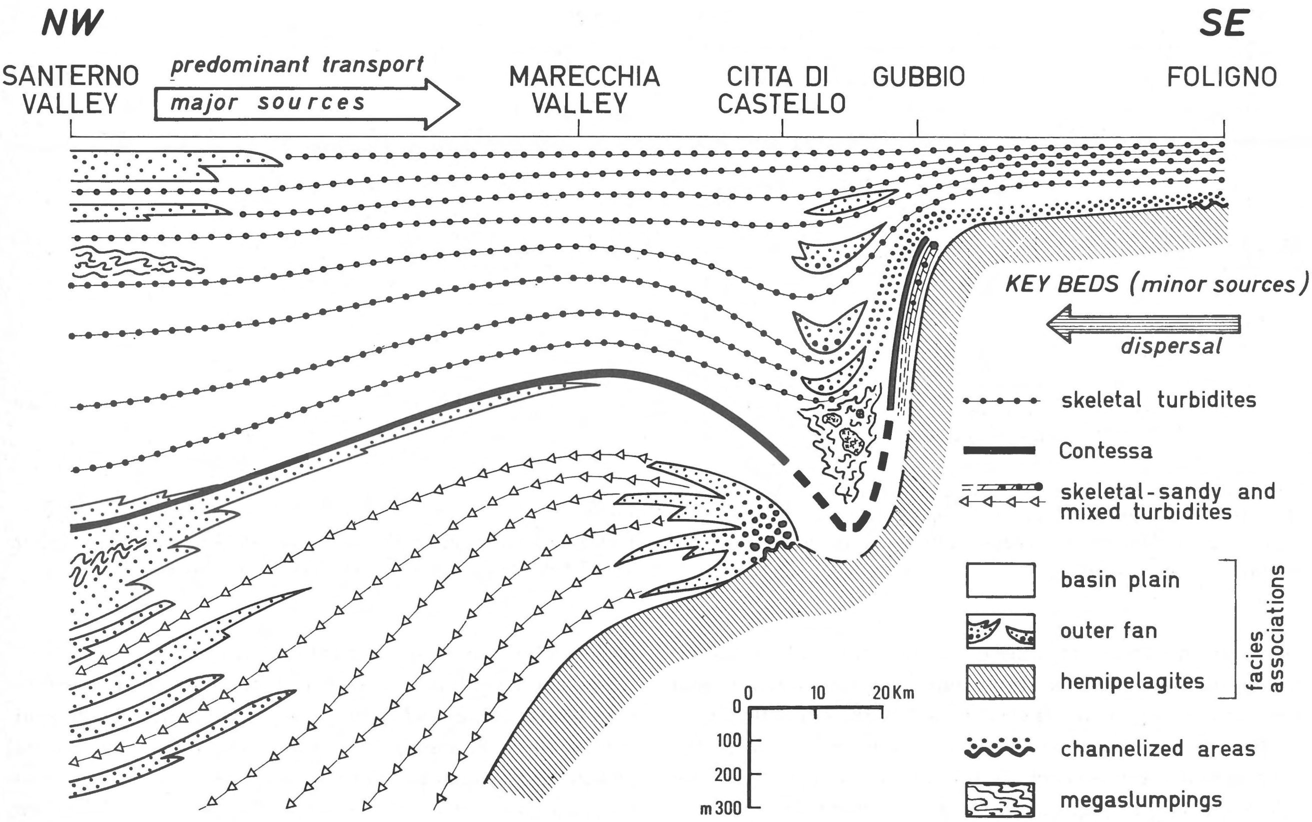

Fig. 10
Schematic longitudinal cross-section of the Marnoso-arenacea basin plain showing intercalation of sandstone bodies, megaslumpings, and calcareous Contessa-like turbidites used as key beds (time lines). Roughly, the pre-Contessa section is Langhian, the post-Contessa Serravallian.

from its tendency to disappear upcurrent, should have been reworked by erosion of turbidity currents from underlying basin-plain deposits.

Petrographical analyses of pre-Contessa and Contessa calcareous sandstones are still lacking (GANDOLFI & ZUFFA, in prep.). However, the gross composition is markedly different from that of the common type of Marnoso-arenacea sandstone: scarcity of mica, abundance of green clasts of various sizes and composition (clay pebbles, pellets of glauconite, grains of serpentinite and chlorite) can be noticed beside the calcareous-fossiliferous content. Moreover, palaeocurrent directions are opposite (toward NW) to the general trend, and the layers can be traced upcurrent (by correlation or walking out) as far as their entry points in the basin (Figs. 10, 12 and 13). Pre-Contessa key layers have two distinct entry points: one is located in Northern Umbria (Città di Castello area), the other near Gubbio (Northeast of Perugia). The Contessa also starts from the Gubbio area, while the colombine can be followed to the far end of the plain and are particularly developed in number and thickness near Foligno. The colombine turbidites reach the maximum length (190 km) known for individual layers in this basin, that is almost the whole length of the formation.

It is worth pointing out that all the calcareous turbidites described above, with the exception of Pre-Contessa ones North of Città di Castello, are included in deep-sea plain deposits or pass into slope facies (chaotic mudstones with olistoliths of shelf skeletal limestones) at their upcurrent terminations. The exception consists in a lateral passage to sandstone bodies interpretable as deep-sea fan deposits (Città di Castello Fan, see Figs. 10 and 12).

Composite sandstone bodies

These units are formed by the direct superposition of thick, sandy turbidites (sandstone beds or couplets with high sand/pelite ratio) showing proximal characters as those already described for upcurrent portions of Contessa-like layers; erosional surfaces between individual beds and absence of hemipelagic interbeds are typical features of their stratigraphy.

The maximum thickness of the sandstone bodies ranges from 3 to 15 m in the sections of figure 6; it does not occur at the proximal end (Santerno section) but some distance downcurrent (15 km in most cases, see section 3). The resulting longitudinal shape is an asymmetrical lens with gentler thinning on the downcurrent side (see idealized models in Fig. 11). The longitudinal rate of thickness change is 2-80 cm per km, that is three to forty times greater than in most individual layers of the common basin-plain association. The lenticularity increases across-current: thickness gradients may be as high as 180 cm/km (RICCI LUCCHI & PIGNONE, in press); the bodies were thus elongated in plan. As for their sizes, estimation primarily depends on where the boundaries are placed; sandstone bodies, in fact, interfinger with thinner and/or muddier layers of the common basin-plain type.

