Mass-Transport Complexes of the Marnoso-arenacea Foredeep Turbidite System (Northern Apennines, Italy): A Reappraisal After Twenty-Years

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ABSTRACT

The Casaglia-Monte della Colonna is one of the best exposed "fossil" mass-transport complex (MTC) cropping out in a foredeep succession exhumed in a mountain chain and represents a unique opportunity to study an internal architecture resulting from the (geologically) simultaneous collapses of an accretionary wedge front, slope, and basin plain deposits. The high variety of internal structures and the different MTC-substratum interactions depend on the geometry of MTC basal contact and the provenance of the remobilized sediments. In the 20 years from our first studies on this MTC, the better condition of some outcrops and the advances in methodological and interpretative tools enable us to provide an update scenario, with more details on the internal structures and a better comprehension of the complex interactions with the substratum.

8.1. INTRODUCTION

Mass-transport deposits (MTDs) represent a common occurrence in exhumed stratigraphic successions in mountain chains worldwide (Alves, 2015; Dykstra, 2005; Shipp et al., 2011; Yamada et al., 2012), and their number further increases considering that several cases of "chaotic" units (sedimentary mélanges or olistostromes) originated from submarine landsliding (Pini, 1999; Alonso et al., 2006; Burg et al., 2008; Camerlenghi & Pini, 2009; Cowan, 1985; Festa et al., 2010a, 2010b, 2012, 2016; Raymond, 1984, 2017; Raymond & Bero, 2015; Wakabayashi, 2011).

MTDs show different internal organization and structures due to sensible changes in composition and consolidation of translated rocks and sediments (Alves, 2015; Dykstra et al., 2011; Pini et al., 2012). An extreme variability exists, therefore, for their morphological aspect, the presence/absence, shape and amount of floaters (large blocks with poorly deformed bed packages), and the style of internal deformations. MTDs may result from multistage and/or multisource depositional events, having a complex internal structure and being made up of different sediments/rocks from various sources (mass-transport complexes [MTCs]; Weimer & Shipp, 2004). Fossil MTCs, especially large-scale and basin-wide ones, are usually complex units involving the entire spectrum of mass-transport processes (Lucente & Pini, 2003; Posamentier & Martinsen, 2011). They often comprise discrete subunits, defined on the base of composition, provenance, structures, and sense of movement. These subunits can represent single mass-transport events, pulses, or discrete masses moving differentially in the same event (Festa et al., 2016; Lucente & Pini, 2003; Ogata et al., 2012b, 2014a; Swarbick and Naylor, 1980). Another key point is the effects that MTDs/MTCs

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can have on the underlying sediments (substrata) (Alves & Lourenco, 2010; Ogata et al., 2014b; Sobiesiak et al., 2016, 2018; van den Merve et al., 2011).

Pini et al. (2012) distinguished three types of MTDs/MTCs in the Apennines, in which the internal movements and translation/emplacement of bodies take place for (i) shear-dominated viscous flows within a muddy matrix (Type 1), (ii) mud-silt-sandy matrix sustained by fluid overpressure (Type 2), and (iii) concentrated shear zones/surfaces with advection of grains and fluid (overpressured basal carpets) (Type 3). This chapter will show an example of a Type 3 MTC cropping out in the Romagna Apennines of Italy, namely, the Casaglia-Monte della Colonna, aiming to show the kinematic of emplacement, mechanism of internal deformation, and how progressive stratal disruption operates down flow, especially addressing the interaction with the substratum.

We are here presenting an updated review of the knowledge about the Casaglia-Monte della Colonna MTC, based on our previous works (Lucente, 2000, 2002; Lucente & Pini, 1999, 2002, 2003, 2008) integrated by new field observations and interpretations matured in more than 20 years of focused observations. 20 years of time modified the outcrops revealing new details. Furthermore, the advancements of computer software and hardware and of digital photography made easily available the 3D reconstructions of outcrops by close-range photogrammetry starting from an array of multiple viewpoint photographs (see, e.g., Bistacchi et al., 2015). We here better define, therefore, the internal features of key outcrops (Casaglia A and B and SP 477 outcrop) through 3D reconstructions of outcrops. We also illustrate parts of the MTC that were not studied before (Santerno sector) or not easily accessible to an international audience (Isola B, Ciriegiolo B, Rio di Gamogna, and Le Piane outcrops) being part of previous works in Italian language (Lucente, 2000, 2002).

8.2. GEOLOGICAL SETTING

The Northern Apennines of Italy are an arcuate orogenic wedge (Figure 8.1a) built up in different tectonic phases from Cretaceous to Plio-Pleistocene (Carmignani et al., 2004; Castellarin et al., 1992; Cerrina Feroni et al., 2002, 2004; Molli et al., 2010). A still active extensional tectonics characterizes the Tyrrhenian side and the axial part of the chain (Bonini et al., 2016; Carmignani et al., 1994; Collettini et al., 2006; Sani et al., 2009), while a contractional tectonics is still active beneath the Po Plain and the Adriatic Sea (Figure 8.1a) (Boccaletti et al., 2011; Bonini et al., 2014, 2016; Toscani et al., 2009).

The structurally highest and the most far traveled structural units, the Ligurian Nappe, comprises deformed stratigraphic successions and mélanges originated from a Jurassic-Eocene ocean belonging to the Alpine Tethys (Internal Ligurian units) and its southeastward transition to the Adria Microplate (External Ligurian and Subligurian units) (Bortolotti et al., 2001; Cerrina Feroni et al., 2002; Marroni et al., 2017; Marroni & Pandolfi, 2007). The internal structural setting of the Internal Ligurian units largely derives from the southeastward dipping subduction of the oceanic crust in a Cretaceous-Paleogene double-vergent accretionary wedge (Malavieille et al., 2016; Marroni et al., 2010, 2017). The structural setting of the External Ligurian and Subligurian units originates from the northwestward directed subduction of the ocean-continent transition and the thinned continental margin of Adria Microplate beneath the accretionary wedge and the Eurasia/Iberia plates (Marroni et al., 2010, 2017; Molli et al., 2010; Molli & Malavieille, 2010).

The southeastward to northwestward switch in subduction is considered to occur in middle Eocene (Ligurian phase). This scenario is not generally accepted, since the age is debated (Argnani, 2012; Boccaletti et al., 1971, 1980; Doglioni et al., 1998; Marroni et al., 2010; Molli et al. 2010) and the paleo-tectonic reconstructions are complicated by the highly extended and articulated continental margin of the Adria Microplate (see, e.g., Marroni et al., 2017) and a very complex paleogeographic and geodynamic scenario (see, e.g., Argnani, 2002; Stampfli et al., 1998, 2002). Thus, although several authors support a change in subduction direction (subduction flip) involving the subduction of the continental margin of the Adria Microplate (see, e.g., Boccaletti et al., 1971; Doglioni et al., 1998; Marroni et al. 2017; Molli, 2008; Molli et al., 2010; Vignaroli et al., 2008), alternative views have been presented (Argnani, 2002, 2012; Faccenna et al., 2001; Principi & Treves, 1984).

However, apart from these different paleo-tectonic models, severe deformation of continental margin of Adria Microplate took place from Oligocene to Recent time in areas originally placed to the SE of the Subligurian domain. This originates the other structural units of the Northern Apennine accretionary wedge, namely, from W/SW to E/NE, the Tuscan units and the Romagna-Umbria and Po Plain fold and thrust belts (Barchi et al., 2001; Carmignani et al., 2001). The onset of these deformations corresponds to the opening of back-arc basins (Liguro-Provençal-Balearic and Tyrrhenian basins) (Carminati et al., 2012; Dewey et al., 1989; Faccenna et al., 2004; Gueguen et al., 1998; Malinverno & Ryan, 1986), up to the emplacement of back-arc oceanic crust (Carminati et al., 2012; Roca, 2001; Sartori, 1990), and to the coupled counterclockwise rotation of the accretionary wedge and the Corsica-Sardinia continental block (Muttoni et al., 2000; Speranza et al., 1997, 2002). Rotation and protracted extension in the back-arc region is responsible for the east/northeastward migration of the

