Formation of Taconic Mélanges and Broken Formations in the Hamburg Klippe, Central Appalachian Orogenic Belt, Eastern Pennsylvania.

Formation of Taconic Mélanges and Broken Formations in the Hamburg Klippe, Central Appalachian Orogenic Belt, Eastern Pennsylvania

Giulia Codegone[1,*], Andrea Festa[1,2], Yildirim Dilek[2]

[1] Dipartimento di Scienze della Terra, Università di Torino, 10125 Torino, Italy;

[2.] Department of Geology and Environmental Earth Science, Miami University, Oxford, OH 45056, USA;

*Corresponding author:

Giulia Codegone

E-mail: giulia.codegone@unito.it

Submitted to:

Tectonophysics

Special Issue: Chaos and Geodynamics: Mélanges, Mélange Forming Processes and Their Significance in the Geological Record

Abstract

The Hamburg Klippe of the Central Appalachian orogenic belt exposed in eastern Pennsylvania displays a complex record of poly-phase mélange and broken formation development in a convergent margin setting. It includes an imbricate stack of tectonic slices, which consist of upper Cambrian to Upper Ordovician deep-water and continental slope sedimentary rocks, emplaced by gravity sliding onto the Laurentian passive margin during deposition of the Upper Ordovician Martinsburg Formation. Based on their internal structure and stratigraphy, the block-matrix ratios and relations, and the inferred tectonic settings of origin, we have differentiated the following mélanges and broken formations, whose evolutionary stages coincide with specific deformational phases in a complete orogenic cycle from subduction to collision: (i) sedimentary broken formations without exotic blocks, formed by *in situ* and local down-slope remobilization during the early stages of closure of the Octoraro Sea basin in the Early Ordovician; (ii) two types of sedimentary mélanges with exotic blocks, formed at the front of the advancing accretionary wedge during the Middle Ordovician subduction of the Laurentian continental margin beneath a microcontinent-magmatic arc tectonic assembly; (iii) layer-parallel, extensional broken formation and a diapiric mélange, formed in the outer trench and at the toe of the accretionary wedge, respectively, during the early-Late Ordovician; (iv) precursory olistostromes, formed during the Late Ordovician collisional episodes as the Hamburg Klippe was emplaced in the Martinsburg Formation on the downgoing Laurentian continental margin; and, (v) contractional deformation-related broken formations, formed at the base of main thrust faults overprinting the previously formed mélanges and broken formations. This sequential development of different mélange types in the Central Appalachians was strongly controlled by the degree of consolidation of the layered strata and their rheological differences, the structural level of mélange formation within the accretionary wedge, and the kinematics of deformational processes.

Key words: Mélange, broken formation, subduction, collision, accretionary wedge.

1. Introduction

Chaotic rock bodies may include olistostromes, mass-transport deposits, broken formations, tectonic mélanges and diapiric occurrences, and commonly form as a result of tectonic, sedimentary and diapiric processes and their mutual interplay and superposition. Their internal structure and architecture display strong evidence for those geological processes that operated in certain tectonic setting(s) and along plate boundaries. The structure and stratigraphy preserved in chaotic rock bodies can also allow us to better understand the tectono-stratigraphic evolution of orogens in which they are preserved (e.g., Ogawa, 1998; Festa et al., 2010a, 2010b). This is the case of different orogenic belts and accretionary complexes around the world where mélanges and olistostromes occur, for example in the Alpine-Himalayan belt (e.g. Ring et al., 1990; Trommsdorff, 1990; Liu and Einsele, 1996; Federico et al., 2007), circum-Mediterranean orogens (e.g., Elter and Trevisan, 1973; Dilek et al., 1999, 2007; Pini, 1999; Okay, 2000; Robertson et al., 2009; Camerlenghi and Pini, 2009; Ghikas et al., 2010; Festa et al., 2010b), Appalachians (e.g., Lash, 1987a; Rast and Horton, 1989; Cousineau and St-Julien, 1992; Tremblay et al., 1995; Ganis and Wise, 2008), circum-Pacific regions (e.g., Hsü, 1968; Matsuda and Ogawa, 1993; Cowan, 1985; Cloos, 1982; Wakabayashi, 1992; Kimura et al., 1996; Kusky and Bradley, 1999; Ikesawa et al., 2005; Yamamoto et al., 2009; Wakabaysahi et al., 2010) and many others.

The Taconic Allochthon of the Central Appalachian orogenic belt of eastern Pennsylvania (Fig. 1) includes some of the best examples of unmetamorphosed chaotic rock body occurrences that provide us with critical structural and stratigraphic evidence to examine the mode and nature of depositional and deformational processes throughout the tectonic evolution of this orogenic belt. (Root and MacLachlan, 1978; Lash and Drake, 1984; Lash, 1987a; Ganis et al., 2001; Ganis and Wise, 2008). These examples mainly occur in the Hamburg Klippe (*sensu* Stose, 1946) or Dauphin Allochthon/Formation (*sensu* Ganis et al., 2001) which represents an allochthon structural assemblage of deep-water and continental slope basin units, late Cambrian – Late Ordovician in age, emplaced by gravity sliding (e.g., Epstein et al., 1972; Root and MacLachlan, 1978; Lash and Drake, 1984; Faill, 1997) within the Late Ordovician foreland basin of Laurentian craton (Martinsburg Formation). Unmetamorphosed chaotic rock bodies (Root and MacLachlan, 1978; Lash, 1987a), “mixed terrains” (Root, 1977), olistostromes bearing huge olistoliths (Ganis et al., 2001; Ganis and Wise, 2008), diapiric and tectonic mélanges (Lash, 1987a) have been described in different and separated sectors of the Hamburg Klippe, and

their meaning discussed to document and interpret the allochthonous origin, structural evolution, and geodynamic significance of this Klippe.

This paper, based on geologic mapping and stratigraphic-structural observations, examines both famous and new examples of chaotic rock bodies (i.e., mélanges and broken formations) of the Hamburg Klippe (*sensu* Stose, 1946) that display structural and stratigraphic lines of evidence for progressive deformation, occurred from pre-to syn-Taconic orogeny (Early to Late Ordovician), and record a complete orogenic cycle in a convergent margin setting from early stage of closure of the Octoraro Sea basin, to subduction-accretion, and finally to obduction and collision. The peculiarity of these examples and, in particular of the subduction-related mélanges hereafter described, is that they formed in a shallow structural and supracrustal level of the Taconic accretionary complex as suggested by the lack of slices or blocks of oceanic crust that, on the contrary, characterize the coeval mélanges formed in relatively deeper subduction-accretion settings (see Ogawa, 1998). The close mutual relationships between diverse processes, state of consolidation of pre-deformed sediments, and stratigraphic and structural position in which chaotic rock bodies formed, strongly controlled their block-in-matrix arrangement allowing a correlation between different types of mélange and broken formation that, in the Hamburg Klippe sector, were subjected to rare attempts of correlation to one another in the past literature.

2. Regional Setting

The Central Appalachians of eastern Pennsylvania (Fig. 1) display a complete geological record of a long-lived evolution from the late Neoproterozoic rifting of the Rodinia supercontinent to the Middle - Late Ordovician collision between Laurentian craton and an assemblage of microcontinents and magmatic arc units that culminated in the Taconic Orogeny (e.g., Dewey, 1969; Dewey and Kidd, 1974; Rowley and Kidd, 1981; Faill, 1997).

After the dismantling of Rodinia (~620 to 580 Ma) a line of microcontinents (i.e., Brandywine and Baltimore Terranes) was separated from Laurentian craton to the NW by a seaway of the western Iapetus Ocean *sensu lato*, the Octoraro Sea (Faill, 1997; Wise and Ganis, 2009). In the late Early Ordovician, this Octoraro Sea began

closing as a result of the subduction of its seafloor eastward beneath the archipelago of these rifted microcontinents and a magmatic arc system. This convergence and the associated subduction zone tectonics produced a northward advancing accretionary wedge (Stevens, 1970; Stanley and Ratcliffe, 1985; Faill, 1997; Stewart et al., 1997; Hibbard et al., 2007; Wise and Ganis, 2009), and resulted in the collision of the microcontinents with the Laurentian margin in the down-going plate during the Late Ordovician. Among the most important tectonic products of this collisional event that are directly related to our study are: (i) development of the Martic Thrust, which emplaced the Octoraro Sea sediments onto the Laurentian continental margin; (ii) emplacement of the Hamburg Klippe (*sensu* Stose, 1946) or the Dauphin Formation (*sensu* Ganis et al., 2001); (iii) overriding of the crustal units of the microcontinents and the magmatic arc system as imbricate thrust sheets over the Laurentian continental margin (Faill, 1997).

2.1. Hamburg Klippe

The Hamburg Klippe (*sensu* Stose, 1946; see Fig. 2) is a structural assemblage of deep-water and continental slope sedimentary units, which range in age from late Cambrian to Late Ordovician. As a direct consequence of the development of the Martic Thrust, collapse of the Octoraro Sea, and obduction of the crustal units of the microcontinents (i.e., Brandywine Terrane) and the magmatic arc, the stratigraphic packages of the Hamburg Klippe were emplaced by gravity sliding (e.g., Epstein et al., 1972; Root and MacLachlan, 1978; Lash and Drake, 1984; Faill, 1997; Ganis et al., 2001; Ganis and Wise, 2008; Wise and Ganis, 2009) onto the leading edge of the carbonate platform of the Laurentian passive margin while the Upper Ordovician Martinsburg Formation was being deposited in the Laurentian foreland basin (e.g., Epstein et al., 1972; Root and MacLachlan, 1978; Lash and Drake, 1984; Faill, 1997; Ganis et al., 2001; Wise and Ganis, 2009). The existence of Baltoscandian conodonts (Bergström et al., 1972; Repetski, 1984; Horton et al., 1989) in the sedimentary units of the Hamburg Klippe suggests that its succession has been deposited adjacent to an offshore microcontinent well isolated from the Laurentian passive margin by an oceanic barrier (e.g., Epstein et al., 1972; Faill, 1997; Ganis et al., 2001; Ganis and Wise, 2008). It could represent the northeastern and most distal part of the tectonic imbricate detached from the Westminster Terrane (Fig. 1; see Ganis and Wise, 2008) deposited in undetermined part of the Octoraro Sea (Lash and Drake, 1984; Lash, 1987a; Faill, 1997; Ganis and Wise, 2008; Wise and Ganis, 2009).