Let us see the internal organization of the bodies (Fig. 11): vertically, the thickness of constituent layers may remain constant, increase upwards or fluctuate; laterally, in particular downcurrent, the body gradually looses its identity by attenuation of erosional surfaces, thinning of sandstone beds, and thickening of hemipelagites, pelitic beds and TBT's. Noticeable is the fact that some layers wedge out or thin considerably within 20-50 km while others extend to the entire plain. This different behaviour cannot be predicted by analysis of facies and sequence in proximal sections, being only revealed by correlation. Also difficult is the prediction of one or the other model of figure 11 on the basis of single vertical sequences, except for case (b) where a thickening-upward trend is matched by an imbricate or offlapping attitude. The downcurrent boundary of the sandstone body can be defined as a transitional zone where most sandstone beds record their maximum rate of thinning and the sequence assumes the typical aspect of the basin-plain association. In this view, the outcropping length varies between 20 and 50 km, the extrapolated length between 150 and 250 km. As for the width, available data do not derive from the bodies of figure 6 (due to lack of outcrops for transverse correlation) but from a younger one exposed in the Santerno valley (RICCI LUCCHI & PIGNONE, in press): the physically observable width is 6-7 km, the extrapolated width 30-50 km.

All sandstone beds of a body have the same composition, in contrast with the vertical variations observed in typical basin-plain sequences. Palaeocurrent distribution is also unimodal and parallel to the basin axis with some more dispersion than in more pelitic basinal layers.

The above description refers to sediments emplaced from NW to SE, i.e. related to the main sources; figures 5, 6 and 10 show the repeated occurrence of these bodies below the Contessa layer and their disappearance above it.

Similar bodies of smaller size crop out in Umbria near Sansepolcro-Città di Castello (Pre-Contessa sequence) and Perugia (post-Contessa). Sandstone beds here show lateral-radiating palaeocurrents and 'apenninic' composition, that is evidence of a lateral input from minor sources.

Megaslumpings

Submarine slumping and sliding are common phenomena in all turbidite basins and involve materials of various origin and degree of consolidation. Volume, shape, composition and style of deformation of resultant accumulations are very variable. Attention is focused here on the large-scale slumped bodies (megaslumpings) which stretch for as much as 20 km

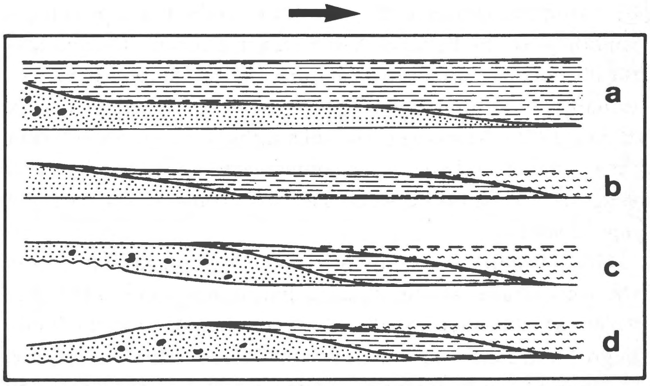

Fig. 11
Longitudinal models of multilayer sandstone bodies interbedded with the pre-Contessa deep-sea plain sequence (from figures 5 and 6). Maximum length is about 50 km. See text for discussion.

parallel to the axis of the Marnoso-arenacea Basin, with a maximum thickness of some hundred metres and a lenticular to tabular shape. These chaotic bodies are composed of intra- and/or extrabasinal sediments, and sometimes also include slabs of ophiolites or other rocks. Extrabasinal materials are remnants of formations originally emplaced in the inner parts of the Apennines geosyncline (Ligurian domain; see also Tuscan-Emilian units, allochthonous units, Argille Scagliose, etc.).

Megaslumpings affected the basin plain to various degrees; part of them are sandwiched between deep-sea plain sediments, others are embedded by slope deposits which in their turn overly a deep-sea plain sequence. It is interesting to notice that megaslumpings interbedded with basin plain layers are also made up of the same type of sediments with minor amounts of slope and shelf facies. They are found at various levels of the succession in Romagna and, more sporadically, in Northern Umbria (e.g., West of M. Nerone). Megaslumpings included in slope deposits (hemipelagic mudstones) are composed mostly of slope-shelf sediments; they crop out extensively on both sides of the Marecchia valley (Verghereto-Badia Tedalda area, age of emplacement: Serravallian-Tortonian) and in Umbria E-NE of Perugia (age of emplacement: Serravallian, early post-Contessa). In the first area, slumping definitely interrupted the deposition of turbidites, whereas the deep-sea plain environment was restored after slumping in the latter one. Extrabasinal masses are associated with both classes of megaslumpings with a preference for the slope type.

The direction of movement of slumped masses can be detected by careful investigation of geometric characters as the orientation of slump-fold axes or shear planes, but inconclusive or contradictory evidence often results. Clearer indications come from the composition of chaotic materials, particularly when shallow-water penecontemporaneous sediments or older extrabasinal units are present. These materials necessarily derived from the inner Apennines and related shelf areas, that is from the Southwest.

An interesting example of shelf-derived materials is given by conglomeratic-shelly olistoliths embedded in megaslumpings of the Perugia-Assisi area in Umbria. Though texturally coarser and more immature, the sediment is compositionally very similar to the Contessa sandstone (RICCI LUCCHI & PIALLI, 1973). Moreover, the olistoliths were emplaced after the Contessa, and near its proximal termination, which clearly suggests a relation between the two events and a common lateral source.

Other peculiar olistoliths associated with megaslumpings in the whole basin are the 'Lucina limestones' (RICCI LUCCHI & VEGGIANI, 1967). Internally, they are chaotic to a maximum degree and consist of a mixture of different sediments (clastic, carbonate) and organisms (brackish-water molluscs and planktonic foraminifera!). The curious faunal assemblage, though obviously reworked, seems to be of intrabasinal origin, as the foraminifera correspond in age to those of the in-place sediments framing the megaslump.

THE DISPERSAL OF SEDIMENT IN THE BASIN PLAIN AND ITS CONTROLLING FACTORS

The interpretation of the sedimentary units described above, is discussed here in relation to basin geometry and topography, depositional environments and sediment distribution. Reference is made to figures 12-15 for the development of the dispersal pattern.