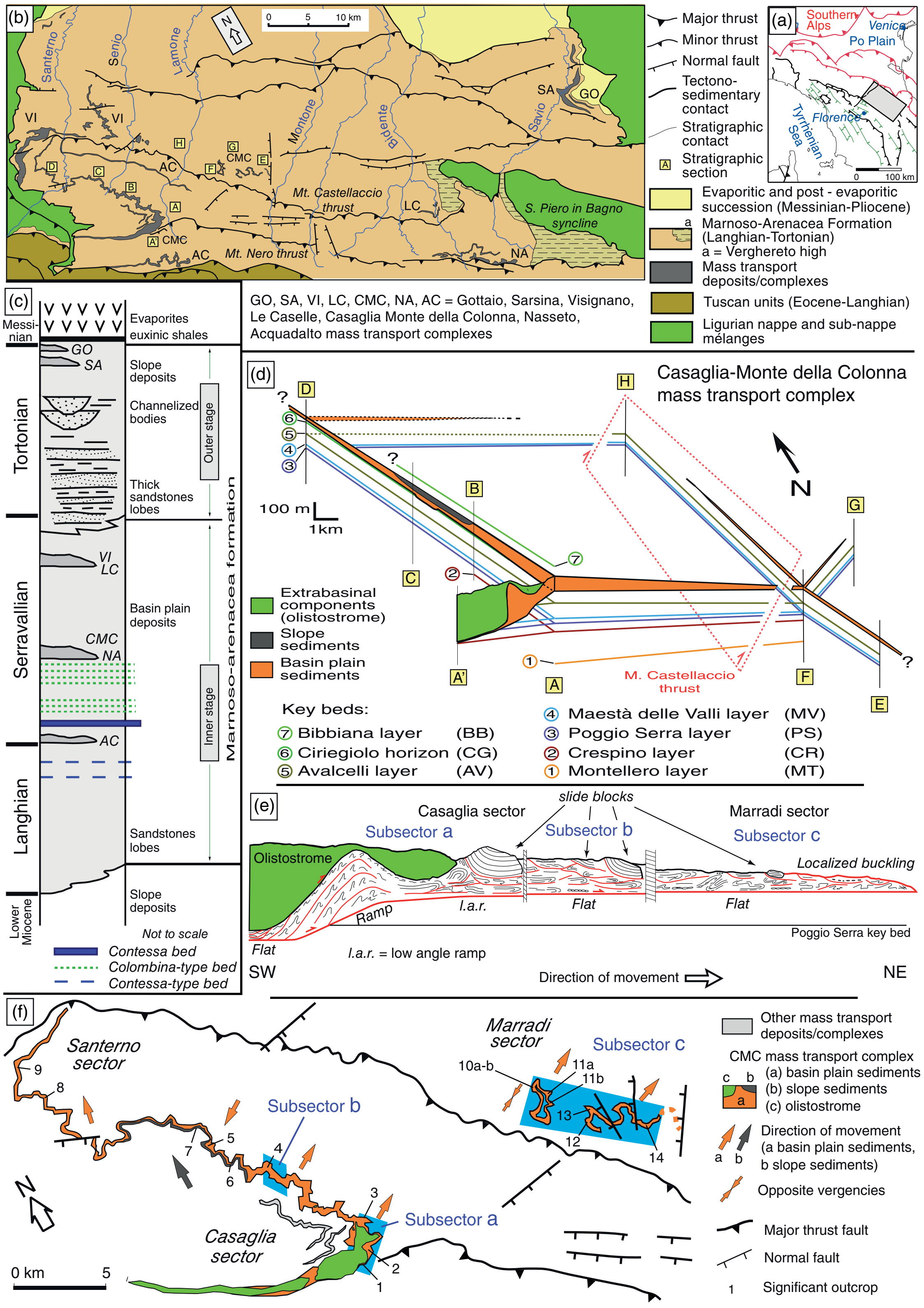

Figure 8.1 (a) Schematic structural map of the Northern Apennines. Key to the tectonic structures: red, thick lines, buried fronts of Northern Apennines and Southern Alps; red, thin lines, buried thrusts; black lines, outcropping structures (thrusts with triangles); green, normal faults. Triangles and barbs indicate hanging wall. Gray box shows the location of (b). Source: Modified from Festa et al. (2010b). (b) Schematic geological map of the Romagna-Tuscan Apennines. (c) Synthetic stratigraphic subdivision of the Miocene succession of the Romagna-Tuscan Apennines focused on the Marnoso-arenacea Formation. (d) Fence diagram illustrating the geometry of Casaglia-Monte della Colonna mass-transport complex with respect to key beds. Locations of stratigraphic sections are shown in (b). (e) Composite transect summarizing the principal structural features observed in the subsectors outlined in (f). (f) Geological map of the Casaglia-Monte della Colonna mass-transport complex, showing its component units, the directions of flow, and the locations of the outcrops described in the text. Source: All the figures are, modified, from Lucente and Pini (2003). (*See electronic version for color representation of this figure*)

accretionary wedge (Boccaletti et al., 1990). Within this framework, the Ligurian Nappe always occupied the highest position in the tectonic stack of the wedge, progressively thrusting over the Tuscan units and the Romagna-Umbria fold and thrust belt. Atop the deforming Ligurian Nappe, slope to shelf, piggyback, satellite basins developed (Epiligurian units; Ricci Lucchi & Ori, 1985).

The Tuscan units and the Romagna-Umbria fold and thrust belt share a common stratigraphy from Permian-Mesozoic continental and marine deposits and Paleogene slope deposits up to Oligocene-Miocene-Pliocene thousands of meter-thick turbiditic successions. The turbiditic successions represent the sedimentary infills of a migrating (and rejuvenating) foredeep complex, which took place onto the flexed Adria continental margin at the front of the Apennine accretionary wedge (Ricci Lucchi, 1986).

The Marnoso-arenacea Formation is the middle to late Miocene infill of this migrating foredeep complex (Boccaletti et al., 1990) exhumed and excellently exposed in the Northern Apennine chain (Ricci Lucchi and Ori, 1985). This formation extends for over 180 km in length and 40 km in width and comprises over 3000 m of deep-water turbidites. The Marnoso-arenacea Formation consists of an older "inner" (Langhian-Serravallian) and a younger "outer" (Tortonian) evolutionary stages (Ricci Lucchi, 1975, 1986). The inner stage represents the phase of maximum subsidence and lateral extent of the basin, with a large development of basin plain turbidites. This stage shows an impressive lateral continuity of individual beds, allowing basin-wide correlations (Amy & Talling, 2006; Ricci Lucchi & Valmori, 1980; Talling et al., 2007; Tinterri et al., 2012).

The sediment dispersal pattern was along the longitudinal axis of a narrow foredeep (Gandolfi et al., 1983; Ricci Lucchi, 1978). Paleocurrent data show a southeast directed transport direction from Alpine sources through multiple entry points. A carbonate platform at the southeastern edge of the basin supplied carbonate turbidites, the so-called "colombine" layers, the calcareous composition of which is easily recognizable in field. Minor and sporadic sources located along the accretionary wedge front at the southwest margin of the basin supplied hybrid megabeds (Contessa and Contessa-like beds; Ricci Lucchi & Valmori, 1980).

Paleocurrent data and bed-by-bed correlation, also across different thrust units, point out an original flat paleo-topography of the basin except for the Verghereto area where a well-documented intrabasinal high developed subsequently to synsedimentary tectonic activity (Amy & Talling, 2006; Lucente, 2004). However, at a closer scale, sedimentary features suggest local topographic control on sedimentation through gentle high (see ponded foredeep of Mutti et al. (2003)). This physiographic framework caused ponding and flow reflection-deflection of turbidity currents and MTDs/MTCs, resulting in changes in sedimentary facies and in lateral thickness of both bed packages and individual layers (Lucente, 2004; Roveri et al., 2002; Tinterri & Muzzi Magalhaes, 2011; Tinterri & Tagliaferri, 2015).

Several MTDs/MTCs characterize the basin plain and the inner slope, involving sediments of various origin and state of consolidation. Frequency peaks in slide distribution occurred in the early Serravallian and late Tortonian, representing phases of enhanced basin-scale instability (Landuzzi, 2005; Lucente & Pini, 2002, 2008).

From a tectonic point of view, the Marnoso-arenacea Formation is a consistent part of the sedimentary succession involved in the lowest and northeasternmost (external) structural unit of the Northern Apennine mountain chain and the Romagna-Umbria fold and thrust belt. The thrust faults and fault-related folds strike out from NW to SE, parallel to the main direction of the Apennine structures (e.g., Capozzi et al., 1991; de Jager, 1979) (Figure 8.1b). This results in broad asymmetric synclines separated by narrow anticlines. Following De Donatis and Mazzoli (1994), the fold geometries are consistent with detachment folds, deformed by breakthrough faults in the hinges and forelimbs, that often evolved in regional-scale thrusts (Figure 8.1b). These structures enucleate during the sedimentation (Bonini, 2006; De Donatis & Mazzoli, 1994; de Jager, 1979), so anticlines originated the intrabasinal highs mentioned earlier (Lucente, 2004; Lucente & Pini, 2003, 2008; Roveri et al., 2002; Tinterri & Muzzi Magalhaes, 2011). Changes in bed thickness occur from the anticlinal hinges to limbs (Panieri et al., 2009; Tinterri & Tagliaferri, 2015; Tagliaferri et al., 2018) with the stratigraphic succession assuming a classic fan-type shape (grow successions; Bonini, 2006; Tinterri and Tagliaferri, 2015).