From a structural point of view the Hamburg Klippe is characterized by two imbricated units (Fig. 1), the Richmond and Greenwich slices (*sensu* Faill, 1997), each of which consists of different minor stacked slices (e.g., Epstein et al., 1972; Root, 1977; Root and MacLachlan, 1978; Lash and Drake, 1984; Lash, 1985a, 1987a; Drake, 1987; Ganis et al., 2001; Ganis and Wise, 2008; Wise and Ganis, 2009) whose internal stratigraphic succession and chaotic rock bodies occurrence were rarely subjected to attempts of correlation to one another in the past literature (see, for example, Lash and Drake, 1984; Faill, 1997; Ganis et al., 2001). The lacking of metamorphism and tectonic slivers (or blocks) of oceanic crust in the Hamburg Klippe supports a shallow (entirely supracrustal) structural position for the original development and imbrications of both the Greenwich and Richmond slices and related bounding thrust surfaces within the forming accretionary complex (Lash et al., 1984; Faill, 1997).

The Greenwich Slice (Figs. 2 and 3) represents the lowermost and external unit consisting of a tectonically thickened succession of Lower to Middle Ordovician pelagic and hemipelagic deposits (mainly red and green shale and mudstones with subordinated deep-water limestone and radiolarian-bearing siliceous shale and chert) that is overlain by Upper Ordovician (*N. gracilis* zone) coarsening-upward turbidites and minor hemipelagites. This coarsening upward succession provides good evidence for a transition from pelagic sediments on an abyssal plain (Lower to Middle Ordovician deep-water limestone and radiolarian-bearing siliceous shale and chert) to outer trench slope and trench axis (Middle Ordovician hemipelagites and turbidite deposits) (Lash and Drake, 1984; Lash et al., 1984; 1985a, 1986a, 1986b). The pelagic deposits are prevalent in the central (Manada Hill Member *sensu* Ganis et al., 2001; Allochthon#1 *sensu* Ganis and Wise, 2008) and western sectors (Enola Allochthon *sensu* Root and MacLachlan, 1978), and subordinated in the eastern one ("miscellaneous units" *sensu* Lash and Drake, 1984). West of Susquehanna River and North of Harrisburg, these pelagic deposits (Fig. 2) are tectonically superposed by greenish-gray shales with interbeds of calcareous graywacke and arenaceous conglomerates and limestones corresponding to the Summerdale Allochthon of Root and MacLachlan (1978). The Upper Ordovician turbidites are instead prevalent in the eastern and central sectors and locally (Dauphin County) these have been interpreted as piggy-back deposits overthrust by Middle Ordovician graywackes bearing olistostostromes (Nyes Road and Shellsville Members; see Ganis and Wise, 2008).

In the central sector of the Greenwich slice (North of Lebanon), the late Lower - Middle Ordovician hemipelagic mudstone and coarse-grained sandstone of outer trench and trench axis, that overly a fault bounded succession of pelagic deposits, are intruded by volcanic rocks (Jonestown volcanic; Figs. 2 and 3) consisting of hypabissal intrusive diabases and ocean-floor basalts with a tholeitic MORB-affinity (pillow lavas and breccias) (Faill, 1997; Ashcroft and Kidd, 2002; Wise and Ganis, 2009). The petrographic/geochemical analyses on the host sediments indicate a dominant continental (and not volcanic arc) source influence (see Lash, 1986b for major details; see also Ashcroft and Kidd, 2002 and Landing et al., 2003). The volcanic rocks are interpreted as a basalt extrusion onto the subsiding outer trench slope prior to collision (Lash, 1986b; Landing et al., 2003) or on the Laurentian foreland either well prior or during the arrival of the subduction system (Ashcroft and Kidd, 2002). Two possible mechanisms for the Jonestown volcanic-sedimentary association have been hypothesized, reflecting respectively the migration of a spreading ridge ("mid-oceanic ridge", Lash, 1986b; "sea mountain", Ashcroft and Kidd, 2002) or a leaky transform fault toward the trench (similar to the subducting Juan the Fuca plate) (see also Landing et al., 2003).

The Richmond Slice (*sensu* Lash and Drake, 1984) represents the uppermost and most internal unit that is tectonically superposed to the Greenwich Slice (Figs. 2 and 3). It is characterized by an upper Cambrian to Middle Ordovician slope and toe-of-slope succession that consists of prevalent thin-bedded gray shale and siltstone (with local graywacke interbeds). These are characterized by abundant massive beds of shelf and/or slope derived material, such as limestone conglomerate and ribbon limestone (Epstein et al., 1972; Root and MacLachlan, 1978; Lash and Drake, 1984; Lash, 1985b; Lash, 1987b).

West of the Susquehanna River (Figs. 2 and 3), chaotic rock bodies (Conodoguinet and Middlesex wildflysches *sensu* Root and MacLachlan, 1978) consisting of mixed autochthonous deposits and allochthonous blocks of Hamburg Klippe-origin are interleaved within the Late Ordovician basal Martinsburg Formation (*C. bicornis* – *D. clingani* zones) as precursors of the final emplacement of the Hamburg Klippe within the Laurentian foreland basin.

3. Types of mélanges and broken formations in the Hamburg Klippe

Based on geological field mapping and structural and stratigraphic analyses, we have differentiated several sedimentary, tectonic and diapiric mélanges and broken formations in the Hamburg Klippe. These mélange and broken formation occurrences differ from each other because of their structural and stratigraphic position within the Klippe, the age and nature of the blocks and the matrix in the mélanges, their internal organization and structural architecture, and the nature of the bounding surfaces.

3.1. Sedimentary mélanges

We have distinguished two different sedimentary mélange occurrences, characterized mainly by the types and distribution of different blocks in them. The main distinguishing criteria between these two types include the percentage of native versus exotic blocks, the nature of the matrix, and the size and distribution of embedded blocks.

*3.1.1. Type 1 – Sedimentary mélange (**SedMé1**)*

Two sub-types have been distinguished. Despite the major differences between their internal features, these two sedimentary mélange types locally show a gradual transition to each other.

3.1.1.1. Sub-Type 1a (**SedMé1a**)

This sedimentary mélange is preserved within the Middle Ordovician (*P. elegans* zone) turbiditic succession of the central and eastern sections of the Greenwich slice. It mainly corresponds to the Shellsville Member of Ganis et al. (2001) (Allochthon #2 of Ganis and Wise, 2008) and to part of the “miscellaneous units” of Lash and Drake (1984).

In the Dauphin/Lebanon Counties (near Shellsville; Fig. 2), **SedMé1a** is characterized by a block-in-matrix fabric and is composed of upper Cambrian to Lower Ordovician exotic blocks, ranging in size from some meters to hundreds of meters (Fig. 4), that are embedded and randomly distributed within a highly deformed matrix made of alternating layers of shale and sandstone and/or hemipelagic shale-mudstone. Blocks are representative of slope and abyssal facies units, such as hemipelagic shale, siltstone and limestone, pelagic variegated shale and

mudstone, ribbon and platy chert, and deep-water limestone derived from the Richmond slice succession (see also Ganis et al., 2001). The matrix displays a pervasive, mainly SSE-dipping scaly cleavage that is strongly parallel to the structural fabric associated with the late Taconic and Alleghenian deformational events. The other deformational features include slumps, contorted beds and boudinage.

In the eastern part of the Hamburg Klippe (east of Lenhartsville, Berks County), the most notable example of **SedMé1a** corresponds to the mélange described by Epstein et al. (1972). Here, it consists of decimeter-sized limestone blocks and a 25-m-long, Lower Ordovician limestone block derived from the Richmond slice succession. The matrix is composed of a red-green mudstone rock, which corresponds to the "miscellaneous units" of Lash and Drake (1984).

3.1.1.2. Sub-Type 1b (**SedMé1b**)

This sedimentary mélange type occurs in the eastern (South of Kempton, Berks County) and western (Summerdale Plaza at Enola, Cumberland County) sections of the Greenwich Slice (Fig. 3), where it is preserved within a Middle Ordovician shaly-hemipelagic succession. It differs from **SedMé1a** in that exotic blocks are less common than the native ones and that both block types are smaller in size in comparison to their counterparts in **SedMé1a**.

The most notable example of **SedMé1a** crops out south of Kempton in Berks County (see also Type II mélange of Lash, 1987a; Fig. 2), where it consists of a lenticular-shaped chaotic rock body up to a few tens of meters thick and hundreds of meters long which internally consists of several minor lenticular chaotic bodies (commonly up to 3-4 meters wide and tens of meters long in size) (Figs. 5A and 5B). These chaotic rock bodies, and the major one, are bounded at their base by irregular erosional surfaces. Blocks within these bodies consist of slope- and abyssal plain-derived sediments (Fig. 5C), such as hemipelagic shale, siltstone and limestone, deepwater limestone, silicified mudstone, pelagic variegated shale, radiolarian-bearing siliceous mudstone and chert. Only small part of these blocks includes extrabasinal, exotic rocks, which are commonly older than the matrix at the time of their emplacement (see also Lash and Drake, 1984; Lash, 1987a). The matrix consists of shale and siltstone displaying primary (non-tectonic) slump and fluidal structures, and a pervasive, SSE-dipping scaly cleavage that is parallel to the regional structural fabric. Tabular and/or long-axis blocks are reoriented

parallel to the fluidal features and to the basal erosional surface (Fig. 5B) of each chaotic body. Upward, these blocks are randomly distributed within a brecciated matrix (Fig. 4B).