Basin geometry

Fig. 10 shows that turbidite deposition started only in post-Contessa time South of Gubbio; moreover, it kept a slow pace in pre-Contessa time between Città di Castello and Gubbio. These facts imply that a raised area receiving slow hemipelagic deposition existed South of Gubbio in Pre-Contessa and Contessa time, and a gentle slope with reduced turbidite sedimentation connected it with the deeper plain extending North of Città di Castello. Later on, the submarine high was downwarped and the basin plain reached its maximum length.

This evidence of synsedimentary vertical movements must be put in relationship with the lateral sedimentary input and gravity sliding occurring in the same area. This stratigraphic context suggests that a transverse fault (or fault system) delimited the basin plain to the SE and exerted a major control on the sedimentation not only by influencing the topography of the basin but also by providing routes (structural channels?) for funneling sediment through the adjacent unstable slope. In Northern Umbria, judging from the uniform thickness of the representative cross-section encompassing the Contessa (Figs. 5 and 6), the basin plain had a smooth and flat topography. In Romagna, some differentiation occurred instead.

Firstly, the Romagna - Umbria boundary, corresponding to the Marecchia Line (section 9 in Fig. 6), was an area of reduced sedimentation, and this condition persisted and became more pronounced with time (compare with Fig. 5). A

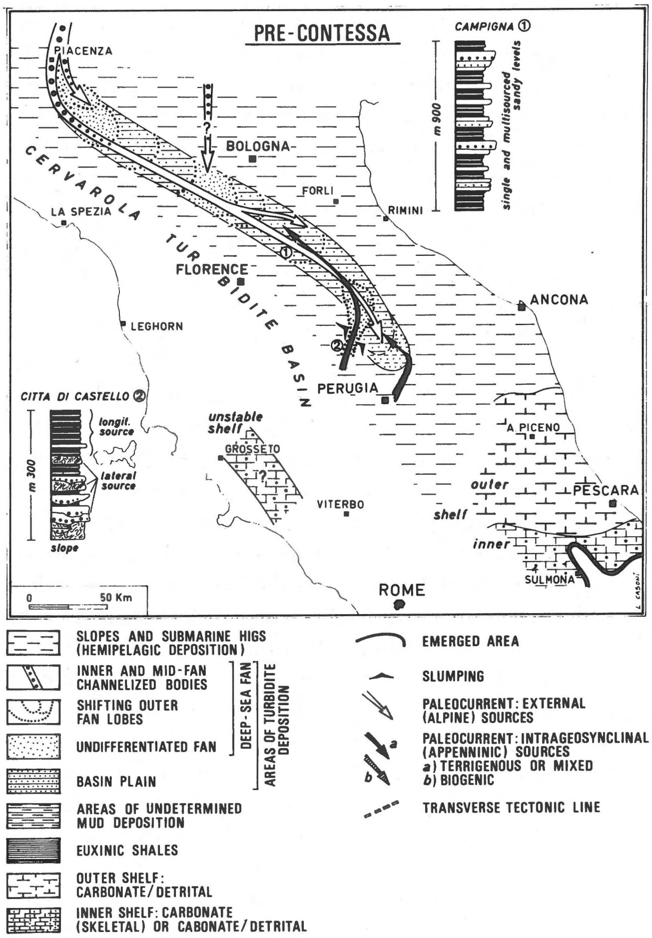

Fig. 12
Dispersal in the first stage of the Marnoso-arenacea sedimentation: longitudinal-bymodal pattern. Length of the basin: 320-350 km. Main sources of clastics located in the southern Alps, evidence of gravelly channel fills in the subsurface (Cortemaggiore gas field), advance and abandonment of the outer-fan lobes into the plain. Two minor intra-apenninic sources supplied mixed detritus (biogenous and terrigenous) in Umbria near Città di Castello (where a fan was built) and Gubbio. They were possibly related to lateral faults.

gradual uplifting took place there and culminated in the formation of the submarine Verghereto High (Fig. 14), a bottleneck which restricted the plain and deflected the turbidity currents northeastward. In the early Tortonian, the high collapsed and a depression was formed where hundreds of metres of allochthonous slabs were emplaced by gravity sliding (Fig. 15).

Secondly, the upwarping of the Savio area was coupled by subsidence of increasing rate in the Bidente (section 6); a depression apparently formed and acted as a selective trap for turbidite mud and fine sand: pelite beds and TBT's, in fact, increase here in number and thickness whereas sandstone beds do not thin or thicken with respect to adjacent sections.

The vertical movements in Romagna (sections 5 to 9) can be seen as a manifestation of tectonic activity along a transverse belt related to the Marecchia Line.

Thirdly, a subsidence maximum occurs in section 3 of the pre-Contessa sequence (Fig. 6) but tends to disappear in post-Contessa time (Fig. 5). It is clearly related to preferential accumulation of sand in the form of composite bodies. The question then arises of whether this accumulation was the effect or the cause of subsidence. If the top of the Contessa is taken as horizontal (see Fig. 6), a topographic depression is simulated; however, several elements (discussed in PAREA & RICCI LUCCHI, 1975; and RICCI LUCCHI & VALMORI, in press) suggest that the Contessa was deposited on a gently inclined bottom dipping southeastward from section 1 to 5, as it comes out by choosing a horizontal datum at a higher level (see Fig. 5). Among other things, the sandstone bodies show erosion surfaces, clay chips and reduced pelitic deposition, i.e. characters which do not seem compatible with a substantial slowing down of turbidity flows such as should be induced by a depression. It can thus be argued that the rate of sand deposition exceeded the rate of subsidence and that upbuilding of sand bodies produced a positive topographic gradient in this area. As a consequence, the subsidence peak should be more apparent than real, or more related to sediment load and compaction than to tectonics. Advance of deep-sea fan lobes into the plain offers a reasonable explanation of bottom convexity (see below, sandstone bodies).

In conclusion, the topographic differentiation of the Romagna part of the plain can be attributed partly to tectonic control (intermediate segment) and partly to sedimentation (proximal segment).