8.3. CASAGLIA-MONTE DELLA COLONNA MTC: PHYSIOGRAPHY AND INTERNAL STRUCTURES

Recognized as originated by mass-transport processes since Renzi (1967), the Casaglia-Monte della Colonna body (shortened in CMC) occurs in the Serravallian Marnoso-arenacea Formation of the inner stage, in the westernmost sector of the Romagna-Tuscan Apennines (Figure 8.1b). Its position in the stratigraphy (Figure 8.1c) is above the Contessa key bed, in an interval characterized by basin plain turbidites, mainly corresponding to facies D_1, D_2, D_3, and G of Mutti and Ricci Lucchi (1972, 1975). An impressive continuity of beds and very distinctive turbidites from different sources (alpine sourced siliciclastic, carbonate "colombine," and southwest sourced hybrid turbidites) define either basin-wide or local key beds. It has been possible, therefore, to outline the 3D stratigraphic relationships of the MTC with the underlying beds (substratum) (Figures. 8.1d) (Lucente 2000; Lucente & Pini, 2003).

Compositionally tripartite, the MTC comprises (i) deformed basin plain deposits, (ii) deformed fine-grained slope deposits, and (iii) extrabasinal material coming from the paleo-Apennine wedge front (Figure 8.1d–f). The extrabasinal component, defined in literature as "olistostrome" (Lucente & Pini, 2003), comprises hectometer- to kilometer-scale, heterogeneous blocks (olistoliths) sourced from the Subligurian units of the Ligurian Nappe (calcarenites and shales, middle Eocene), the Epiligurian slope basin (shales, cherty shales, and volcanoclastic layers, early Miocene), and the "closure" deposits of the Tuscan foredeep turbidites (shales and sporadic sandstone beds, early to middle Miocene) (see Lucente, 2000; Lucente & Pini, 2008). Each block maintains the original bedding and internal tectonic structures (folds, faults, cleavage, and boudinage). They are, therefore, not only extrabasinal but also belong to different structural units and have different composition, ages, and fabric with respect to the Marnoso-arenacea intrabasinal components; thus they can be considered as exotic (Festa et al., 2010a, 2010b, 2012). Nonetheless, a typical element of classic olistostromes (see Flores (1955); Type A of Lucente and Pini (2003)), the fine-grained matrix bounding the blocks, is lacking (see Type C olistostromes of Lucente and Pini (2003)).

A kinematically coherent association of slump horizons and slide blocks causes the remobilization of the intrabasinal component (basin plain and slope deposits) (Type 3 MTCs of Pini et al. (2012)) (Figure 8.1e). The differential movement of individual detached bed packages of different dimensions is incrementally achieved along shear zones and surfaces. Beds are laterally continuous and block-in-matrix intervals (debrites) are not common, being present only locally at the top (co-genetic debris flow). Meters to ten of meter-thick zones of intense stratal disruption (up to block-in-matrix fabric) develop less frequently within and at the base of the MTC due to severe folding and boudinage of beds (Lucente & Pini, 2003).

In this chapter, we will focus on the intrabasinal components, referring to Lucente and Pini (2003, 2008) for the extrabasinal one. A southwest to northeast transport is recorded in the basin plain and extrabasinal components in the southeasternmost area of Casaglia and the Marradi sectors (Figure 8.1f), while in the northwestern area, the basin plain component displays a southward to northward sense of movement (Santerno sector; Figure 8.1f) (Lucente, 2000; Lucente & Pini, 2003). Two superposed sub-bodies characterize the central part of the Casaglia sector with northeast to southwest transported basin plain deposits underlying S- to N-translated slope deposits.

8.3.1. The Southwest to Northeast Directed Basin Plain Deposits: Casaglia Sector

This is the most distinctive part of the CMC body, where its bottom surface depicts a staircase trajectory. The changes in the basal angle with respect to the substratum beds, shown in Figure 8.1d and e, correspond, from SW to NE, to:

1. an almost layer-parallel translation zone (lower flat, stratigraphic section A′);
2. an extrusion zone cutting the stratigraphic column for over 200 m (ramp, between stratigraphic sections A′ and A, with a cutoff angle of 8°);
3. a low-angle ramp (northeast and north of section A until the subsector b with a cutoff angle of less than 1°); and
4. an upper flat above the Ciriegiolo key bed (subsector b, stratigraphic section B).

The distribution and style of structures change in the diverse part of the MTC as summarized in Figure 8.1e (Lucente & Pini, 2003).

The best exposure of the translation zone crops out in a road cut (Figure 8.2a) close to Casaglia Village (Casaglia "A," outcrop 1 in Figure 8.1f). Thrusting of bed packages occur along discrete listric shear surfaces, which change down flow from layer parallel (flat) to a low-angle ramp. Thinner beds develop recumbent folds bounded by shear surfaces and with curved hinge lines (sheathlike folds). Lucente and Pini (2003) inferred the direction of movement, here and in the other CMC sectors, from fold axis distribution and vergence, using the separation arc method (Hansen, 1971; Woodcock, 1979).

A debrite composed of blocks of sandstones dispersed in a silty-clayey matrix characterizes the upper part of the outcrop beneath the olistostromes. The Marnoso-arenacea Formation below the debrite is thin-bedded, fine-grained, and intensely deformed up to a complete stratal disruption with isolated boudins and rootless slump folds.

The Casaglia "B" outcrop (2 in Figure 8.1f) shows a large section of basin plain deposits and subordinate slope facies arranged in large-scale anticlines and stacked by thrusting (see also Lucente and Taviani (2005)) (Figure 8.2b). This stacking causes thrust surfaces to be folded and uprighted. Folds share a common northeastward vergence with a single counter-verging fold. This zone corresponds to the steepest part of the ramp.

The Bibbiana-Monte della Colonna outcrop (outcrop 3 in Figure 8.1f), at the edge of the ramp, shows hectometer-scale outsized blocks (slide blocks) bounded by belts of metric-scale folds (Figures 8.2c and 8.3a–c). In these belts, folds change from close to isoclinal toward NE with their axial planes following the attitude of the belt, changing from steeply inclined to recumbent with a predominant

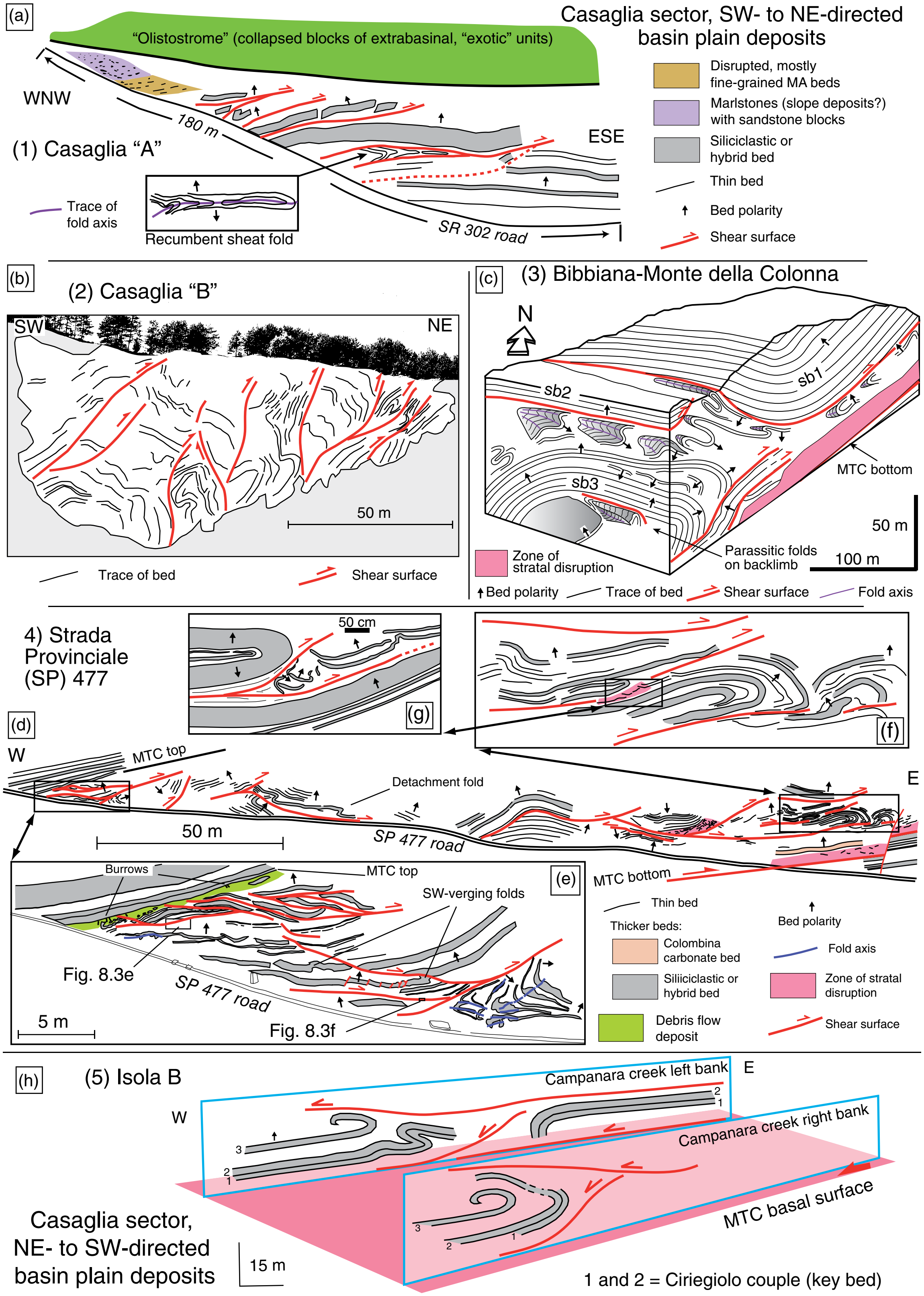

Figure 8.2 Line drawings of key outcrops in the Casaglia sector of the Casaglia-Monte della Colonna mass-transport complex. All the figures refer to the northeast directed basin plain deposits, except (h) illustrating the basal structures of the southwest directed part of the mass-transport complex. Numbers before the outcrop names refer to the locations in Figure 8.1f. (c) and (g) are from Lucente and Pini (2003), modified. (h) is from Lucente (2000), modified.