In the western section of the Greenwich Slice (Summerdale plaza at Enola; Figs. 2 and 3) **SedMé1b** shows similar characteristics of the above described example (see also the Summerdale Allochthon of Root and McLachlan, 1978). Blocks of limestone, graywacke, sandstone and chert (up to a few decimeters in size) are randomly distributed within a matrix of alternating layers of gray shale and graywacke (Fig. 6A). However, locally the long-axes of tabular blocks are strongly aligned with the cleavage developed along reverse shear zones (Figs. 6B, 6C, and 6D). This cleavage, which is pervasive at millimeter scale, steeply dips to SE (Fig. 6D) and it is aligned to high angle minor thrust faults related to the ENE-striking regional thrust superposing, to the SE, the Middle Ordovician coherent stratigraphic succession of the Greenwich slice onto the chaotic rock bodies of the Summerdale Allochthon (Figs. 6B and 6C). The occurrence of slump folds within the blocks (see also Root and McLachlan, 1978) suggests that the sediments making up these blocks were not completely lithified at the time of deformation. Erosional surfaces at the base of chaotic bodies are not preserved and/or overprinted by tectonics. Farther west, between Harrisburg and Carlisle (Figs. 2 and 3), the **SedMé1b** mélange type is poorly exposed and is composed of upper Cambrian-Lower Ordovician limestone blocks randomly distributed within a Lower-Middle Ordovician matrix consisting of pelagic sediments grading upward into and/or locally interfingered with hemipelagic and turbiditic deposits (Fig. 6E). The block sizes range from decimeter to tens of meters. This sedimentary mélange corresponds to the Enola Allochthon of Root and MacLachlan (1978).

*3.1.2. Type 2 – Sedimentary Mélange (**SedMé2**)*

This mélange type consists of several chaotic bodies interleaved within the Upper Ordovician (C. *bicornis* zone; Ganis et al., 2001) lower shale unit of the Martinsburg Formation. The **SedMé2** corresponds to the “mixed terranes” of Root (1977) and to the Conodoguinet and Middlesex wildflysch units of Root and MacLachlan (1978) that represent transitional units between the overlying Greenwich Slice and the Martinsburg foreland basin (Figs. 2 and 3).

The Conodoguinet wildflysch consists of several block-in-matrix bodies, up to kilometer-long and several meters thick, with tabular, elongated and rounded blocks of both intrabasinal and exotic (with respect to the Martinsburg

Formation) rocks floating with a random distribution in a dark-gray shaly matrix. The blocks, centimeter to decimeter in size, consist of limestone and gray shale, limestone breccia, massive limestone, red and green shale, chert, siltstone and graywacke with some rare, larger blocks (up to decimeters in size) of limestone and shale. The matrix is composed of alternating layers of gray shale and siltstone with rare graywacke interbeds, and displays a pervasive, SSE-dipping, scaly cleavage that is parallel to the regional structural fabric (see also Geyer, 1970, Root, 1977; Root and MacLachlan, 1978).

In the Middlesex area, at the westernmost termination of the Greenwich Slice, the shale units of the Martinsburg Formation are prevalent and are interbedded with chaotic limestone horizons (hundred of meters long and tens of meters thick), comparable with those of the Enola Allochthon (see Root and MacLachlan, 1978 for major details).

3.2. Broken Formations

We have distinguished three types of broken formations (*sensu* Hsü, 1968) in the study area. These broken formations differ from the above-described sedimentary mélanges in that they do not contain exotic blocks.

*3.2.1. Type 1 – Broken Formation (**BrFm1**)*

This type is preserved within the slope and toe-of-slope succession of the late Cambrian to late Early Ordovician Richmond Slice (Virginville Fm. of Lash and Drake, 1984). In the Berks County near Bernville (see also Epstein et al., 1972), and at the Sacony Bridge near Virginville (see also Lash and Drake, 1984; Figs. 2 and 3), block-in-matrix layered horizons (up to one meter thick and probably several hundreds of meters long) include limestone blocks and fragments enclosed within a mudstone matrix (Fig. 7A). Both the blocks and the matrix are lithologically similar to the surrounding and interstratified carbonate sediments in which they are interleaved. The limestone blocks are imbricated and/or irregularly folded (up to decimeter-size) by slump structures with fold axes aligned parallel to the rarely exposed slip surface and/or to the direction of block imbrication (Fig. 7A). The basal surface of these chaotic bodies corresponds to an intraformational, gravitationally induced slip surface. The layered chaotic horizons are spatially associated with ribbon limestone beds, which show pinch-and-swell structures, boudinaged and slumped beds (Figs. 7A and 7B).

In the Onyx Cave (west of Virginville, Berks County), the block-in-matrix deposits include tabular and barely rounded blocks, up to decimeters long, floating with a random distribution in a homogeneous sandstone matrix (rarely muddy in Leesport area) that locally intrude the overlying well bedded succession. The matrix is devoid of sedimentary structures, except for locally developed fining-upward grading (Figs. 7A and 7C). The blocks consist of intrabasinal laminated to massive limestone, lime mudstone, calcarenite, sandstone, sandy-limestone and gray shale derived from deep-water slope and/or shallow-water shelf successions (see also Epstein et al., 1972; Lash and Drake, 1984).

*3.2.2. Type 2 – Broken Formation (**BrFm2**)*

This type is preserved mainly in the lower Upper Ordovician graywacke succession in the eastern section of the Greenwich Slice (Figs. 2 ad 3; see also Lash, 1985a, 1987a, 1989). The main characteristic feature of the **BrFm2** is a gradual increase in deformation from normal bedded succession to strongly deformed block-in-matrix fabric (Fig. 8A). This transition occurs within tens of meter-thick packages of alternating graywacke and thin mudstone layers that are commonly bounded by slumped horizons (Fig. 8A). The best examples occur south of Albany (Berks County, see also Type I mélange of Lash, 1987a). The two end members of this broken formation are represented by: (1) undeformed decimeter to meter-thick sandstone beds alternating with decimeter-thick mudstone interlayers, which show weak to moderate fissility (Fig. 8A); (2) strongly deformed, meter to tens of meters-thick, foliated mudstone horizons enveloping lenticular-shaped blocks of sandstone (Fig. 8B). The long axis of these sandstone blocks are aligned parallel to a bedding-parallel foliation steeply dipping to SW (Fig. 8E), which forms millimeter to centimeter-wide discrete shear zones in the mudstone (Fig. 8B).

In the strongly deformed part of this broken formation, edges of the phacoidal and lozenged-shaped sandstone blocks are deformed by centimeter to decimeter-scale extensional faults (Figs. 9A and 9B). Faulting-related deformation gradually decreases toward the inner part of the blocks, which range in size from a few centimeters to several meters. The phacoidal and lozenged-shaped sandstone blocks (Figs. 9A and 9B) typically lack internal sedimentary structures, such as graded bedding, convolute and/or parallel lamination, ripples, which, in contrast, occur within undeformed sandstone away from the deformation zones. Tension fractures occur perpendicular to less-deformed beds with varying thicknesses, resulting in irregular lower and upper bed surfaces, which, in turn, grade into pinch-and-swell structures and finally into isolated boudins suggesting layer-

parallel extension. The mudstone layers show a gradual increase of the foliation development according to the increase of deformation. The foliation is well aligned to boudinated layers and wraps around the isolated blocks accommodating their layer parallel extensional deformation through C"-type shear bands (*sensu* Passchier and Trouw, 2005) developed at small angle to the foliation (Fig. 9A). All blocks, boudinated layers, and foliation dip at high angle to SW as well as the undeformed coherent succession (Fig. 8E).

S-C shear fabrics, SW-dipping reverse faults (decimeters to meters long), and a poorly pervasive scaly cleavage system associated with the Taconic and/or Alleghenian orogenic events (Fig 8D) crosscut at lower angle this type of broken formation and constitute the third type of broken formation (see below *Type 3 – Broken Formation*).

*3.2.3. Type 3 – Broken Formation (**BrFm3**)*

This type is ubiquitous in the Middle to Upper Ordovician succession of the Greenwich Slice, and it is strictly related to the Taconic and/or Alleghenian phase thrusting that deformed the Hamburg Klippe after its emplacement in the Martinsburg foreland basin. The most common feature of this type of broken formation is a well-defined, structurally ordered block-in-matrix arrangement showing a gradual decrease of stratal disruption away from the thrust faults. Thus, the rocks display gradation from strongly deformed and disrupted shear zones (Fig. 10A) to undeformed, well-bedded successions. The thickness of this broken formation can be anywhere from tens to hundred of meters. The structurally ordered block-in-matrix arrangement is characterized by mesoscale S-C shear zones defining centimeter to decimeter sized, lenticular to sigmoidal lithons. The more competent beds are dismembered into angular-shaped boudins that are centimeters to decimeters long. These boudins are aligned parallel to the main thrust and the S-C shear zones (Fig. 10B) and/or reoriented with respect to the bedding surfaces as result of rotation consistent with the sense of shear. The fine-grained matrix displays a millimeter to centimeter-scale pervasive scaly cleavage and it is, in turn, deformed by contractional S-C shear zones. The intersection of R and P shear planes defines shear lenses (L-shear *sensu* Naylor et al., 1986) that are consistent with the pervasive scaly cleavage. Another distinguishing feature is the repetition at different scales of the same structural fabric elements that are related to and consistent with the Taconic and/or Alleghenian stress field.