As for the areal extension of the whole deep-sea plain, an evaluation is limited by the constraints imposed by post-Tortonian tectonics, in particular by the truncation of outcrops to the NW (Sillaro Line) and the SW (Cervarola overthrust). Hypotheses can be made on the basis of bed geometry: it can be remarked that several turbidites emplaced from the SE (see for example, Contessa or COL-5, Figs. 5 and 8) still have a great thickness near the NW truncation. This implies that they continued beyond it. By extrapolating their rate of thickness change from Gubbio to the Santerno (=120 km), these layers should be given an additional length of 100-300 km. Even if these figures are judged excessive, being based on linear extrapolation, it is certain that the length of the deep-sea plain far exceeded 200 km in post-Contessa time. By using the same approach to estimate the width, values of 50-300 km are obtained on the assumption that the layers were not laterally confined. If their 'monster' thickness and length are considered, the above assumption seems to be quite unrealistic. This imposes a reduction of the highest width estimates: values around 50 km, or between 50 and 100 km, are appropriate for the geological context. Notice that the facies maps of figures 12-15 are based on the present extent of outcrops plus the inferred axial continuation of the Marnoso-arenacea beneath the Po Plain.

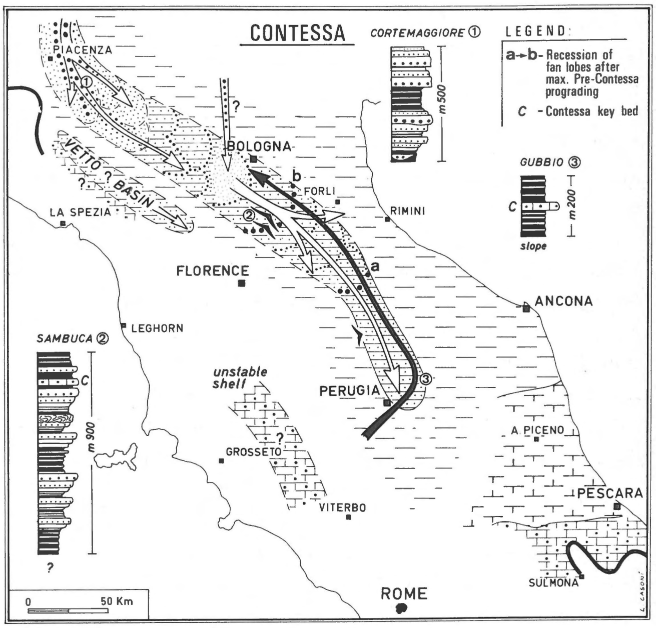

Fig. 13
The basic dispersal pattern persists but sedimentation shows a transgressive trend: fan lobes recede northward, the Città di Castello fan is abandoned, the area of the deep-sea plain is extended. The Contessa turbidity current comes down the fault line delimiting the SE end of the basin, and mantles the whole width of the plain with more than 20 m of sediment over a distance in excess of 140 km. The same source supplies other minor flows.

The normal depositional events

Thin-bedded turbidites were deposited by dilute turbidity currents which carried only fine sand and mud to the plain. Had these currents abandoned their coarser load on the adjacent fan area? Did all turbidity currents reach the plain? In other terms: must the deep-sea plain turbidites be considered as distal extensions of outer fan layers or do they form a distinct group of deposits? These are the main questions concerning the 'normal' turbidite sedimentation in the basin plan. To answer them, some points must be made.

Firstly: hemipelagites are thicker and more regularly interbedded with the basin plain than outer fan turbidites (compare, as an example, figures 11 and 13 in RICCI LUCCHI, 1975-b). This means that longer pauses elapsed in the plain between the arrival of successive flows: therefore, not all currents reached the plain, but only larger ones.

Secondly: correlation shows a high continuity for basinal beds, which means a great volume and momentum was needed to drive the currents on a flat bottom.

Thirdly: basinal TBT's have a thicker pelitic bed than outer fan layers (see again figures 11 and 13 of RICCI LUCCHI, 1975-b; and also JOHNS & MUTTI, in press). This can be explained by a by-pass of the fan area by most turbidite mud. Moreover, upcurrent wedging of sandstone beds (Fig. 9 c and d) points out that by-pass of sand also occurred.

Fourthly: some TBT sandstones increase in thickness and sand/pelite ratio upcurrent toward the fan area (Fig. 9 b), which suggests they are distal portions of outer fan turbidites.

In conclusion, a smaller number of turbidity currents was deposited in the plain compared to the fan; these currents were larger than those limited to the fan area, and deposited either on both fan and plain or were confined to the plain owing to sedimentary by-pass. In any case, basin-plain turbidites form a distinct facies from a genetic viewpoint. Consequently, evidence from both Marnoso-arenacea and Hecho basins (JOHNS & MUTTI, in press) does not support the assumption (NORMARK, 1978; WALKER, 1978) that outer fan and basin plain are undistinguishable morpho-sedimentary units.

Let us come now to the distal thickening of the pelite bed shown by many layers; it suggests that ponding, in addition to by-pass, was a common phenomenon of this deep-sea plain. For a comparable situation in modern abyssal plains, see BENNETS & PILKEY (1976) and HOYT & FOX (1977).

Small-scale, accidental unevenness of the bottom is revealed by unsystematic lateral changes of thickness; protuberances higher than a few decimeters could not be surmounted by the thinnest flows (see onlap of thin turbidites on hemipelagites).

With regard to the dominant longitudinal dispersal, it can be explained by the axial deflection of flows wherever their entry points were located and whatever direction they formerly had. This also means that 'normal' turbidity currents reaching the plain were affected by confinement and consequently had a large size compared to the size of the basin. Furthermore, the bipolar pattern (modes at 180°) implies that the currents could flow either way along the axis and there was no topographic gradient (or a very low one).

The exceptional depositional events

The impressive volume of Contessa-like layers has several implications:

(1) It is of the same order as that of major turbidites known in modern oceans (see, for example, HEEZEN ET AL., 1954; KUENEN, 1964, 1967; HOYT & FOX, 1977) but was accumulated in a much smaller basin, which resulted in an 'excess' thickness.

(2) The transporting current was confined by basin slopes and 'channeled' along the axis of the basin (see longitudinal dispersal).

(3) If not all, at least the largest flows that reached the basin plain via a canyon-fan system (the majority of those coming from Northern sources) certainly exceeded the capacity of fan valleys and by-passed the fan area with almost their entire load still in suspension.