upside-down bed attitude. The contact between slide blocks and fold belts are abrupt, marked by millimeter-thick shear zones. Folds in slide blocks show a southwest to northeast transition, from a steeply inclined close fold (slide block 3) with associated parasitic folds (Figure 8.3c, d) to gentle folds (slide block 1) originated from accommodation of bed packages above listric normal faults. An interval of increasing stratal disruption with boudins and disrupted folds characterizes the basal part and accommodate the largest strain (Figure 8.2c).

The outcrop along the SP 477 road (outcrop 4, formerly known as SS 477 outcrop; Lucente & Pini, 2003) develops onto the upper flat. Normal faults already recognized in Lucente and Pini (2003) extend also in deeper parts of the MTC and have a down-flow continuation in faults parallel to beds and basal contact (flats) and in low-angle thrust cutting upsection (spoon-shaped faults; van der Merwe et al., 2011) (Figure 8.2d, e). Detachment folds develop above the flats and become recumbent, close to isoclinal folds in the thrust (Figure 8.2d, f, g).

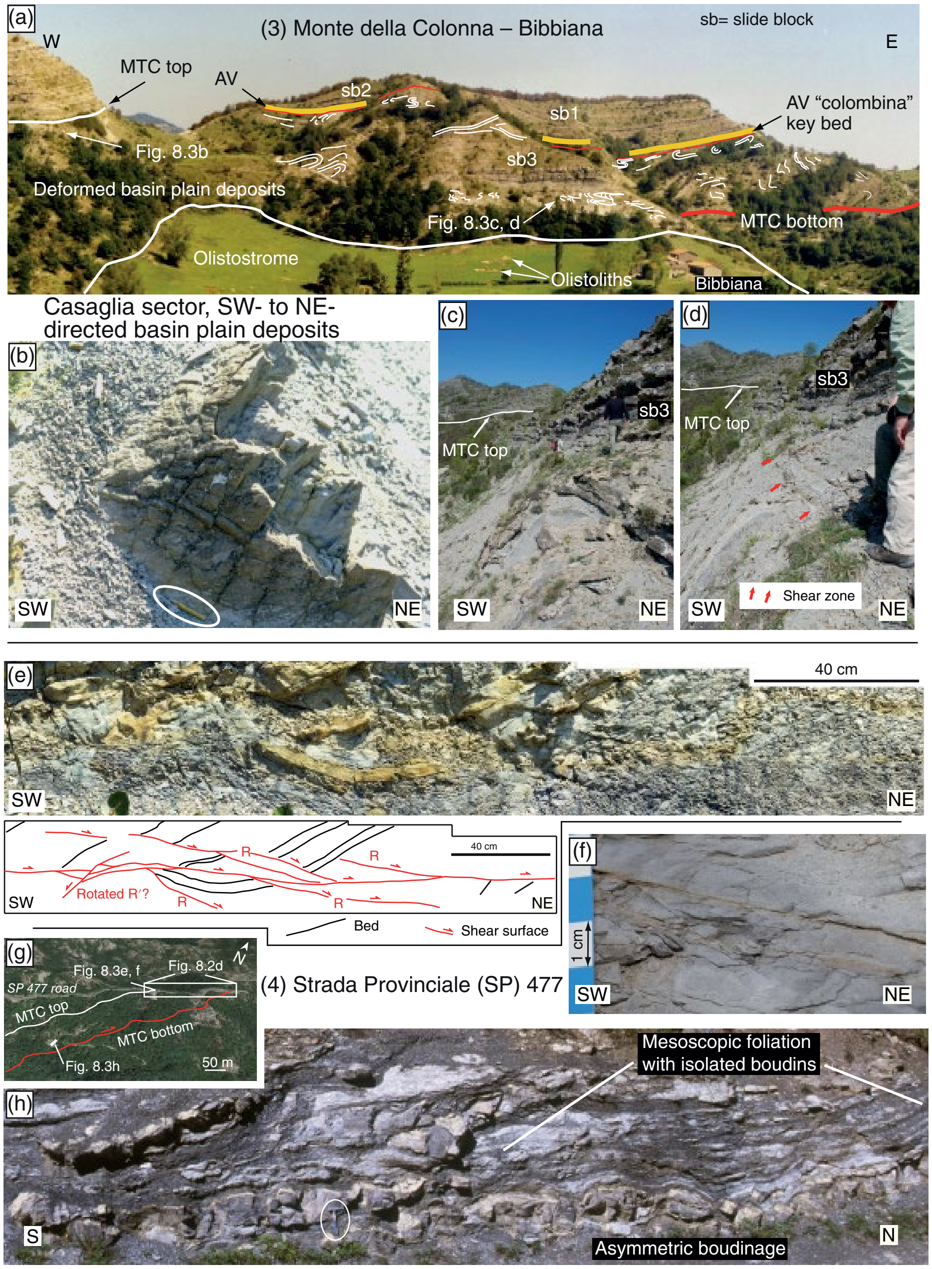

Figure 8.3 Photographs illustrating some key features of the deformed basin plain deposits of the Casaglia sector. Numbers before the outcrop names refer to the locations in Figure 8.1f. Line drawing in (a) is from Lucente and Pini (2003) modified. (c) and (d) show the parasitic folds on the backlimb of the upright fold constituting slide block 3.

Stratal disruption occurs when faults cut up the stratigraphic succession (Figure. 8.2g). Slide blocks are smaller than in the Bibbiana-Monte della Colonna outcrop, and some of them are upside down (Figure 8.2d). As already shown in Lucente and Pini (2003), the upper part of the MTC displays an array of horses (extensional duplex), which overlies a system of listric normal faults (Figure 8.2e). The normal faults crosscut an interval characterized by isolated slump folds and boudins dispersed in a finer-grained matrix (debrite), which corresponds to the last stage of MTC deposition (co-genetic debris flow). This suggests that the activity of normal faults extended after the CMC emplacement. Normal faults cut previous contractional features, such as asymmetric folds, testifying a first phase of southwestward translation (Figure 8.2e). Asymmetric domino-type boudinage (Etchecopar, 1977; Rodrigues & Pamplona, 2018) occurs in the lowest part of the MTC and laterally evolves in block-in-matrix features, showing clear mesoscopic foliation due to stretching of finer-grained beds (Figure 8.3h). Domino-type boudinage suggests a top to the NE movement in predominant simple shear regime, which is also coherent with the clockwise rotation and sigma-like structures affecting the separated boudins (Figure 8.3h).

8.3.2. The Southwest to Northeast Directed Basin Plain Deposits: Marradi Sector

Basin plain turbidites and hemipelagic beds prevail in the Marradi sector. Beds are thinner than in the Casaglia sector, often lacking the "b" interval (D_2 and D_3 of Mutti and Ricci Lucchi (1972, 1975)), which may suggest a provenance from more marginal (southwesterly?) position of the basin plain (Lucente, 2000). In the sector, the basal contact shows a constant flat attitude and corresponds to the more distal, spilling-over zone of the CMC, which reaches here its minimum thickness (20–10 m). The different outcrops share strong deformation caused by folding and symmetric, flattening-type, or asymmetric boudinage. Folds are developed at meters to tens of centimeters scale (Figures 8.4a–e, and 8.5a–g, l).

A general planar bed attitude, almost parallel to the basal contact, characterizes the Val del Calvo outcrops (10a-b in Figure 8.1f). Recumbent folds with limbs pinched and swelled in either symmetric or asymmetric (shear band type) style, deform the overall bedding (Figure 8.4a, b). Internal deformation (layer-parallel extension?) can increase, locally developing isolated boudins and rootless slump folds (Figure 8.4c). Although the general fold vergence is toward NE, counter-verging (southwest facing) folds systematically occur (Figure 8.4a, b). Low-angle normal faults cause bedding rotation and cleavage (Figure 8.4b).