The BrFm3 overprints most of the previously formed mélanges and broken formations (Figs. 6D and 8D). This is the case, for example, of the **BrFm2** described South of Albany (Berks County) where reverse shear zones locally reactivate the previously formed foliation and planes of fissility (Fig. 8D), or the case of the **SedMé1b** (Fig. 6D) at Summerdale Plaza of Enola (west of Susquehanna River) and south of Kempton (Berks County), respectively. In the first case, the reverse shear zones and scaly cleavage affect at lower angle the BrFm2 resulting in the dismemberment and NE-verging imbrications of the previously formed boudinated succession, and rotation at lower angle of previously formed isolated blocks (see Fig. 8D and compare it with Fig. 8C). In the second case, the originally random distribution of polymictic blocks is locally reoriented by NW-verging shear zones and to a scaly cleavage related to the development of a ENE-striking regional thrust. Blocks long axis shows a SE-dipping reorientation as shown in Fig. 6D.

3.3. Diapiric mélanges (DpMé1)

Only one mappable example of a diapiric mélange has been recognized in the study area, and it corresponds to the diapiric mélange originally described by Lash (1987a) in the Greenwich slice (*sensu* Lash and Drake, 1984) north of Kutztown (Berks County; Figs. 2 and 3). It is a km-long, irregular-shaped, and east-west elongated chaotic body that was emplaced into the accreted Middle to Upper Ordovician (*P. elegans* - *N. gracilis* zones; Lash and Drake, 1984; Ganis et al., 2001) succession consisting of alternating layers of shale and graywacke. Although no intrusive contacts characteristic of diapiric mélanges (see Orange, 1990; Dela Pierre et al., 2007; Festa, 2011) are exposed, the internal deformational fabric and the block-in-matrix arrangement strongly agree with a diapiric origin. We have defined two zones of deformation (core and marginal zones *sensu* Dela Pierre et al., 2007; Festa et al., 2010a; Festa, 2011) within the chaotic body on the basis of an increasing amount of deformation toward the margins and the distribution of blocks in the matrix (Figs. 11A and 11E).

The marginal zones (~150-250-m-wide) are characterized by a block-in-matrix fabric, defined by a pervasive scaly cleavage dipping at medium angle (35°-55°) toward the core zone (Fig. 11F), and S-C fabrics showing opposite sense of shear along the opposite margins. Mesoscale deformation fabrics, such as the scaly cleavage and S-C fabric, indicate N- and S-verging reverse movements on the western and eastern margins, respectively. Blocks enclosed in the mudstone matrix are polymictic and intrabasinal, composed of graywacke, mudstone,

limestone, and chert. They range in size from a few centimeter to a few decimeters, and are mainly elongated and lenticular in shape showing a common orientation parallel to the scaly cleavage and the shear zones in the matrix (Fig. 11C).

The core zone (~400-m-wide; Figs. 11A and 11D) does not show a pervasive scaly cleavage, and the blocks are mainly irregular, angular and randomly distributed within the shaly matrix (Figs 11B and 11D). Their long axis plunges at lower angle with respect to the blocks long axis of the marginal zone showing mainly a NNE and SSE-plunging and subordinate NE and SW one (Fig. 11F). The larger blocks that occur only within the core zone consist of blocks of a coherent stratigraphic succession that is defined by m-thick beds of laminated graywacke with local interlayers of limestone and mudstone. These blocks can locally be several meters wide and more than 10 meters long. In places, the edges of the blocks are cut by open fractures filled by a scaly mudstone (see also Lash, 1987a).

4. Discussion

Different types of mélanges and broken formations occur in diverse stratigraphic and structural position within the Hamburg Klippe as a result of the operation and the interplay of tectonic, sedimentary and diapiric processes that were spatially and temporally associated with specific tectonic settings during the evolution of the Appalachian orogenic belt. Based on their internal structure and stratigraphy, the block-matrix ratios and relations, and the inferred tectonic settings of origin, we have differentiated the following mélanges and broken formations, whose evolutionary stages coincide with specific deformational phases in a complete orogenic cycle of the Appalachian orogenic belt history from subduction to collision.

4.1. Timing and geodynamic setting of mélange formation

4.1.1. Early Ordovician tectonic stage: mélange formation in ocean-continent transition zones

The association of ribbon limestone beds and block-in-sandy matrix layered horizons of **BrFm1**, preserved within the late Cambrian–Lower Ordovician slope and toe-of-slope succession of the Richmond Slice, shows different

degrees of stratal disruption of the originally coherent sedimentary succession. The occurrence of pinch-and-swell structures, boudinaged and slumped beds within the ribbon limestone beds is consistent with deformation of poorly consolidated or non-consolidated sediments on a low-energy slope and/or in a toe-of-slope environment (Fig. 12A). Here, the unconsolidated state of the sediments and the competence difference between the limestone beds and the matrix may have favored deformation and initial disruption of sediments through layer-parallel extension and slump folding during down-slope mass-movement. The final product is represented by broken formations (*sensu* Hsü, 1968), which do not contain exotic blocks, and whose block-in-matrix fabric results from local remobilization and *in situ* disruption of coherent layered horizons (see also Type 1 mélange of Cowan, 1985).

The block-in-matrix layered bodies of the Onyx Cave (Berks County) that are characterized by polymictic blocks randomly distributed within a sandy matrix differ from the above described chaotic horizons in that their homogeneous matrix is devoid of any sedimentary structures and ductile deformation. Fragmentation of the blocks suggests that they were consolidated prior to dismemberment. Moreover, their intrabasinal (not-exotic) origin, low degrees of lateral displacement and rotation of blocks, and intrusion of sandy matrix, fit nicely with the inferred *in situ* processes of disruption (Fig. 12A). Liquefaction-related deformation of un-cemented sandy layers as a result of earthquake shaking represents the most prominent mechanism related to this *in situ* deformation. Similar chaotic deposits are described by Yamamoto et al. (2009) in the Miura-Boso accretionary complex onshore Central Japan.

The strict association of ribbon limestone beds and block-in-sandy matrix layered horizons suggests that gravity-driven processes of downslope transport of sediments may have occurred starting with the *in situ* stratal deformation of the original bedded succession facilitated by rheological contrasts. On the basis of the nature and age of the deformed sediments, we envision that these sedimentary processes may have operated in the transition zone between a rifted (and thinned) microcontinental margin and oceanic crust (Fig. 11A) where the Richmond Slice succession was deposited. During the Early Ordovician, as the initial stages of subduction began to close the Octoraro Sea basin, deformation of the transition zone rocks in the upper plate occurred favoring effective mechanisms as earthquake-shaking able to induce *in situ* stratal disruption followed by sedimentary instability.

4.1.2. Middle Ordovician tectonic stage: Formation of subduction-related mélanges

The polymictic assemblages of the **SedMé1a** and **SedMé1b** include, among others, exotic blocks of slope and/or shelf facies (such as ribbon and platy limestones) that are lithologically similar to the upper Cambrian(?) – Lower Ordovician rocks of the Richmond Slice (see also Epstein et al., 1972; Root and MacLachlan, 1978; Lash and Drake, 1984; Ganis et al., 2001). The dominant occurrence of continental supply and the lacking of volcanoclastic material within the Middle Ordovician sediments and mélanges matrix (Lash, 1986b) suggest that the structural (and paleogeographic) position of the magmatic arc did not affect the sedimentation of pelagic, hemipelagic and trench sediments of the accretionary complex. During the Middle Ordovician, deep-water sediments of the Richmond Slice were already imbricated within the northward advancing accretionary wedge (Fig. 12B) formed in response to the SE-dipping subduction of Laurentia beneath the microcontinent – magmatic arc units (e.g., Lash and Drake, 1984; Faill, 1997). To the SE with respect to the accretionary complex, the magmatic arc started to be obducted over the microcontinent causing it to descend to depth (see Faill, 1997) and its frontal part to be sliced and involved in the accretionary complex.

Large blocks (up to hundreds of meters in size) of the **SedMé1a** represent slipped “exotic” blocks (with respect to depositional basin), originating from the front of the advancing accretionary wedge, and emplaced into the unconsolidated Middle Ordovician trench and slope deposits (Fig. 12B). The strong contrast in deformation style between the large upper Cambrian – Lower Ordovician olistoliths and their younger (Middle Ordovician) matrix suggests that these olistolithic blocks were already well lithified at the moment of their collapse and emplacement. Although the high shear resistance of lithified rocks inhibit their download collapse (e.g., Alonso et al., 2006), gravitational spreading represents the most effective mechanism in controlling their emplacement. After their initial collapse, different types of mass-wasting phenomena, starting from gravity sliding and followed by slumping and debris flows, contributed to the final emplacement of **SedMé1a** in downslope deposits. Similar mechanisms have been proposed by Alonso et al. (2006) for the emplacement of large blocks (up to several kilometers in size) of the Porma Mélange in the Varisican Foreland of the Iberian Peninsula in Spain.

The **SedMé1b** differs from the **SedMé1a** based mainly on the much smaller size (up to meters) of its blocks and the percentage of native blocks with respect to exotic ones (of Richmond Slice-affinity). The general

characteristic features of the **SedMé1b** are consistent with emplacement as debris flows (Fig. 12B). The internal arrangement of these chaotic bodies experienced repeated downslope mass-flows (such as slumps and turbidity currents) up to their final emplacement into fine-grained deposits of the outer trench. The prevalent non-exotic nature of the blocks suggests that at this time the innermost part of the Greenwich Slice succession was already tectonically imbricated within the accretionary wedge (Fig. 12B). Lash and Drake (1985) and Lash (1986a) interpreted the **SedMé1b**, as described from South of Kempton, as a product of large, deeply incised submarine canyons in front of the accreted successions.

The **SedMé1a** and **SedMé1b** represent different products of sedimentary (gravitational) processes occurred during the Middle Ordovician in balancing the dynamic equilibrium of the critically tapered front of the accretionary wedge (frontal tectonic erosion *sensu* von Huene and Lallemand, 1990). Gravitational instability eroded, at first, the older imbricated successions (Richmond Slice) forming **SedMé1a** (Fig. 12B). Then, the younger ones (inner part of Greenwich Slice) forming **SedMé1b** that were emplaced in a more distal position with respect to the first sedimentary mélange type. Triggering mechanisms might have been various depending on a combination of several factors that controlled the slope oversteepening and instability at the wedge front such as tectonic removal at the base of an accretionary wedge, subduction of advancing oceanic spreading ridge or seamount, subduction erosion and thrust faulting and folding. In this scenario, the basaltic extrusion of the Jonestown volcanic (interpreted as a Middle Ordovician spreading ridge; see Lash, 1986b; Ashcroft and Kidd, 2002; Landing et al., 2003) into the subsiding trench slope, and its inferred migration toward the trench (see Lash, 1986b), may have represented the most probable and effective mechanism in triggering the gravitational instability at the wedge front of the accretionary complex.