(4) Purely sedimentary processes, such as a big stream flood, could not deliver such tremendous single inputs (we must imagine incredible drainage basins and meteorological events); consequently, instantaneous collapses triggered by tectonic activity are needed after long phases of sediment accumulation in coastal areas.

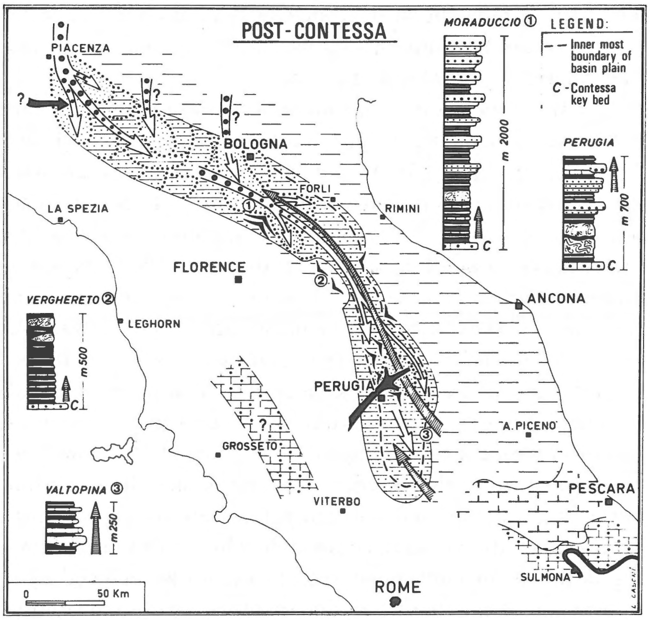

Fig. 14

Further extension of the plain (to the SE) which reached its maximum length (more than 200 km). Activation of a new clastic source along the Perugia line and outbuilding of a minor fan (M. Urbino), and of a bioclastic source in Latium-Abruzzi platforms. Increasing tectonic instability of both basin flanks: temporary or permanent constrictions of the basin plain exerted by large scale slumpings and formation of the Verghereto high (2).

Contessa-like layers thus represent a peculiar sedimentary feature of a basin plain in an unstable tectonic setting of alpine type. In this respect, another fact must be stressed: the largest deposits of this class were derived from minor sources which gave a bulk contribution of negligible importance to the basin filling. This is the case for the Contessa and pre-Contessa calcareous turbidites whose detritus was provided by an unstable shelf area supporting benthic life and receiving the products of erosion of pre-Miocene apenninic rocks; the shelf is to be located SW of the Marnoso-arenacea plain. This is also the case for the post-Contessa colombine whose source area must be found in a shelf devoid of terrigenous sediments near the SE end of the plain (Latium-Abruzzi platforms). The conclusion is then reached that the Miocene Apenninic domain, though being in a state of stress, comprising emerged land areas, and facing the Marnoso-arenacea trough, was only a minor supplier of sediment.

The highly catastrophic character of the Contessa-like flows is matched by their sporadic occurrence: this is reflected by the fact that most of them did not build deep-sea fans and were not related to a long-living depositional system. The hypothesis of a tectonic control for triggering and driving the transport is thus reinforced (see transverse faults in figures 1 and 16).

The longitudinal geometry of the Contessa-like layers, as shown by the cross-sections of figures 5 and 6 and schematized in figure 9, is greatly influenced by the presence versus absence of a deep-sea fan in the proximal part. Case (a), showing an exponential trend of thinning near the entry point, is the most typical indicator of a base-of-slope devoid of fan (see, for example, the type Contessa). Case (b) may occur in the same situation (see some colombine) but also in a lateral relation with a fan (see layers from the NW). Cases (c) and (d) exemplify the by-pass of the fan with the upcurrent wedging of both sand and mud; the only difference consists in the position of maximum sand accumulation (in case (c) nearer to the fan slope). This model is obviously more common for Contessa-like layers related to the main depositional system (see, for example, layer A-1 in Fig. 6). Owing to the higher volume and competence of the flow, the sand load by-passed the fan more frequently than in normal events. For the same reasons, also the effect of ponding near the distal end of the basin plain was more pronounced.

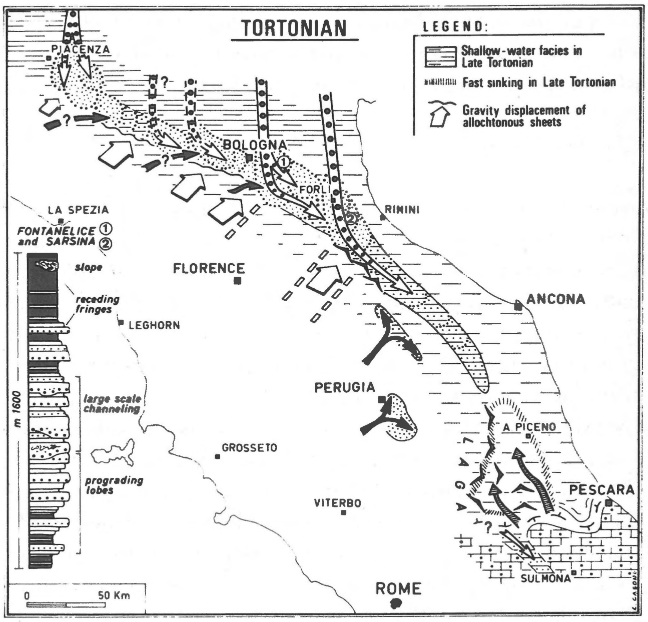

Fig. 15
End of sedimentation in the deep-sea plain; uplifting, gravity movements, displacement of subsidence-deposition axis to NE; progradation of fan bodies (including inner channelized portions: see 1 and 2) into a very narrow trough with unstable slopes. Set up of two minor intramontane turbidite basins in Umbria with a diverging palaeocurrent pattern (double axial deflection). Bioclastics of the Abruzzi platform empty into the newly formed Laga Basin.