In the Tramanzo outcrops (11a-b in Figure 8.1f), a complex system of superposed recumbent and often refolded folds, with contorted hinges and associated parasitic folds, dominate in the upper part of the body (Figure 8.5a, c). In the lower part, beds tend to be subparallel and appear deformed by small detachment folds (box folds and counter-vergent folds; Figures 8.4e and 8.5b). Fold limbs are thinned, but continuous, with few examples of flattening-type, pinch-and-swell boudinage and few isolated oblate boudins. Hinge zone thickening is observed in the largest majority of cases.

The Pian di Lorino outcrop (12 in Figure 8.1f) shows a peculiar style of progressive deformation of the bedding, implying a layer-parallel, flattening-type boudinage (pinch and swell), subsequently reworked into a stacking of blocks (Figure 8.5d, f), and a last folding stage (Figure 8.5d, e). Folds occur at a different scale (meter to tens of meters scale), with moderate to gently inclined axes (overfolds) and vergence toward NE (Figure 8.5d). Low-angle thrusts are also present (Figure 8.5d).

Listric faults (Figure 8.5g) characterizes the Rio Gamogna outcrop (13 in Figure 8.1f). They are characterized by cumulative displacement achieved by incremental movement along millimeter-thick shear zones (Figure 8.5k) and evolve down flow from normal faults to layer-parallel faults (detachments). This creates detachment folds in the hanging wall, cleavage, and pinch-and-swell, flattening-type boudinage of thin sandstone/siltstone beds (Figure 8.5g, h). Thicker beds are characterized by asymmetric domino-type boudinage (Figure 8.5i), suggesting a general simple shear deformation. Meter-scale undeformed blocks of thin-bedded turbidites occur at the top of the MTC (Figure 8.5g).

The Le Piane outcrops (14 in Figure 8.1f) displays large-scale, close to recumbent folds in the upper part, deforming both fine-grained and thick, coarse beds (Figure 8.5l). A clear axial plane cleavage occurs in thicker beds. Other similar beds in the same deformed bed packages appear involved in folds as isolated symmetric lenses due to layer-parallel boudinage.

8.3.3. Casaglia Sector, Central Zone: The North Verging Slope Deposits

Slope deposits are the exclusive component of the upper CMC body and show higher deformation than their basin plain counterpart show. The overall structural attitude is dominated by systems of gently dipping to recumbent folds, shear surfaces acting as normal faults, and pinch-and-swell, constriction-type boudinage of the coarser beds (Tc-e turbidites). Coarser beds (Tc-e, Td-e) appear deformed into strongly flattened, isolated folds, often coaxially refolded by progressive shear deformation (Farrell & Eaton, 1987). This produced non-cylindrical folds (true sheath folds have not observed) and spiral-like,

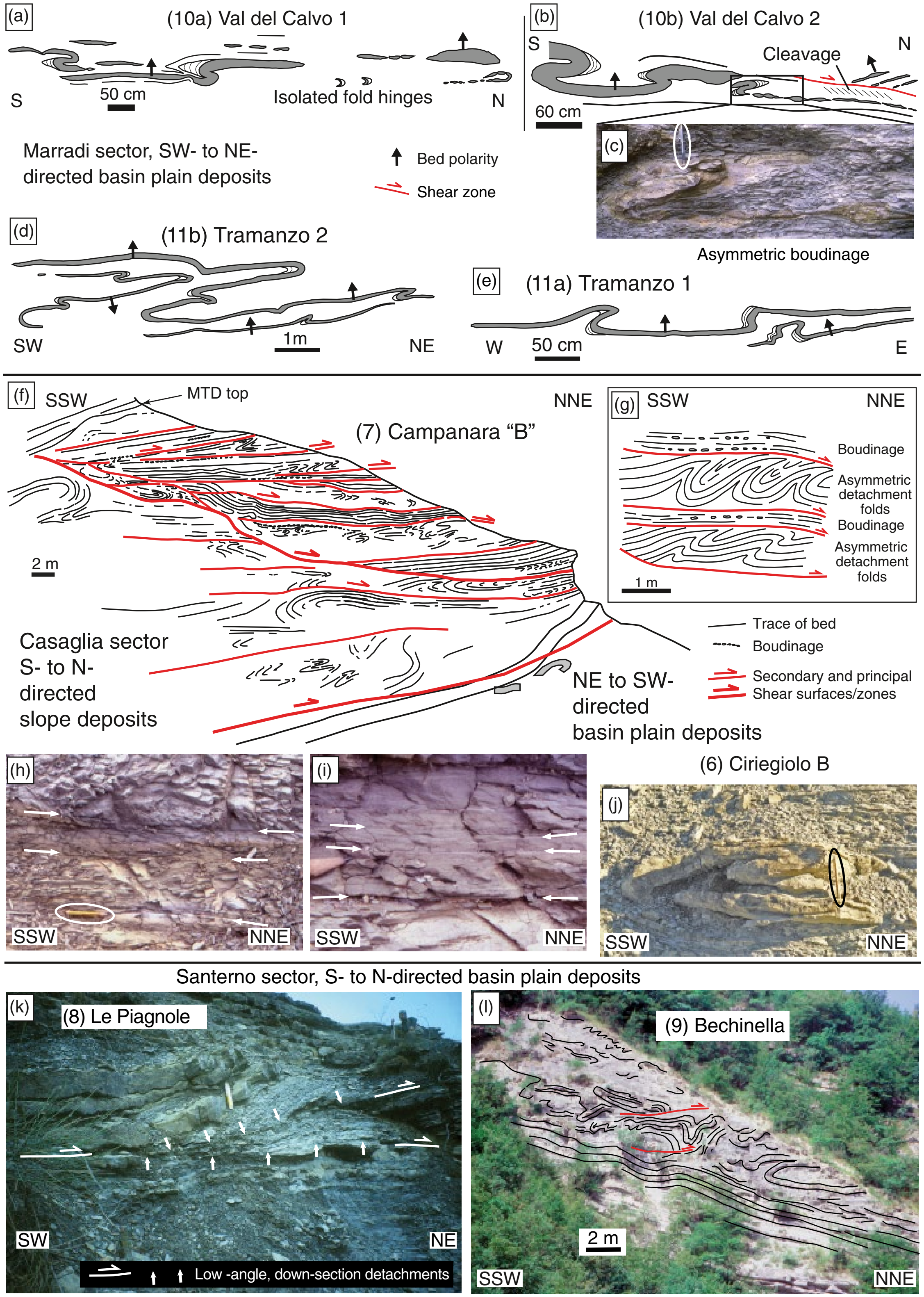

Figure 8.4 Photographs and line drawings showing key features of the deformed basin plain deposits in the Marradi sector (a–e), the deformed slope deposits in the Casaglia sector (f–j), and the deformed basin plain deposits in the Santerno sector (k and l). White arrows in (h) and (i) point out the shear surfaces associated with the listric principal shear zone of (f). Pen and pencils are for scale in (c, h, and J): pencil tip is for scale in (i). Numbers before the outcrop names refer to the locations in Figure 8.1f. (d–g) are from Lucente and Pini (2003), modified. (a) and (b) are from Lucente (2000), modified.