4.1.3. Early Late Ordovician tectonic stage: Subduction-related mélanges

During the early Late Ordovician (*N. gracilis* zone), the fine-grained trench deposits were rapidly and unconformably overlain by thick turbiditic sediments consisting of alternating layers of graywacke and rare mudstone of microcontinental origin. These rocks now crop out in the eastern (from Hamburg to east of Schuylkill River) and central (Dauphin and Lebanon Counties) sections of the Greenwich Slice respectively. Locally, these turbidites are deformed by **BrFm2** (e.g., South of Albany, Berks County) that shows a gradual

transition from normal bedded succession to a strongly deformed zone of block-in-matrix fabric without exotic blocks.

The alternating slumped and extensionally sheared block-in-matrix horizons of the **BrFm2** with consolidated blocks displaying scarce extensional faults at their margins, support gravitational collapse associated with submarine sliding as the main disruption mechanism (Fig. 13), rather than tectonic deformation (see Type I tectonic mélange of Lash, 1987a). During sliding, poorly lithified graywacke sediments were disrupted and sheared by extensional faults, while interbedded mudstone layers underwent continuous deformation. Thus, the same submarine sliding processes produced different deformation styles and diverse chaotic products (slumping and broken formations), depending on the degree of sediment lithification during sliding (Fig. 12). Only the upper, and relatively less-deformed, unconsolidated parts of these decameter-scale deformed packages of sedimentary rocks show widespread boudinage structures related to rapid dewatering in water-saturated alternating sandstone and mudstone.

These structural features characterizing the **BrFm2** are consistent with deformation patterns which occurred at shallow structural level in an outer trench environment at the front of the advancing accretionary wedge (Fig. 13). Here, thrusting was the main triggering mechanisms inducing these intraformational gravitational processes.

The **diapiric mélange** (**DpMé1**) in the eastern section of the Greenwich slice occurs in an innermost structural position with respect to the **BrFm2**, and at the base of the thrust fault superposing the Richmond slice onto the Greenwich slice (Fig. 13). The zonation of deformation and the block-in-matrix arrangement inside the chaotic body, the occurrence of hydraulic features within the hard blocks, the opposite sense of shearing along the margins of the diapiric body, are some of the diagnostic features of mélange formation by diapiric processes (see also, Orange, 1990; Dela Pierre et al., 2007; Festa, 2011). The occurrence of huge blocks (up to ten of meters long) within the core zone and a pervasive scaly cleavage in the marginal zone are consistent with extrusion mechanism of poorly consolidated and overpressured sediments (acting as a viscous fluid) under metastable conditions ("extrusion like toothpaste" *sensu* Higgings and Saunders, 1967) (see also, Komar, 1972; Bishop, 1978; Orange, 1990; Dela Pierre et al., 2007; Festa, 2011).

The occurrence of this diapiric mélange in the footwall of Richmond Slice is consistent with the abrupt increasing of tectonic loading related to the superposition of the Richmond Slice onto the Greenwich Slice within the imbricated stack of the advancing accretionary wedge (Fig. 13). Structural observations and mapping show that in the eastern section of the Hamburg Klippe, this superposition occurred during the early Late Ordovician (from syn-to post *N. gracilis* zone). In the central and western sections, respectively, the Middle Ordovician turbidites bearing the **SedMé1a** (Allochthon #2 of Ganis and Wise, 2008) were thrust over the fine-grained Middle Ordovician sedimentary strata (e.g., Manada Hill Mb. of Ganis et al., 2001; Allochthon #1 of Ganis and Wise, 2008; Enola Allochthon of Root and MacLachland, 1978) containing the **SedMé1b**.

4.1.4. Late Ordovician tectonic stage: Mélange development associated with collisional and intracontinental deformation

The characteristics of the **SedMé2** (Middlesex and Conoguinet wildflysch) are consistent with classical precursory olistostromes (*sensu* Elter and Trevisan, 1973) occurring in front of an advancing nappe (Fig. 14A) and/or thrust systems (see Camerlenghi and Pini, 2009; Festa et al., 2010a, 2010b). These cohesive debris flows represent a good time constraint for the emplacement of the Hamburg Klippe in the foreland basin of the Martinsburg Formation that occurred in the Late Ordovician (*C. bicornis* – early *D. clingani* zones of Caradoc) during a continental collision episode (Fig. 14B) (Ganis et al., 2001).

A general agreement exists on gravitational sliding of unlithified sediments as mechanism of emplacement of the Hamburg Klippe (see, e.g., Epstein et al., 1972; Root and MacLachlan, 1978; Lash and Drake, 1984; Faill, 1997; Ganis et al., 2001; Ganis and Wise, 2008; Wise and Ganis, 2009). Recently, Ganis and Wise (2008) and Wise and Ganis (2009) pointed out that part of the Hamburg Klippe (i.e., the Dauphin Formation of Ganis et al., 2001; part of the Greenwich slice of this paper, see Fig. 3) is made up of diverse piled allochthonous units which have moved into the Martinsburg foreland basin during different geological events. Then, the Hamburg Klippe, that they compared to the Snake Hill Formation (see English et al., 2006) in the Huston foreland, cannot be regarded as an extensive thrust sheet isolated by erosion as, on the contrary, the Taconic Allochthons of Vermont, New York, New England and Newfoundland have been interpreted (e.g., Bosworth and Vollmer, 1981; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985; Drake et al., 1989; Hatcher et al., 1989; Karabinos et al., 1998; Hibbard et al., 2006; 2007).

In our opinion, the poor outcrop conditions of the studied sector do not allow to discuss in detail the nature of the Hamburg Klippe emplacement (i.e., gravity sliding vs. thrusting). Some criteria, commonly used in the past literature to discriminate between the gravitational or tectonic emplacement of the Taconic Allochthons in Vermont and New England (e.g., Zen, 1967, 1972; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985), resulted as not completely diagnostic (see Karabinos et al., 2003). These criteria were based on the dipping (toward or away from the transport or emplacement direction) of basal surfaces bounding the different allochthonous units, or the sequence (westward or eastward) of their superposition (e.g. Zen, 1967, 1972; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). In the same way, and in addition to the above described criteria, the occurrence of precursory olistostromes (i.e., **SedMé2**) in the Late Ordovician Martinsburg Formation is not diagnostic of gravitational sliding for the emplacement of the Hamburg Klippe. These olistostromes only suggest that part of the stratigraphic succession of the Hamburg Klippe (i.e., the source area) was poorly lithified during early stage of its emplacement. On the contrary, useful informations could result in analyzing the deformational features related to the surfaces bounding at the base both the piled slices and the Hamburg Klippe. For example, the occurrence of a thin overpressured horizon formed by a mixture of water and loose sediments (i.e., hydroplaning; see Mohrig et al., 1998; Lucente and Pini, 2003; Pini et al., 2012) or, by contrast, of a contractional shear zone characterized by structural associations that are all coherent with the regional stress field, could strongly help in distinguishing between gravitational sliding or thrusting, respectively. However, these surfaces are not exposed in the studied sector hampering a detailed discussion of the nature and mode of emplacement of the Hamburg Klippe that, in turn, can be only speculative.

Precursory olistostromes (i.e., **SedMé2**), as well as, most of the mélanges and broken formations described in this study were subsequently overprinted by the late Taconic and/or Alleghenian tectonic deformational episodes, whose main product is represented by the **BrFm3** occurring mainly along shear zones associated with thrust-faulting. This tectonic deformation occurs progressively along weakness horizons and detachment levels affecting consolidated sediments and forming broken formations (without exotic blocks). This process is typical of intracontinental deformation within a nappe stack (type 6b2 of Festa et al., 2010a, 2010b).

5. Conclusions

The Early to Late Ordovician time window was a key interval for the geodynamic evolution of the Central Appalachian orogenic belt. During this time interval, a complete orogenic cycle occurred in a convergent margin setting driven by a SE-dipping subduction of the Laurentian passive margin beneath a series of microcontinents and the associated magmatic arc.

In the Hamburg Klippe, different types of mélanges and broken formations display a record of different tectonic stages of this orogeny that occurred sequentially either through a progressive supracrustal evolution from one type of mélange to another one, or by stratal disruption processes (Figs. 12-14). As in other orogenic belts and accretionary wedges around the world (see also Festa et al., 2010a, 2010b and references therein), we also see in the Central Appalachians a close relationship between the mélange types and the tectonic setting of their formation (Tab. 1).

The Early Ordovician broken formations (**BrFm1**) reflect earthquake-shaking triggering mechanisms resulting in *in situ* stratal disruption and local downslope remobilization of deep water sediments deposited in the transition zone between a rifted microcontinental margin and oceanic crust. During the Early to Middle Ordovician, diverse types of subduction-related sedimentary mélanges (**SedMé1a** and **SedMé1b**; corresponding to Type 4a of Festa et al., 2010a), embedding exotic blocks derived from microcontinents, were formed by mass-wasting processes related to tectonic erosion at the front of an accretionary wedge in response to subduction of oceanic crust beneath the microcontinent. In the early Late Ordovician (*N. gracilis* zone), early tectonic pulses related to the advancing accretionary wedge reached unconsolidated trench turbidites inducing extensional shearing and formation of broken formations (**BrFm2**). In contrast, within the imbricate stack of the accretionary wedge tectonic loading provided by the advancing wedge induced upward rise of a diapiric mélange (**DpMé1**).