The sandstone bodies

In the view of the proposed depositional model, the piling-up of several layers deriving from a single source, their proximal character and the lenticular shape of the resulting sand body are more compatible with a deep-sea fan than with a basin-plain environment. Building of sand lobes is inferred to take place in the outer fan beyond the mouths of distributary channels located in the inner fan; the sedimentation rate being higher than in the surrounding plain, the lobe can grow both vertically and laterally encroaching onto the plain until the feeding channel is abandoned by avulsion. The abandoned lobe sinks into the underlying compacting sediments and is covered by deep-sea plain deposits. If sand supply is again delivered by one or more channels re-occupying the older position, a new lobe advances into the plain. An evolutionary trend of this type seems to have occurred in the proximal segment of the Marnoso-arenacea basin plain during pre-Contessa time (Fig. 10). Sandstone lobes of the main fan system record a phase of maximum progradation immediately before deposition of the Contessa; after that, pronounced recession of the fans occurred. It was possibly related to a transgressive phase in shelf areas with consequent shortening of sand supply in coastal systems. Emplacement of the Contessa seems to confirm that shelves were affected by drowning and tectonic crises in this phase.

The simple geometrical model of a progradational sand body (thickening-upward sequence, offlapping layers) emerges from detailed correlation of pre-Contessa deposits (Fig. 11 b). However, other more complex models tend to characterize the largest bodies (Fig. 11 c), where lateral and vertical accretion are combined in several possible ways (more examples should be studied). As for case (a) of figure 11, there is reasonable doubt that it does not represent a fan lobe, but an accidental or special type of sand accumulation within the plain itself; actually, the body looses its identity rather rapidly downcurrent but its constituent layers can be traced for long distances into the plain.

Considering that the estimated width of the sand lobes is comparable with the estimated width of the plain, and that the lobes attained a great elongation parallel to the basin axis (see Figs. 12-15), it seems logical to assume that the outer parts of the main fans were laterally confined by the basin flanks. The palaeocurrent pattern is in agreement with this assumption, its scattering around the mean being much lower than would be expected in the ideal case of an unconfined fan (Fig. 16). Furthermore, the whole fan body was distorted, its apical portion having a transverse orientation (aligned with the submarine channels which connected it to the Alps) whereas the outer part was longitudinally deflected. This longitudinal distortion contributed to enhance the parallelism of the overall palaeocurrent pattern (TEN HAAF, 1959). Incidentally, we can remember that longitudinal palaeocurrents were considered as the most puzzling feature of turbidite basins for many years, and stimulated the advocates of contour currents. The study of continental margins demonstrated, more recently, that growth of submarine fans parallel to the continental slope, that is at 90° to the feeding canyon, is not uncommon in modern basins. Examples are the fans of La Jolla (SHEPARD ET AL., 1969; PIPER, 1970; NORMARK, 1970), Astoria (NELSON, 1968; NELSON ET AL., 1970) and Redondo (HANER, 1971).

From what is said above, the conclusion can be drawn that deep-sea fan deposits confirm the model of an 'oversupplied' basin with an almost choked depositional system. Most turbidity currents were laterally confined and their deposits developed the vertical dimension exceedingly; only an adequate rate of subsidence could compensate for the 'inadequate' area of the basin, and prevent complete filling.

The megaslumpings

Apart from a few sporadic sources in Umbria, we have seen that the Southwestern slope of the Marnoso-arenacea Basin was sedimentarily inactive. On the other hand, it was tectonically active, with resultant instability and emplacement of megaslumpings and olistostromes. Some of them, mostly composed of slope-shelf and extrabasinal sediments, reflect the tendency of the slope to encroach onto the basin plain and include slabs detached from the front of allochthonous units moving toward the Adriatic area. These chaotic bodies obstructed the Southwestern part of the plain causing local deviations of turbidity currents. These local anomalies of the palaeocurrent pattern are not easy detectable, the angle of deflection being not greater than the random dispersion of measurements (30-40°).

The megaslumpings consisting mainly of basin plain sediments (Santerno-Lamone and Mandrioli-Savio areas in Romagna) were not the expression of 'tectonic progradation' of the main slope. Rather, they resulted from tilting of the basin plain, particularly of elongated segments of it parallel to the axis of the basin. Horizontality of the bottom was re-established after slumping and deposition of deep-sea plain turbidites went on. The implication is that temporary slopes formed on a previously flat depositional area, and caution should be used, as already pointed out by KUENEN (1967), in interpreting all large-scale slumps as indicators of a permanent regional slope.

Among the slabs of penecontemporaneous shelf sediments included in megaslumpings, 'Lucina limestones' are unique and deserve a comment. They were already lithified during the final emplacement but never show traces of original bedding (nor are sediments with Lucina known in place elsewhere). The peculiar mixing up of materials widely differing in composition, state of consolidation and bathymetry seems to indicate multiple phases of slumping starting from an unstable shore zone. An analogy can be suggested with an avalanching snow ball, but no modern counterparts are known to me except in cartoons.

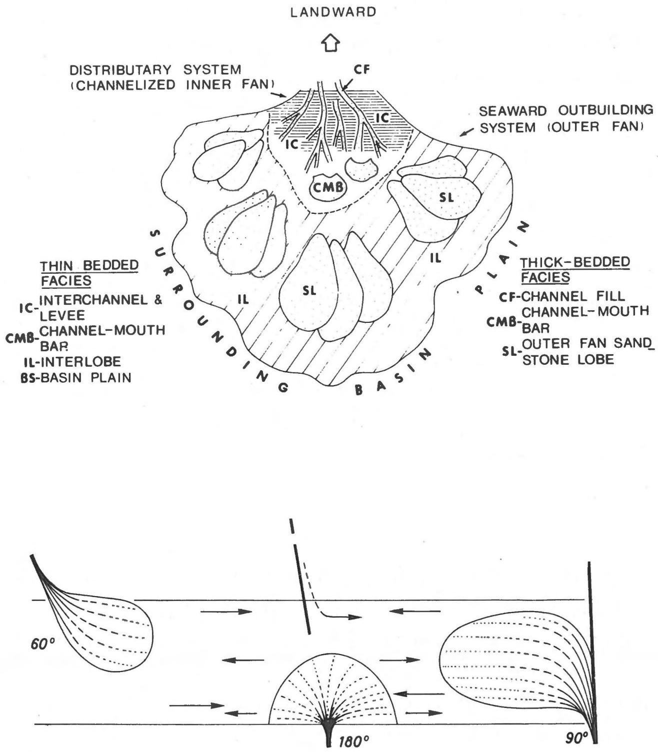

Fig. 16
Above: ideal (unconfined) model of a deep-sea fan/deep-sea plain depositional system (from Mutti & Ricci Lucchi, 1975).
Below: idealized model of the Marnoso-arenacea deep-sea plain with transversal faults, distorted fans and a longitudinal-bipolar dispersal pattern.