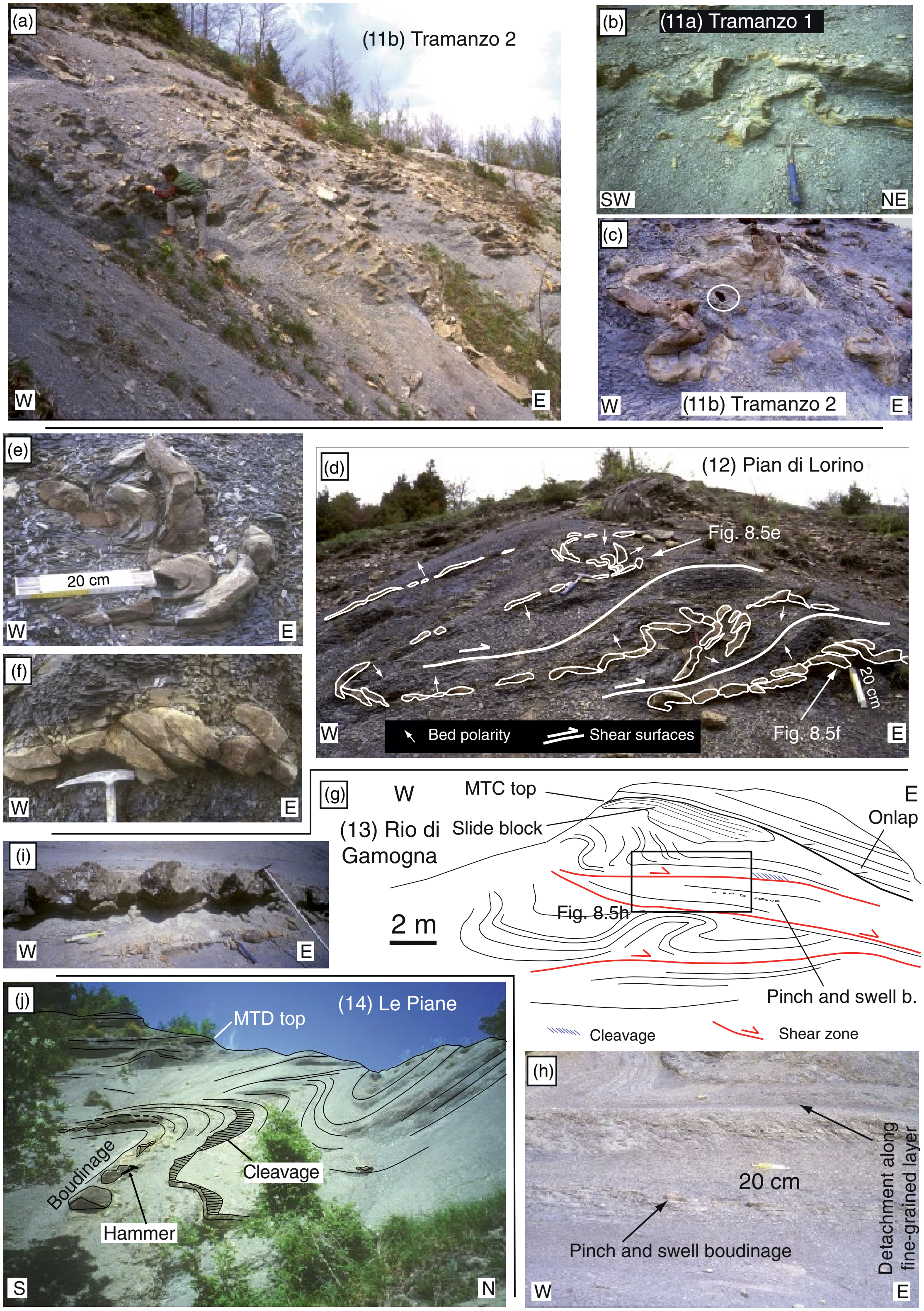

Figure 8.5 Photographs and line drawings showing key features of the northeast directed basin plain deposits of the Marradi sector. Numbers before the outcrop names refer to the locations in Figure 8.1f. Lens cap (6 cm in diameter) is for scale in (c). (g) and the line drawing on (j) are from Lucente (2000), modified.

axially refolded folds (Figure 8.4j) (Alsop & Marco, 2013). Strong layer-parallel extension often occurs as suggested by isolated boudins and rootless slump folds. The occurrence of reverse faults, triangle zones, and buckle folding of boudin trains also suggests local compression (Lucente, 2000).

The best exposed outcrop, the Campanara outcrop (outcrop 7 in Figure 8.1f; see Figure 8.4f), allows observations on a notably continuous shear surface arranged as a normal, listric major (master) fault, which connects smaller low-angle listric normal faults in the hanging wall (Figure 8.4f, g). These faults appear as shear surfaces/bands, systematically associated with trains of prolate-shaped boudins and asymmetric detachment folds, the axial surface of which is progressively rotated down flow (Figure 8.4f, g). In the footwall, shear surfaces/bands are less continuous and clear, the continuity of the beds is no greater than a few meters, and deformation is higher due to severe flattening-type (oblate) boudinage, asymmetric folds, and stacking of boudins. The deformation seems prevailingly associated with a certain amount of simple shear, which become greater in some parts of the body, causing dispersion of isolated boudins and fold hinges in a sand-silt matrix.

8.3.4. Casaglia Sector, Central Zone: The Southwest Verging Basin Plain Deposits

In this zone, the lower body of the CMC comprises basin plain deposits similar to the ones described before for the easternmost zone (mainly D_1, D_2, and D_3 of Mutti and Ricci Lucchi (1972, 75)). Sense of transport constantly shows a northeast to southwest direction, and the general organization of the body, from bottom to top, implies three to four meters of concentrated deformation with asymmetric domino-like boudinage and isolated fold hinges, followed by meter-scale recumbent folds with thinned and disrupted overturned limbs.

The strong basal interaction with the substratum in this area is testified by a scour ripping up the Ciriegiolo key beds (west of section B in Figure 8.1f). The Isola outcrop displays the down-flow, layer-parallel displacement of a 10 m thick bed package comprising the Ciriegiolo key beds (beds 1 and 2 in Figure 8.2h) along a weaker, thin-bedded, and fine-grained interval (see, e.g., Butler & McCaffrey, 2010). Two detachment folds occur above the layer-parallel detachment surface exposed along the left bank of the creek. The shearing related to the mass transport above caused spiral-like (re)folding of the detached beds (Figure 8.2h).

8.3.5. Santerno Sector: The North Verging Basin Plain Deposits

A low-angle ramp characterizes this zone showing an average cutoff angle of less than 1°. In the Le Piagnole locality, the top part of the MTC shows shear surfaces displacing beds in a downsection direction (Figure 8.4k), transitioning down flow in spoon-shaped faults. Pinch-and-swell, constriction-type boudinage and cleavage occur near fault surfaces. Isolated boudins made up of thinner beds occur when strain increases and are locally subject to north verging stacking. Meter-scale folds deform beds that have been previously boudinaged as described for the other outcrops.

The Bechinella outcrop shows gently dipping overfolded to recumbent synclines, with strongly flattened anticlinal counterparts (Figure 8.4l), representing detachment folds originated from the main basal contact and two shear surfaces (thrusts). Folds become progressively more asymmetric down flow and recumbent to isoclinal in the median part of the outcrop. Basal contact has a staircase shape, with a low-angle ramp overlaid by ripped up and stacked chunks of beds. Trains of smaller-scale recumbent folds characterize the middle-upper part, depicting a progressive decrease in bed continuity upward and down flow.

8.4. SHEAR ZONES

Discrete shear zone or surfaces accommodate differential movements of slide blocks and detached bed packages, displacement along listric normal faults, thrust, and at the base of detachment fold trains. They do not show brittle/frictional features such as striations, mineral recrystallizations (slikenfibers), or mesoscopic evidence of cataclasis, showing instead the following features:

1. Thin (around 1–5 cm thick) silty-clayey beds represent the décollement surfaces that enable the onset of detachment folds, as evidenced in the displaced slope deposits of the Casaglia sector (Figure 8.5h);
2. Mechanical discontinuities (e.g., fault surfaces) cutting and offsetting beds and bed packages (Figures 8.3e, f and 8.4h), which can be outlined either by a thin (<1 mm) layer of less cemented silt, finer than the host rocks (Figure 8.4i), or by sand grains coarser than the host rocks (Figure 8.3f). The latter are usually dispersed along fault surfaces according to the sense of movement, but clearly originate from disaggregated sandstone beds.

These fault surfaces never occur as isolated features; smaller subsidiary surfaces usually branch/splay out from the larger one. A typical example is the normal faults of the extensional duplex system exposed in the SP 477 outcrop (Figure 8.3e), which are locally complicated by secondary fault surfaces corresponding to R planes (low-angle, synthetic Riedel planes of Riedel (1929)). Both R and P planes (P or thrust planes; see Skempton, 1966) characterize other outcrops of the CMC, such as the Campanara one (see Section 8.3.3).

Mesoscopic ductile faults are common structures related to shallow level deformation in accretionary prisms and slides (see Hanamura & Ogawa, 1993; Maltman, 1988; Yamamoto et al., 2005, 2009) and have been related to a mechanism of independent granular flow, with rotation and translation of grain, enabled by low effective confining stress and fluid overpressure (Ogata et al., 2014a). A similar mechanism may be sustained here, as suggested by dedicated preliminary study performed on oriented samples of fault surfaces collected in the Bibbiana area (Dykstra, 2005).

These mesoscopic ductile faults represent the surfaces along which the differential movement of the slide blocks took place. A direct linkage with detachment and recumbent folds, boudinage (see the examples of the Campanara outcrop), and boudin stacking is clear. These features appear to be contemporaneous with all the phases of internal deformation and do not seem to characterize just the later stages as suggested by Martinsen and Bakken (1990).

8.5. DOMAINS OF INTERNAL DEFORMATION

The geometric attitude of the basal contact strongly influences the internal structures, since the distribution of zones with a similar deformation style (deformational domains [DD]; Figure 8.6a) follows local changes in the basal contact angle. The high-angle ramp in the Casaglia area corresponds to the DD-8 (Figure 8.6a), characterized by stacking and folding of thrust sheets originated in the lower flat (translation zone, DD-9), and to the development of secondary fold trains. Lucente and Pini (2003) highlighted the role of the emplacement of the extrabasinal component (olistostromes) in further remobilizing, dragging, and (re)accumulating the intrabasinal component, which is in turn arranged into folded by the antiformal thrust stack. High local compression originated here an intense fluid expulsion and elutriation and the onset of chemosynthetic communities after the CMC emplacement (Lucente & Taviani, 2005).

The edge of the extrusion zone, represented by the transition from ramp to low-angle ramp, corresponds to a change in structural style from a system of upright folds (DD-7) to spoon-shaped listric faults associated with gently inclined to recumbent folds (DD-6) (Figure 8.6b). Folds are organized in a continuous belt bounded by slide blocks with their axial surfaces following the belt boundaries (Figures 8.2c and 8.6b). Folds often have their forelimbs more extended or are completely overturned (label d in Figure 8.6b). Due to their geometry, folds can originate from (a) entire fold trains translated from deeper zones (ramp zone), (b) parasitic fold detached from bedded slide blocks along shear zones (see Figure 8.3c–d), and (c) erosion by shear of the base of slide blocks during their down-flow movement (see a, b, and c labels in Figure 8.6b).