The Late Ordovician collision between the accretionary wedge and the downgoing Laurentian margin resulted in the emplacement of precursory olistostromes (**SedMé2** corresponding to Type 6a1 of Festa et al., 2010a) in the Martinsburg foreland basin. These sedimentary mélanges announced the final emplacement (Late Ordovician, *C. bicornis* – *D. clingani* zones) of the Hamburg Klippe onto the Martinsburg Formation. Subsequently, both the Hamburg Klippe and the Laurentian margin units were deformed together into Alpine-scale recumbent folds and

fold and thrust structures during the later stages of the Appalachian orogenic belt development. The tectonic deformation associated with these later episodes of orogenic events produced broken formations (i.e. **BrFm3**) that commonly overprint the previously formed mélanges and broken formations.

The internal structure and stratigraphy of these different types of chaotic rock bodies (i.e., mélanges and broken formations) suggest that the sequential evolution of mélange formation in the Central Appalachians was strongly controlled by the consolidation degree of the primary, layered succession; rheological contrasts within the pre-deformed succession; the structural level in which mélange formed; and, kinematics of deformational processes (fast vs. slow-related deformation).

The described examples show that, at shallow structural levels within an evolving accretionary complex, the mixing of exotic and non-exotic blocks in mélange formation is related exclusively to sedimentary mass-wasting processes, whereas tectonic processes produce only broken formations lacking exotic blocks but typically showing a gradual transition from bedded succession to strongly deformed block-in-matrix arrangement (e.g., **BrFm3**). Tectonically deformed block-in-matrix fabric with blocks of exotic nature (e.g., **SedMé1b** of Summerdale Plaza at Enola) is a result of overprinting of the previously formed sedimentary mélanges by the later Taconian and Alleghenian events. The latest and more penetrative tectonic events can significantly modify the internal structure of the previously formed mélanges and related processes. This observation is important to keep in mind while studying polygenic mélanges (in particular metamorphic ones) produced and affected by the superimposed tectonic events (e.g., Dela Pierre et al., 2007; Festa et al., 2010a; Festa, 2011; Codegone et al., this volume). The lacking of true tectonic mélanges with exotic blocks of oceanic crust, directly included by tectonic process within the mélanges matrix (typical of subduction-accretion processes; see Ogawa, 1998), is related to the structural position in which the Hamburg Klippe was formed within the accretionary complex before its final emplacement onto the Martinsburg foreland basin. This example provides, in fact, diagnostic elements to recognize different types of mélanges and broken formations formed from pre-to syn-Taconic orogeny (Early to Late Ordovician) during a progressive deformation occurred at shallower and entirely supracrustal levels of the Taconic accretionary complex, and it records a complete orogenic cycle in a convergent margin setting from the early stages of closure of the Octoraro Sea basin, to subduction-accretion, and finally to obduction and collision.

ACKNOWLEDGMENTS

We thank the Guest Editor Y. Ogawa, the Editor-in-chief F. Storti, N. Hayman and the other two anonymous reviewers for their careful comments that helped to improve this paper. GC and AF thanks the Department of Geology and Environmental Earth Science of the Miami University for the kind hospitality during field work.

References

Alonso, J.L., Marcos, A., Suárez, A., 2006. Structure and organization of the Porma mélange: progressive denudation of a submarine nappe toe by gravitational collapse. Am. J. Sci. 306, 32-65.

Ashcroft, T.J., Kidd, W.S.F., 2002. Geology and Geochemistry of the Jonestown volcanics, Pennsylvania (Abstract). Geol. Soc. Am., Abstract with Programs 34 (1), A20.

Bergström, S.M., Epstein, A.G., Epstein, J.B., 1972. Early Ordovician North Atlantic province conodonts in eastern Pennsylvania, in: Geol. Surv. Res. 1972, USGS Prof. Pap. 800-D, D37-D44.

Bishop, R.S., 1978. Mechanism for emplacement of piercement diapirs. AAPG Bull. 62, 1561–1583.

Bosworth, B., Vollmer, F.W., 1981. Sructures of the Medial Ordovician flysch of eastern New York: deformation of synorogenic deposits in an overthrust environment. J. Geology 89, 551-568.

Camerlenghi, A., Pini, G.A., 2009. Mud volcanoes, olistostromes and Argille scagliose in the Mediterranean region. Sedimentology 56, 319-365.

Codegone G., Festa A., Dilek Y., Pini G.A., 2012, Small-scale polygenic mélanges in the Ligurian accretionary complex, Northern Apennines, Italy, and their implications for superposed mélange evolution in orogenic belts. Tectonophysics, doi: 10.1016/j.tecto.2012.02.003

Cloos, M., 1982. Flow melanges: numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California. Geol. Soc. Am. Bull. 93, 330-345.

Cousineau, P.A., St-Julien, P., 1992. The Saint-Daniel Melange: evolution of an accretionary complex in the Dunnage terrane of the Quebec Appalachians. Tectonics 11 (4), 898-909.

Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America. Geol. Soc. Am. Bull. 96, 451-462.

Dela Pierre, F., Festa, A., Irace, A., 2007. Interaction of tectonic, sedimentary and diapiric processes in the origin of chaotic sediments: an example from the Messinian of the Torino Hill (Tertiary Piedmont Basin, NW Italy). Geol. Soc. Am. Bull. 119, 1107-1119.

Dewey, J.F., 1969. Evolution of the Appalachian/Caledonian orogen. Nature 222, 124-129.

Dewey, J.F., Kidd, W.S.F., 1974. Continental collision in the Appalachian – Caledonian orogenic belt: variations related to completed and incompleted suturing. Geology 2, 543-546.

Dilek, Y., Furnes, H., Shallo, M., 2007. Suprasubduction zone ophiolite formation along the periphery of Mesozoic Gondwana. Gondwana Res. 11, 453-475.

Dilek, Y., Thy, P., Hacker, B., Grundvig, S., 1999. Structure and petrology of Tauride ophiolites and mafic dike intrusions (Turkey): implications for the Neo-Tethyan ocean. Geol. Soc. Am. Bull. 111, 1192–1216.

Drake, A.A., Jr., 1987. Geologic map of the Topton quadrangle, Lehigh and Berks Counties, Pennsylvania: USGS Geologic Quadrangle Map GQ-1609, scale 1:24,000.

Drake, A.A., Jr., Sinha, A.K., Laird, J., Guy, R.E., 1989. The Taconic orogen, in: Hatcher, R.D., Jr., Thomas, W.A., Viele, G.W. (Eds.), The Appalachian-Ouachita orogeny in the United States: Boulder, Colorado, Geol. Soc. Am., Geology of North America F-2, 101-177.

Elter, P., Trevisan, L., 1973. Olistostromes in the tectonic evolution of the Northern Apennines, in: De Jong, K.A, Scholten, R. (Eds.), Gravity and Tectonics. New York, John Willey and Sons, 175-188.

English, A. M., Landing, E., Baird, G. C., 2006. Snake Hill-reconstructing eastern Taconic foreland basin litho- and biofacies from a giant mélange block in eastern New York, USA. Paleogeography, Paleoclimatology, Paleoecology 242, 201–213.

Epstein, J.B., Epstein, A.G., Bergström, S.M., 1972. Significance of Lower Ordovician exotic blocks in the Hamburg klippe, eastern Pennsylvania, in: Geological Survey Research 1972, USGS Prof. Pap. 800-D, D29-D36.

Faill, R.T., 1997. A geologic history of the north-central Appalachians, Part 1, Orogenesis from the Mesoproterozoic through the Taconic orogeny. Am. J. Sci. 297, 551-619.

Federico, L., Crispini L., Scambelluri, M., Capponi, G., 2007. Ophiolite mélange zone records exhumation in a fossil subduction channel. Geology 35, 499-502.

Festa, A., 2011. Tectonic, sedimentary, and diapiric formation of the Messinian melange: Tertiary Piedmont Basin (northwestern Italy), in: Wakabayashi, J., Dilek, Y. (Eds.), Melanges: Processes of formation and societal significance. Geol. Soc. Am. Spec. Pap. 480, 215-232. doi:10.1130/2011.2480(10).

Festa, A., Pini, G.A., Dilek, Y., and Codegone, G. (2010a) - Mélanges and mélange-forming processes: a historical overview and new concepts, in: Dilek, Y. (Ed.), Alpine Concept in Geology. Int. Geol. Rev., v. 52 (10-12), 1040-1105. DOI: 10.1080/00206810903557704.

Festa, A., Pini, G.A., Dilek, Y., Codegone, G., Vezzani, L., Ghisetti, F., Lucente, C.C., and Ogata, K. (2010b) - Peri-Adriatic mélanges and their evolution in the Tethyan realm, in, Dilek, Y. (Ed.), Eastern Mediterranean geodynamics (Part II). Int. Geol. Rev., v. 52 (4-6), 369-406. DOI: 10.1080/00206810902949886.

Ganis, G.R., Wise, D.U., 2008. Taconic events in Pennsylvania: datable phases of a ~ 20 m.y. orogeny. Am. J. Sci. 308, 167-183.

Ganis, G.R., Williams, S.H., Repetski, J.E., 2001. New biostratigraphic information from the western part of the Hamburg klippe, Pennsylvania, and its significance for interpreting the depositional and tectonic history of the klippe. Geol. Soc. Am. Bull. 113, 109-128.

Geyer, A.R., 1970. Geology, mineral resources and environmental geology of the Palmyra Quadrangle, Lebanon and Dauphin Counties. Pa. Geol. Surv., Fourth Series, Bull. A 157D, 46.

Ghikas, A.C., Dilek, Y., and Rassios, A.E., 2010, Structure and tectonics of sub-ophiolitic mélanges in the Western Hellenides (Greece) and implications for Ophiolite emplacement tectonics: Int. Geol. Rev., v. 52, p. 423–453.