CONCLUSIONS

The narrow and elongated Marnoso-arenacea Basin distorted the depositional system formed by deep-sea fans and basin plain. This system was 'oversupplied', that is both normal and exceptional turbidite events had a large size compared to the area of the acceptor basin. Consequently, turbidity flows, though being introduced from the basin sides, were deflected along the basin axis at their entry points. The main source area was located in the Southern Alps and tended to shift eastward from Langhian to Tortonian; the related deep-sea fan system occupied the Northwestern part of the basin and extended in a pulsating way along its axis. The ensuing dispersal pattern, as shown by palaeocurrents, is longitudinal. However, the direction of supply (across the Padan shelf) was transverse to the depositional axis, i.e. lateral. The same is true for the spasmodic influxes of intra-apenninic materials (minor sources) as indicated, in this case, also by palaeocurrents (Città di Castello and Perugia areas in Umbria). It can be said that the dispersal pattern of this basin was longitudinal with regard to deposition, lateral with regard to sedimentary input. The only case of completely longitudinal transport is related to a minor source of bioclastics located at the far (SE) end of the basin. In conclusion, a longitudinal palaeocurrent pattern is not necessarily related to longitudinal sources, as confirmed by modern basins (e.g., Californian Borderland) and other flysch basins (e.g., Carpathians).

Another important point must be stressed about the longitudinal model of dispersal: it is unimodal in deep-sea fan deposits, bimodal in deep-sea plain facies. This difference is matched by unimodality versus plurimodality in sandstone composition, and reflects the different topographic expression of the two deep-sea environments. The plain, which represents the deepest area of a turbidite basin, can be reached by turbidity currents deriving from different sources; it is thus characterized by multi-sourced turbidites (KELLING & STANLEY, 1975). Furthermore, its horizontal bottom allows turbidity currents to travel in different directions (only two opposite directions are possible in the case of a narrow, elongate plain causing lateral confinement). The fan, on the other hand, is elevated above the plain and receives sediment only from its feeding canyon, whereby it is characterized by single-sourced turbidites and unimodal palaeocurrents (two modes at 90° may occur in the case of axial distortion, see Fig. 16). A major tool is thus available for discriminating among ancient deep-water deposits.

The interplay of synsedimentary tectonics, submarine slumping, growth and recession of deep-sea fans modified the areal extent and the topography of the Marnoso-arenacea plain, but the basic dispersal pattern did not change drastically (see Figs. 12-14) until subsidence ceased and the plain disappeared in late Serravallian. In Tortonian time, turbidite deposition became faster, sandier and confined in very narrow troughs (a sort of structural channels) which developed mainly Northeast of the previous plain but in a few cases within its former contours (stage of choked fans and intramontane basins, see Fig. 15).

Geometrical analysis of individual turbidite layers, composite sandstone bodies and chaotic bodies was made possible by mapping and long-distance correlation of outcropping sections. It enabled the clarification of the internal organization and the mutual spatial relationships of sedimentary bodies, and showed their spectacular size: a single turbidite, for example, could occupy an area as large as 200 km x 25-50 km, and a volume as great as 35 km^3.

ACKNOWLEDGEMENTS

L. M. J. U. van Straaten, J. J. H. C. Houbolt, and the Royal Geological and Mining Society of The Netherlands are warmly thanked for inviting me to give this key-note address at MEGS II.

The following colleagues and students who helped in measuring and correlating sections are gratefully acknowledged: G. C. Parea, T. H. Nilsen, R. Pignone, E. Valmori, C. Mercatali, M. Toniolo, L. Calderoni and G. G. Ori. A. Castellarin is thanked for critically reading the manuscript.

Field work was supported by Consiglio Nazionale Ricerche, Rome.

REFERENCES

Bennetts, K. R. W. & O. H. Pilkey 1976 Characteristics of three turbidites, Hispaniola-Caicos Basin-Bull. Geol. Soc. Amer. 87: 1291-1300.

Bouma, A. H. 1962 Sedimentology of some flysch deposits - Elsevier (Amsterdam): 168 pp.

Cipriani, C. & P. Malesani 1963 Ricerche sulle arenarie. IX. Caratterizzazione e distribuzione geografica delle arenarie appenniniche oligoceniche e mioceniche - Mem. Soc. Geol. It. 4: 339-375.

Enos, P. 1969 Anatomy of a flysch - J. Sedim. Petr. 39: 680-723.

Haner, E. B. 1971 Morphology and sediments of Redondo submarine fan, Southern California - Bull. Geol. Soc. Amer. 82: 2413-2432.

Heezen, B. C., D. B. Ericson & M. Ewing 1954 Further evidence for a turbidity current following the 1929 Grand Banks earthquake - Deep-Sea Res. 1: 193-202.

Hesse, R. 1965 Herkunft und Transport der Sedimente im bayerischen Flyschtrog - Zeitschr. deutsch. Geol. Gesell. 116: 403-426.

——1974 Long-distance continuity of turbidites: possible evidence for an Early Cretaceous trench-abyssal plain in the East Alps - Bull. Geol. Soc. Amer. 85: 859-870.

——1975 Turbiditic and non-turbiditic mudstone of Cretaceous flysch sections of the East Alps and other basins - Sedimentology 22: 387-416.

Hoyt, W. H. & P. J. Fox 1977 Long-distance turbidite correlations in Horseshoe Abyssal Plain (abs.) - Bull. Amer. Ass. Petrol Geol. 61: 797.

Johns, D. R. & E. Mutti (in press) The role of sedimentary by-passing in the genesis of basin plain and fan fringe turbidites - Mem. Soc. Geol. It.

Kelling, G. & D. J. Stanley (1975) A model for longitudinal transport within a modern multi-source basin - Proc. IXth Int. Congr. Sedim. (Nice) Theme V: 237-242.

Kuenen, Ph. H. 1964 Deep-sea sands and ancient turbidites. In: A. H. Bouma & A. Brouwer (eds.): Turbidites - Elsevier (Amsterdam): 3-33.

——1967 Emplacement of flysch-type sand beds - Sedimentology 9: 203-243.

Kuenen, Ph. H. & C. I. Migliorini 1950 - Turbidity currents as a cause of graded bedding - J. Geol. 58: 91-127.