The upper flat above the Ciriegiolo horizon (subsector b in Figure 8.1b) shows again undeformed slide blocks separated by shear zones and spoon-shaped faults, which make up the thickest part of the MTC, having only a thin shear zone (up to some meters thick) at the base (DD-5). In comparison with the Bibbiana-Monte della Colonna area (DD-6), however, the thickness of bedded slide blocks and fault-bounded bed packages is reduced; thus the number of faults inside the body is higher and the fold belt is lacking. Typically, faults are associated with intense stratal deformation, with the development of sigmoidal structures, asymmetric domino-type boudinage (Figure 8.2e), and detachment folds. The axial surfaces of such folds are progressively rotated to horizontal (recumbent folds) at the fault tips or at the ramps. Here the forelimbs are subject to strong flattening and elisions. In places (Figure 8.6c), recumbent folds become isoclinal due to the loading exerted by overlying slide blocks (Figures 8.2f–g). Zones of localized stratal disruption occur at the front of advancing isoclinal folds (Figure 8.2g) with development of parasitic folding, boudinage, and boudin stacking (Lucente & Pini, 2003).

The basal zone of concentrated deformation is evident between Bibbiana-Monte della Colonna (outcrop 3 in Figure 8.1f and DD-6 in Figure 8.6a) and SP 477 outcrop (outcrop 4 and DD-5). It is related to prevailing simple shear deformation recorded by pervasive isoclinal folding and asymmetric boudinage of either domino or shear band types, causing stretching of less competent beds and separation of blocks (isolated boudins) (Etchecopar, 1977; Rodrigues & Pamplona, 2018; Swanson, 1992).

In the domain DD-3, the deformation is severely partitioned in the slope sediments, as in the emblematic case of the Campanara (outcrop 7 in Figure 8.1f; see Figure 8.4a–c). Here a normal listric fault bounds a more organized upper limb (hanging wall), with normal faults separating folded bed packages, and a more stratally disrupted and generally deformed footwall. Extension prevails in the hanging wall, while the footwall shows evidence of a prevailing simple shear related deformation, with greater stratal disruption due to severe boudinage, folding, and stacking of blocks. The marked difference between the hanging wall and footwall suggests that the main listric fault represents the boundary and gliding plane between a translated slide block (floater) and the more deformed and mobile substrate.

DD-4 domain displays an internal strain partitioning similar to the other parts of the CMC that moved above the upper flat onto the Ciriegiolo key bed (DD-5) and the more internal low-angle ramp (DD-6). Meter-scale folds deforming prevailingly continuous beds overlap a basal shear zone of concentrated stratal disruption. The main difference stands in the direction of movement, opposed to the main body of CMC, and the presence of a kilometer-sized scour ripping up the Ciriegiolo key beds.

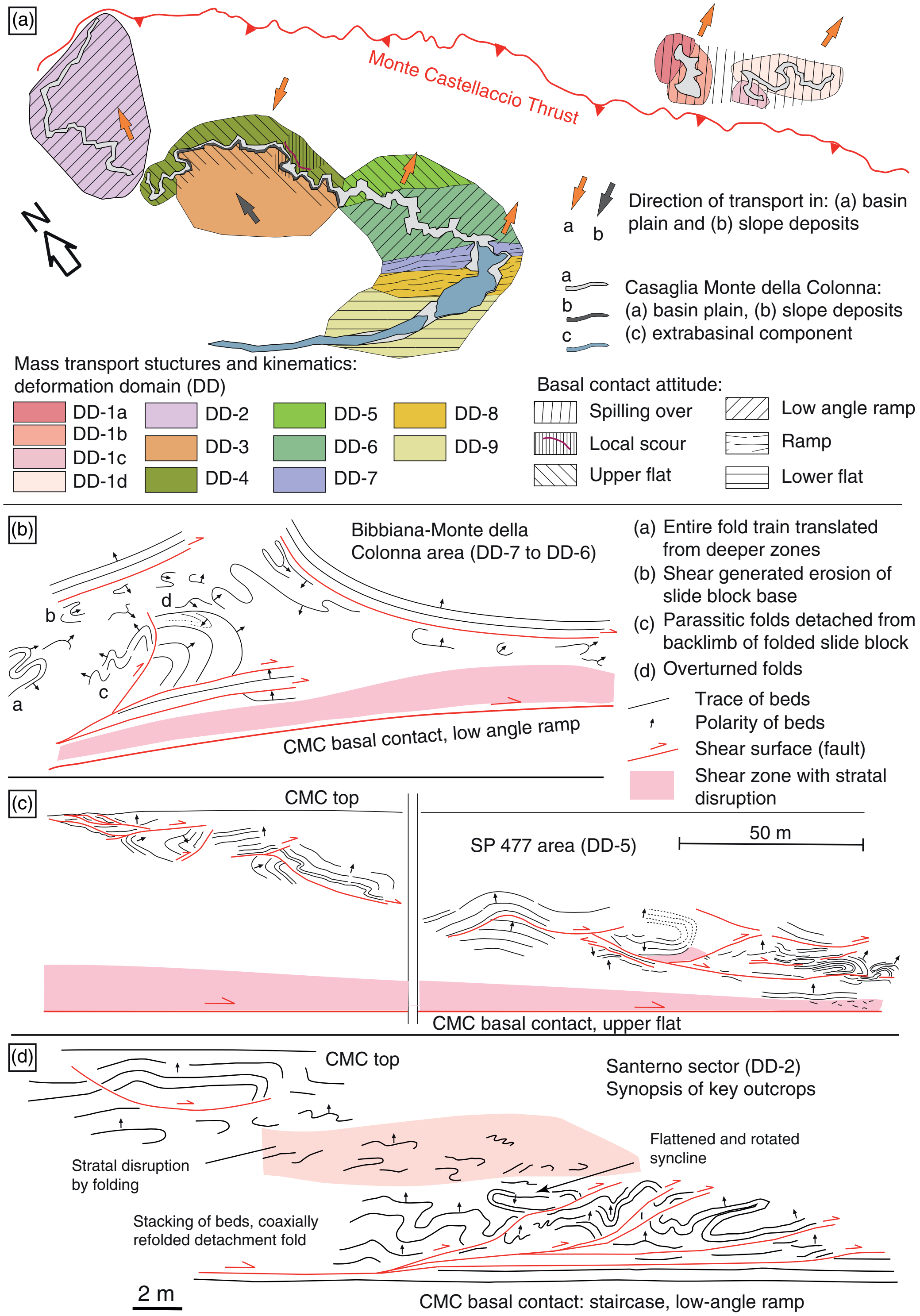

Figure 8.6 (a) Distribution of the domains characterized by similar deformation style and features versus attitude of basal contact in the Casaglia-Monte della Colonna mass-transport complex. (b–d) interpretative, synoptic diagrams based on key outcrops.

The deformation scenario in the Santerno sector (DD-2; Figure 8.6d) differs from the two previous zones, since detachment folds originated from the basal contact and stacking of ripped up beds (Figure 8.4f) replaces the stratally disrupted shear zone. Close and upright detachment folds evolve down flow into gently inclined, asymmetric tight folds. A progressive flattening and disruption of fold limbs occurs upsection, causing the development of recumbent isoclinal folds, isolated or arranged in smaller systems. Spoonlike faults and undeformed, bedded slide blocks characterize the upper part. Bed packages bounded by spoonlike faults and slide blocks are thinner than the other isopic zones.

Trains of recumbent folds with planar curvilinear axes deform the thinner beds of Marradi sector (DD-1a, DD-1b, DD-1c, DD-1d) in association with curved shear zones and cleavage. A generalized stretching of fold limbs couples with a pronounced thickening of hinges. The upper part of the body hosts meter-scale slide blocks (floaters) deformed by listric normal faults and meter-scale folds acting on either undeformed or symmetrically boudinaged beds

Style of deformation changes according to the different subdomains: in DD-1a (exemplified by outcrops 10a-b), stretching of fold limbs often results in symmetric and asymmetric pinch-and-swell boudinage, reaching extreme extension within narrow belts of aligned isolated boudins and rootless slump folds. Boudinage style suggests both pure (flattening of beds) and simple shear (sub-simple shear; Fossen & Cavalcante, 2017). Subdomain DD1b (outcrops 11a-b) shows a lower part with packages of almost continuous beds, relatively poorly deformed by small-scale detachment folds (Figure 8.5e), which dip at low angle to the basal surface of CMC. The upper part shows a more complex system of stacked recumbent folds with contorted hinges and limbs (Figure 8.5b–d). The latter are much more continuous than in DD-1a. Meter-scale, close to tight asymmetric folds deforming stacked boudins characterize the subdomain DD-1c (outcrop 12). This suggests a regime of protracted, progressive deformation in which simple shear dominated flow overprints flattening-type extension (oblate pinch-and-swell boudinage), causing subsequent stacking of boudins and, then, folding.