Hatcher, R.D., Jr., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, S., Wiltschko, D.V., 1989. Alleghanian orogen, Chapter 5, :in Hatcher, R.D., Jr., Thomas, W.A., Viele, G.W. (Eds.), The Appalachian–Ouachita Orogen in the United States: Boulder, Colorado, Geol. Soc. Am., The Geology of North America F-2, 233–318.

Hibbard, J.P., van Staal, C.R., Rankin, D.W., 2007. A comparative analysis of pre-Silurian crustal „building blocks" of the northern and southern Appalachians, in: Wintsch, R. (Ed.), Rodgers Memorial Issue, Part 1. Am. J. Sci. 307, 23–45.

Hibbard, J.P., van Staal, C.R., Rankin, D.W., Williams, H., 2006. Lithotectonic map of the Appalachian orogen, Canada-United States of America. Geol. Surv. Can., Map 2096A, scale 1:1,500,000.

Higgings, G.E., Saunders, J.B., 1967. Report on 1964 Chatman mud island, Erin Bay, Trinidad, West Indies. AAPG Bull. 51, 55–64.

Horton, J. W., Drake, A. A., Jr., Rankin, D. W., 1989. Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Applalachians, in: Dallmeyer, R. D. (Ed.), Terranes in the circum-Atlantic Paleozoic Orogens. Geol. Soc. Am. Spec. Pap. 230, 213–245.

Hsü, K.J., 1968. Principles of melanges and their bearing on the Franciscan-Knoxville problem. Geol. Soc. Am. Bull. 79, 1063-1074.

Ikesawua, E., Kimura, G., Sato, K., Ikehara-Ohmori, K., Kitamura, Y., Yamaguchi, A., Ejiie, K., Hashimoto, Y., 2005. Tectonic incorporation of the upper part of oceanic crust to overriding plate of a convergent margin: an example from the Cretaceous-early Tertiary Mugi Mélange, the Shimanto Belt, Japan. Tectonophysics 401, 217-230.

Karabinos, P., Stoll, H.M., Hepburn, J.C, 2003. The Shelburne Falls arc- Lost arc of the Taconic orogeny, in: Brady, J., and Cheney, J. (eds.). New England Intercollegiate Geologic Conference, Amherst, Massachusetts, B3-1 – B3-17.

Karabinos, P., Sampson, S.D., Hepburn, J.C., Stoll, H.M., 1998. Taconian orogeny in the New England Appalachians, collision between Laurentia and the Shelburne Falls arc. Geology, 26, 215–218.

Kimura, G., Maruyama, S., Isozaki, Y., Terabayashi, M., 1996. Well-preserved underplating structure of the jadeitized Franciscan complex, Pacheco Pass, California. Geology 24, 75-78.

Komar, P.D., 1972. Flow differentiation in igneous dikes and sills: Profi les of velocity and phenocryst concentration. Geol. Soc. Am. Bull. 83, 3443–3448. DOI: 10.1130/0016-7606(1972)83[3443:FDIIDA]2.0.CO;2.

Kusky T.M., Bradley, D.C., 1999. Kinematic analysis of mélange fabrics: examples and applications from the McHugh Complex, Kenai Peninsula, Alaska. J. Struct. Geol. 21, 1773-1796.

Landing, E., Pe-Piper, G., Kidd., W.S.F., Azmy, K., 2003. Tectonic setting of outer trench slope volcanism: pillow basalt and limestone in the Taconian orogen of eastern New York. Can. J. Earth Sci. 40, 1773-1787.

Lash, G.G., 1985a. Accretion-related deformation of an ancient (early Paleozoic) trench-fill deposit, central Appalachian orogen. Geol. Soc. Am. Bull. 96, 1167-1178.

Lash, G.G., 1985b. Geologic map of the Kutztown quadrangle, Berks and Lehigh Counties, Pennsylvania. USGS Geologic Quadrangle Map GQ-1577, scale 1:24,000.

Lash, G.G., 1986a. Sedimentology of channelized turbidite deposits in an ancient (early Paleozoic) subduction complex, central Appalachians. Geol. Soc. Am. Bull. 97, 703-710.

Lash, G.G., 1986b. Sedimentology of and geochemical evidence for Middle Ordovician near-trench volcanism in the central Appalachian Orogen. J. Geol. 94, 91-107.

Lash, G.G., 1987a. Diverse melanges of an ancient subduction complex. Geology 15, 652-655.

Lash, G.G., 1987b. Geologic map of the Hamburg quadrangle, Schuylkill and Berks Counties, Pennsylvania. USGS Geologic Quadrangle Map GQ-1637, scale 1:24,000.

Lash, G.G., 1989. Documentation and significance of progressive microfabric changes in Middle Ordovician trench mudstones. Geol. Soc. Am. Bull. 101, 1268-1279.

Lash, G.G., Drake, A.A., Jr., 1984. The Richmond and Greenwich Slices of the Hamburg klippe in eastern Pennsylvania – Stratigraphy, sedimentology, structure, and plate tectonic implications. USGS Prof. Pap. 1312, 40.

Lash, G.G., Lyttle, P.T., Epstein, J.B., Jr., 1984. Geology of the Hamburg allochthon, an accreted terrane in Eastern Pennsylvania, and relations to surrounding rocks. 49th Field Conf. Pennsylvanian Geologists, Guidebook, 151.

Liu, G., Einsele, G., 1996. Various types of olistostromes in a closing ocean basin, Tethyan Himalaya (Cretaceous, Tibet). Sediment. Geol. 104, 203-226.

Lucente, C.C., Pini, G.A., 2003. Anatomy and emplacement mechanism of a large submarine slide within the Miocene foredeep in the Northern Apennines, Italy: a field perspective. Am. J. Sci. 303, 565-602.

Matsuda, S., Ogawa, Y., 1993. Two-stage model of incorporation of seamount and oceanic blocks into sedimentary mélange: geochemical and biostratigraphic constraints in Jurassic Chichibu accretionary complex, Shikoku, Japan. Island Arc 2 (1), 7-14. DOI: 10.1111/j.1440-1738.1993.tb00071.x

Mohrig, D., Whipple, K.X., Hondzo, M., Ellis, C., Parker, G., 1998. Hydroplaning of subaqueous debris flows. Geol. Soc. Am. Bull. 110(3), 387–394.

Ogawa, Y., 1998. Tectonostratigraphy of the Glen App area, Southern Uplands, Scotland: anatomy of Ordovician accretionary complex. J. Geol. Soc. London 155, 651-662.

Okay, A.I., 2000. Was the Late Triassic orogeny in Turkey caused by the collision of an oceanic plateau?), in: Bozkurt, E., Winchester, J.A., Piper, J.D.A. (Eds.), Tectonics and magmatism in Turkey and the surrounding area. Geol. Soc. London Spec. Publ. 173, 25-41.

Orange, D.L., 1990. Criteria helpful in recognizing shear-zone and diapiric mélanges: examples from the Hoh acretionary complex, Olympic Peninsula, Washington. Geol. Soc. Am. Bull. 102, 935-951.

Passchier, C.W., Trouw, R.A., 2005. Microtectonics. Springer Berlin Heidelberg New York. 365.

Pini, G.A., 1999. Tectonosomes and olistostromes in the Argille Scagliose of the Northern Apennines, Italy. Geol. Soc. Am. Spec. Pap. 335, 73.

Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente, C.C., Codegone, G., 2012. Sedimentary mélanges and fossil mass-transport complexes: a key for better understanding submarine mass movements?, in: Yamada et al. (Eds.), Submarine Mass Movements and their consequences, Advances in Natural and Technological hazards Research 31, Springer Science+Business Media B.V. 2012, 585-593. doi: 10.1007/978-94-007-2162-3_52

Rast, N., Horton, J.W., Jr., 1989. Melanges and olistostromes in the Appalachians of the United States and mainland Canada: an assessment, in: Horton, Jr., J.W., Rast, N. (Eds.), Mélanges and olistostromes of the Appalachians. Geol. Soc. Am. Spec. Pap. 228, 1-16.

Repetski, J.E., 1984. Conodonts from the Greenwich slice of the Hamburg klippe near Greenawald, Pennsylvania, in: Lash, G.G., et al. (Eds.), Geology of an accreted terrane: the eastern Hamburg klippe and surrounding rocks, eastern Pennsylvania: Annual Field Conference of Pennsylvania Geologists, 49th, Reading, Pennsylvania, guide book. Harrisburg, Field conference of Pennsylvania Geologists, Inc., 92-93.

Ring, U., Ratschbacher, L., Frisch, W., Dürr, S., Borchert, S., 1990. The internal structure of the Arosa Zone (Swiss-Austrian Alps). Geol. Rundsch. 79 (3), 725-739.

Robertson, A.H.F., Parlak, O., Ustaömer, T., 2009. Melange genesis and ophiolite emplacement related to subduction of the northern margin of the Tauride-Anatolide continent, central and western Turkey. Geol. Soc. London Spec. Publ. 311, 9-66.

Root, S.I., 1977. Geology and mineral resources of the Harrisburg west area, Cumberland and York counties, Pennsylvania. Pa. Topogr. Geol. Surv. Atlas 148ab, 106.

Root, S.I., MacLachlan, D.B., 1978. Western limit of Taconic allochthons in Pennsylvania. Geol. Soc. Am. Bull. 89, 1515-1528.

Rowley, D.B., Kidd, W.S.F., 1981. Stratigraphic relationships and detrital composition of the Medial Ordovician flysch of westen New England: implications for the tectonic evolution of the Taconic orogeny. J. Geology 89, 199-218.

Stanley, R., Ratcliffe, N., 1985. Tectonic synthesis of the Taconian Orogeny in Western New England. Geol. Soc. Am. Bull. 96, 1227–1250.

Stevens, R.K., 1970. Cambro-Ordovician flysch sedimentation and tectonics in western Newfoundland and their possible bearing on a proto-Atlantic. Geol. Assoc. Can. Spec. Pap. 7, 165-178.