Mutti, E. 1969 Studi geologici sulle isole del Dodecaneso (Mar Egeo). X. Sedimentologia delle Arenarie di Messanagros (Oligocene-Aquitaniano) nell'isola di Rodi - Mem. Soc. Geol. It. 8: 1027-1070.

——1974 Examples of ancient deep-sea fan deposits from circum-Mediterranean geosynclines. In: R. H. Dott & R. H. Shaver (eds.): Modern and ancient geosynclinal sedimentation - S.E.P.M. Special Publ. 19: 92-105.

——1977 Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South-central Pyrenees, Spain) - Sedimentology 24: 107-131.

Mutti, E. & F. Ricci Lucchi 1972 Le torbiditi dell'Appennino settentrionale: introduzione all'analisi di facies - Mem. Soc. Geol. It. 11: 161-199.

——1975 Turbidite facies and facies associations. In: E. Mutti, G. C. Parea, F. Ricci Lucchi, M. Sagri, G. Zanzucchi, G. Ghibaudo & S. Iaccarino: Examples of turbidite facies and facies associations from selected formations of the Northern Apennines - Field Trip A-II Guidebook, IXth Int. Congr. Sedim. (Nice): 21-36.

——1978 Turbidites of the Northern Apennines: introduction to facies analysis - Inter. Geol. Rev. 20: 125-166.

Nelson, C. H. 1968 Marine geology of Astoria deep-sea fan - Unpubl. thesis Oregon State University: 287 pp.

Nelson, C. H., P. R. Carlson, G. V. Byrne & Tau Rho Alpha 1970 Development of Astoria canyon-fan physiography and comparison with similar systems - Marine Geol. 8: 259-291.

Normark, W. R. 1970 Growth patterns of deep-sea fans - Bull. Amer. Ass. Petrol. Geol. 54: 2170-2195.

——1974 Submarine canyon and fan deposits. In: R. H. Dott & R. H. Shaver (eds.): Modern and ancient geosynclinal sedimentation - S.E.P.M. Spec. Publ. 19: 56-68.

——1978 Fan valleys, channels, and depositional lobes on modern submarine fans: characters for recognition of sandy turbidite environments. Bull. Amer. Ass. Petrol. Geol. 62:912-931.

Parea, G. C. 1975 The calcareous turbidite formations of the Northern Apennines. In: E. Mutti, G. C. Parea, F. Ricci Lucchi, M. Sagri, G. Zanzucchi, G. Ghibaudo & S. Iaccarino: Examples of turbidite facies and facies associations from selected formations of the Northern Apennines - Field Trip A-II Guidebook, IXth Int. Congr. Sedim. (Nice): 57-62.

Parea, G. C. & F. Ricci Lucchi 1975 Turbidite key beds as indicators of ancient deep-sea plains - Proc. IXth Int. Congr. Sedim. (Nice) Theme1: 235-242.

Piper, D. J. W. 1970 Transport and deposition of Holocene sediment on La Jolla Deep-sea Fan, California - Marine Geol. 8: 211-228.

Renzi, G. 1964 Un probabile livello guida nella Formazione Marnoso-arenacea romagnola nei dintorni di Marradi e Palazzuolo - Quaderni Studi Romagnoli 1: 15-20.

Ricci Lucchi, F. 1969-a Recherches stratonomiques et sédimentologiques sur le flysch Miocène de la Romagne (Formation Marnoso-arenacea) - Proc. IVth Sess. Comm. Medit. Neog. Strat., Giorn. Geol. (2) 35: 163-198.

——1969-b Channelized deposits in the Middle Miocene Flysch of Romagna (Italy) - Giorn. Geol. 36: 203-282.

—— 1975-a Miocene paleogeography and basin analysis in the Periadriatic Apennines. In: C. Squyres (ed.): Geology of Italy - Tripoli (1977) 2: 129-236.

——1975-b Defositional cycles in two turbidite formations of northern Apennines - J. Sedim. Petrol. 45: 1-43.

——1975-c Sediment dispersal in turbidite basins: examples from the Miocene of Northern Apennines - Proc. IXth Int. Congr. Sedim. (Nice) Theme 5: 347-352.

Ricci Lucchi, F. & G. Pialli 1973 Apporti secondari nella Marnoso-arenacea: 1/Torbiditi di conoide e di pianura sottomarina a Est-Nordest di Perugia - Boll. Soc. Geol. It. 92: 669-712.

Ricci Lucchi, F. & R. Pignone (in press) Ricostruzione geometrica parziale di un lobo di conoide sottomarina - Mem. Soc. Geol. It.

Ricci Lucchi, F. & E. Valmori (in press) Basin plain deposits of the Marnoso-arenacea: an analytical study - Mem. Soc. Geol. It.

Sagri, M. 1972 Rhythmic sedimentation in the turbidite sequences of the Northern Apennines (Italy) - Proc. 24th Int. Geol. Congr. 6: 82-87.

——1974 Rhythmic sedimentation in deep-sea carbonate turbidites (Monte Antola Formation, Northern Apennines) - Boll. Soc. Geol. It.: 1013-1027.

Scholle, P.A. 1971 Sedimentology of fine-grained deep-water carbonate turbidites, Monte Antola Flysch (Upper Cretaceous), Northern Apennines, Italy - Bull. Geol. Soc. Amer. 82: 629-658.

Seilacher, A. 1967 Bathymetry of trace fossils - Marine Geol. 5: 413-428.

Sestini, G. (ed.) 1970 Development of the Northern Apennines Geosyncline - Sedim. Geol. 4: 648 pp.

Shepard, F. P., R. F. Dill & U. von Rad 1969 Physiography and sedimentary processes of La Jolla Fan and Fan Valley - Amer. Ass. Petrol. Geol. Bull. 53: 390-420.

Stanley, D. J. 1970 Flyschoid sedimentation on the outer Atlantic Margin off Northeast North America. In: J. Lajoie (ed.): Flysch sedimentology in North America - Geol. Ass. Canada Spec. Paper 7: 179-210.

Ten Haaf, E. 1959 Graded beds of the Northern Apennines - Unpubl. Thesis Univ. Groningen: 102 pp.

Walker, R. G. 1967 Turbidite sedimentary structures and their relationship to proximal and distal environments - J. Sedim. Petrol. 37: 25-73.

—— 1978 Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. Bull. Amer. Ass. Petrol. Geol. 62: 932-966.