Counter-verging (southwestward) folds and box folds are common features in these subdomains, being particularly abundant in subdomain DD-1b. They have been tentatively interpreted as related to a frontal confinement due to intrabasinal highs or deceleration of the leading edge of MTC due to deposition-emplacement (see Lucente & Pini, 2003).

The subdomain DD-1d (outcrops 13 and 14) represents the upper part of the MTC, hosting slide blocks of undeformed bedded sequences bounded by and meter-scale folds deforming both continuous and symmetrically boudinaged beds. Listric normal faults are responsible for slide block movement.

Deformation in subdomains DD-1a to DD-1d originates by flattening and simple shear acting concomitantly (sub-simple shear), and often in superposition, throughout the MTC. Although more evident in subdomain DD-1c, this alternation of extension and compression is documented in all the subdomains, as already described by Lucente and Pini (2002). Internal pulses or “waves” of differential decreasing/increasing translation velocity may explain this behavior.

Flattening structures (pure shear) together with simple shear suggest a certain amount of lateral spreading, compatible with a condition of spilling/spreading of remobilized sediments over the basin floor. In the same way, strong bed extension developed in more continuous beds (from DD-1b to DD-1a) may represent local increase in lateral spreading. This interpretation is supported by the position of these extended zones, fitting well with the flat basal surface and the distal position, but is not completely compatible with the coexisting buckling effects (box folds and counter-vergencies) observed in subdomains DD-1a, DD-1b, and DD-1c. Spreading might represent a stage of free extension of the remobilized sediments, overprinted and/or alternated with generalized simple shearing due to faster/slower advance of the upper part of the MTC. Buckling might originate during the last stages of deceleration and emplacement of the CMC slide mass.

Poorly deformed, detached bed packages and coherent, meters to ten of meter-scale folds are present atop the MTC in the more easterly, distal subdomain (DD-1d). They occur above the most deformed parts representing the most external slide blocks.

8.6. ORIGIN OF THE DISPLACED INTRABASINAL SEDIMENTS AND MECHANISM OF TRANSLATION

The intrabasinal beds involved in the Casaglia-Monte della Colonna MTC are the same found in the underlying stratigraphic section (substratum). The displaced sediments in the deformation domains from DD-8 to DD-5 derive from the stratigraphic succession below the CMC basal contact, as directly suggested by the presence of AV and MV key beds in more MTC outcrops (Lucente, 2000) (see, e.g., Figure 8.3a). Here the translation of the MTC materials occurs by extrusion from the ramp and confined spilling over with prolate-type extension. Simple shear is present and overprint (or alternate) with extension, in an overall progressive fashion. Prevalence of simple shear on extension characterizes the lowest part of the body (the always present basal shear zone) or fold belts, and stratal disruption zones originated by the relative movement of large slide blocks. The differential independent movement of slide blocks and detached bed packages along spoon-shaped shear surfaces enables a flow-type mobility for the largest part of the MTC. Internal deformation progressively increases in slide blocks and detached bed packages down flow (compare Bibbiana-Monte della Colonna and SP 477 outcrops), causing a more diffuse folding and the onset of systems of internal faults (Figures 8.2d, f, g, and 8.6c). This ultimately causes the decrease in size of slide blocks and bed packages. Folds progressively tightened in recumbent isoclinal folds.

A source of the counter-verging basin plain deposits above the upper flat (DD-4) cannot be directly recognized, since the likely related ramp has been eroded. Sediments involved in this branch of CMC are basin plain deposits very similar to those exposed below the MTC. A direct provenance form the local substratum with a short transport and the in situ deformation of the substratum is observable in the scour zone, but the style of deformation in the rest of the CMC recalls the ones observed in the other northeasterly sectors (DD-8–DD-5), suggesting a protracted translation and a more distal provenance.

An unsolved point is the nature of the contact between the northeast and southwest moving masses (DD-5 and DD-4) above the same layer (Ciriegiolo key bed), particularly because of the unfavorable outcrop conditions in this key area.

Concerning the slope sediments of domain DD-3, the deflection due to the already spilled-over, northeast moving basin plain sediments (DD-7–DD-5) can be the reason for the northward direction of movement. The preserved continuity of beds and the strong internal organization of listric normal fault systems inside the large slide block in the upper part of the MTC are possibly inherited structures associated with the initial stage of slope failure. This hypothesis may explain the strong contrast with the much more deformed and disrupted lower part, which is a more common style of internal deformation in the CMC, and the marked difference between this slide block and the other ones observed.

In the Marradi sector, the CMC shows internal beds similar to the underlying section, but the flat attitude of substratum and the flattening-type extension associated with simple shear seem to favor the hypothesis of lateral and frontal spreading in a non-confined spilling-over zone. Such beds cannot derive from the ramp zones because the sedimentary facies does not correspond. A provenance from a more proximal area located southward of the translation-extrusion zone is also not plausible because the obstacle of the masses extruded from the ramp. In this framework, they might derive from an intermediate part, now not preserved because of the shortening exerted by the Monte Castellaccio thrust and subsequent erosion. These deposits should have been dragged by northeastward movement of basin plain deposits. The stacked, poorly deformed beds at the base of MTC in DD-1c may correspond to eroded portion of substratum related to this mechanism and translated down flow.

The Santerno sector represents a low-angle ramp with the basal contact progressively rising from the Ciriegiolo key beds up to 10 m above. The basal contact shows a staircase attitude with longer flat zones alternated to small ramp that cut, translate, and stack few beds (Figure 8.6d). Composition and facies of involved basin plain sediments correspond to those of the Casaglia sector and the ones in the same Santerno sector. The style of folds and their upward progressive disruption upward support a mechanism of inclusion of substrate for the lower part, while the upper component (bed packages involved in folds and spoonlike faults) can originate from more southerly or southwesterly areas. Following this hypothesis, the direction of movement can be compatible with a provenance from failures southwest of the Casaglia sector and the deflection of the displaced sediments along the direction of the basin due to the obstacle of the masses already extruded (paleo-bathymetry) in the Casaglia-Bibbiana area (see Lucente & Pini, 2003). A provenience from a closer, independent southwesterly source, thus placed northwestward of Casaglia sector, is an alternative hypothesis (Lucente, 2004).

It is worthy to note that the internal style of the CMC in the Santerno sector recalls the general organization observed in the Marradi sector, with bed packages detached from substratum and passing upward to trains of folds and higher disruption of beds, and the absence of the consistent basal shear zone typical of other sectors. Movement along faults is important in the slope deposits and in the Bibbiana to SS 477 outcrops, being less important in the Marradi and Santerno sectors where slump-like structure dominate. This similitude is not striking, however, since Santerno sector CMC lacks the flattening-type boudinage and shows the unique feature of detachment folds ripped up from the substratum (Figure 8.6d). This sector is more compatible with a depositionally confined type of MTC and not a spilling-over one (Ogata et al., 2012a).

8.7. CONCLUDING REMARKS

The Casaglia-Monte della Colonna body represents one of the best and continuously exposed “fossil” MTC in foredeep succession exhumed in a mountain chain. This allows the unique opportunity to study the internal architecture of a submarine landslide complex resulting from the (geologically) simultaneous collapses of the accretionary wedge front (Ligurian Nappe derived extra-basinal), slope, and basin plain deposits (see Lucente & Pini, 2008). The different angles of the basal contact on the substratum cause changes in flow mechanics, internal structures, and deformational regime (stretching vs. flattening vs. simple shear).

After 20 years from the pioneering work of Lucente (2000), we better understood the internal structures and substrate-MTC interactions in the lower flat and in the ramp of the Casaglia zone (Casaglia A and B outcrops) and in the Santerno sector. The latter was not interpreted in detail before. We also presented materials that were not easily available to an international audience (Lucente, 2000, 2002), as in the case of the southwest translated basin plain deposits of the Isola sector. We also propose a new interpretative scheme according to the areal distribution of the internal deformation features linked to geometry of the MTC base.

Nonetheless, some open problems remain, for instance, the characterization of the mechanisms preconditioning and triggering the wedge-slop-basin plain failure. In previous work, we suggested the onset and failure of a temporary slope (following Ricci Lucchi (1978)) and the contemporaneous collapse of the slope and front of the wedge due to retrogressive failure. The CMC and the other bodies containing Ligurian Nappe derived materials, slope, and basin plain deposits (Visignano, Nasseto and Le Caselle MTCs, Landuzzi, 2005; Lucente, 2004; Lucente & Pini, 2003) suggest that the instability of the entire frontal system of the wedge-slope-basin plain repeatedly occurred in the inner stage of Marnoso-arenacea foredeep. The Nasseto and CMC units pertain to the same stratigraphic horizon, being constrained by the same regional-scale key beds (Lucente, 2000, 2004; Lucente & Pini, 2003), suggesting that basin-wide instability occurred.

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