Stewart, K.G., Adams, M.G., Trupe, C.H., 1997. Paleozoic structural evolution of the Blue Ridge thrust complex, western North Carolina, in: Stewart, K.G., Adams, M.G., Trupe, C.H. (Eds.), Paleozoic structure, metamorphism, and tectonics of the Blue Ridge of western North Carolina. Carolina Geol. Soc. 1997 Field Trip Guidebook, 21-31.

Stose, G.W., 1946. The Taconic sequence in Pennsylvania. Am. J. Sci. 244, 665-696.

Tremblay, A., Malo, M., St-Julien, P., 1995. Dunnage zone Québec, in: Williams, H. (Ed.), Geology of the Appalachian-Caledonian Orogen in Canada and Greenland. Geol. Surv. Can., Geology of Canada 6, 179-187.

Trommsdorff, V., 1990. Metamorphism and tectonics in the Central Alps: the Alpine lithospheric mélange of Cima Lunga and Adula. Mem. Soc. Geol. It. 45, 39-49.

von Huene, R., Lallemand, S., 1990. Tectonic erosion along the Japan and Peru convergent margin. Geol. Soc. Am. Bull. 102, 704–720.

Zen, E-An, 1967. Time and space relationships of the Taconic allochthon and autochthon. Geol. Soc. Am. Spec. Pap. 97, 107 p.

Zen, E-an, 1972. The Taconide Zone and the Taconic Orogeny in the Western Part of the Northern Appalachian Orogen. Geol. Soc. Am. Spec. Pap 135, 72 p.

Wakabayashi, J., 1992. Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California. J. Geol. 100, 19-40.

Wakabayashi, J., Ghatak, A., Basu, A.R., 2010. Suprasubduction-zone ophiolite generation, emplacement, and initiation of subduction: A perspective from geochemistry, metamorphism, geochronology, and regional geology. Geol. Soc. Am. Bull. 122, 1548-1568. DOI: 10.1130/B30017.1

Wise, D.U., Ganis, G.R., 2009. Taconic Orogeny in Pennsylvania: a ~ 15 – 20 m.y. Apennine-style Ordovician event viewed from its Martic hinterland. J. Struct. Geol. 31, 887-899.

Yamamoto, Y., Nidaira, M., Ohta, Y., Ogawa, Y., 2009. Formation of chaotic rock units during primary accretion processes: examples from the Miura-Boso accretionary complex, central Japan. Island Arc 18, 496-512.

Figure Captions

Figure 1 – Location (A) and structural sketch map (B) of the Pennsylvania Great Valley. Modified from Hibbard et al. (2006), and Wise and Ganis (2009).

Figure 2 – Simplified geological-structural map of the Hamburg Klippe, and locations of the studied examples of mélange and broken formation. Modified from Faill (1997), Root and MacLachlan (1978), and Hibbard et al. (2006).

Figure 3 – Stratigraphic and structural relationships between the tectonic units of the Hamburg Klippe and the Laurentian margin succession. Modified from Rooth and MacLachland (1978), Lash (1986a, 1986b), and Ganis et al. (2001).

Figure 4 – Sedimentary Mélange 1a (**SedMé1a**). Outcrop sketch (A) showing meters to tens of meters elongated blocks of Lower Ordovician limestone included in a mudstone matrix (east of Shellsville, Dauphin/Lebanon Counties). (B) Close-up of the matrix surrounding the larger limestone block.

Figure 5 – Sedimentary Mélange 1b (**SedMé1b**). Outcrop sketch (A) showing a lenticular chaotic mass-transport body bounded at the base by an erosional surface. Long-axis blocks are aligned to this surface (B) passing upward to a random distribution. In detail (C), the photograph show the alignment of elongated blocks (deepwater limestone, silicified mudstone, and siltstone) included in brecciated matrix (south of Kempton, Berks County).

Figure 6 – Sedimentary Mélange 1b (**SedMé1b**). (A) Centimeter to decimeters rounded to angular blocks (limestone, graywacke, and sandstone) randomly included in a gray shaly matrix (Summerdale plaza at Enola, Cumberland County). (B) Simplified geological of the eastern sector of the Greenwich slice at Enola, PA (Summerdale Allochthon) showing the structural relationships of the coherent succession of the Greenwich slice and the chaotic rock bodies of the Summerdale Allochton (modified after Root, 1977). Location in Fig. 2. (C) Geological map of the Summerdale plaza (Enola, PA) showing the

interbedding of the SedMé1 chaotic body within the coherent bedded succession of the Summerdale Allochthon. Note the alignment of blocks long axis to the SE-dipping cleavage related to the NW-verging thrusting episodes. Location in Fig. 6B. (D) Mesoscale data from the SedMé1b at Summerdale plaza (Enola, PA) (Schmidt net, lower hemisphere). Note the alignment of long axis lineation of the elongated blocks of the BrFm1b and the cleavage and reverse fault related to Alleghenian tectonic episodes. (E) Centimeter to decimeters rounded blocks of light gray limestone embedded with random distribution in hemipelagic fine-grained sediments (left bank of the Conodoguinet River, west of Enola)

Figure 7 – Broken Formation 1 (**BrFm1**). (A) Schematic line-drawing (not-to-scale) showing the stratigraphic relationships between the two types of chaotic bodies characterizing the BrFm1. (B) Monomictic block-in-matrix horizons, closely associated with ribbon limestone beds (Sacony Bridge east of Virginville, Berks County). (C) Polymictic tabular blocks in a homogeneous sandy matrix that devoid of sedimentary structures (Onyx Cave near Virginville, Berks County).

Figure 8 – Broken Formation 2 (**BrFm2**). (A) Outcrop photograph showing the typical transition (arrow) from normal bedded succession to block-in-matrix fabric in alternating graywacke and mudstone. (B) Close-up of (A) showing a lenticular long-axis graywacke block aligned to the mm-scale scaly fabric that pervaded the mudstone matrix (south of Albany, Berks County). (C) Mesoscale data from the BrFm2 at Albany, Berks County showing the alignment of coherent bedding, foliation and blocks long axis lineation (Schmidt net, lower hemisphere). (D) Mesoscale data showing the overprinting of the deformation related to the formation of the BrFm3 on the previously formed BrFm2 at Albany, Berks County (Schmidt net, lower hemisphere). Note, by comparing Figs 6C and 6D, the different plunge of long axis lineation of elongated blocks of BrFm2 and BrFm3 respectively.

Figure 9 – Broken Formation 2 (**BrFm2**). Examples of phacoidal and lozenged sandstone blocks produced by centimeters to decimeters extensional faults (A and B) and layer-parallel extension (C) (south of Albany, Berks County). In Fig. 9A white lines indicate C″-type shear bands (*sensu* Passchier and Trouw, 2005) developed at small angle to the foliation.

Figure 10 – Broken Formation 3 (**BrFm3**). (A) Schematic line-drawing (not-to-scale) showing the typical structurally-ordered block-in-matrix fabric related to late Taconic/Alleghenian thrusting of this type of tectonic broken formation. Note the gradual decrease of stratal disruption away from the fault. (B) Close-up of (A) showing S-C shear zones defined by the imbrications of decimeter-sized blocks of sandstone that are in turn aligned with a pervasive scaly cleavage affecting the mudstone matrix (south of Albany, Berks County).

Figure 11 – Diapiric Mélange (**DpMé1**). (A) Simplified sketch (not-not-scale) of the zonation of deformation and block-in-matrix fabric of the diapiric mélange showing an increasing amount of deformation from the core to the marginal zones. (B) Outcrop sketches showing the alignment of blocks to the shear zones and cleavages affecting the marginal zone (C), and the random distribution of meter to tens of meters blocks in the core zone (B, D) (north of Kutztown, Bercks County). (E) Geological map of the DpMé1 at Kutztown (Bercks County) showing the zonation of deformation and the relationships with the hosting rocks of the Greenwich slice, the Richmond slice and the Lehigh Valley succession. Location in Fig. 2. (D) Mesoscale data from the DpMé1 (Schmidt net, lower hemisphere) showing the different distribution of the long axis lineation of the elongated blocks of the marginal and core zones.

Figure 12 – Conceptual model for the formation and emplacement of mélange and broken formation during Early to Middle Ordovician times. See text for a detailed explanation. (A) During Early Ordovician, downslope mass-movement of the normal bedded slope succession and earthquake-shacking related to early stages of subduction formed the two types of Broken Formation1 (**BrFm1**) at the "microcontinent"-ocean transition. (B) During Middle Ordovician, the Sedimentary Mélanges 1a and 1b (**SedMé1a** and **SedMé1b**) were formed by different types of mass-transport phenomena related to slope instability triggered by the SE-dipping subduction of oceanic crust and inferred spreading ridge below the microcontinent.

Figure 13 – Conceptual model for the formation and emplacement of mélange and broken formation during early Late Ordovician time (*N. gracilis* zone). See text for a detailed explanation. Early tectonic pulse related to the advancing accretionary wedge induced layer-parallel extension in unconsolidated trench

turbidites forming the Broken Formation 2 (**BrFm2**). Tectonic loafing provided by the stacked units induced upward rise of unconsolidated sediments forming the diapiric mélange (**DpMé1**).

Figure 14 – Conceptual model for the formation and emplacement of mélange and broken formation during Late Ordovician time. See text for a detailed explanation. (A) The collision between the accretionary wedge and Laurentian margin resulted in the emplacement of precursory olistostromes (**SedMé2**) in the Martinsburg foreland basin. These olistostromes announced during Late Ordovician time (*C. bicornis* to early *D. clingani* zone) the final emplacement by gravitational sliding (B) of the Hamburg Klippe (HK). The subsequent late Taconic and/or Alleghenian tectonic deformations overprinted most of these mélanges and broken formations forming produced the Broken Formation 3 (**BrFm3**).

Table 1 – Classification of the Taconic mélanges and broken formations on the basis of nature of the blocks, block-in-matrix arrangement, process and tectonic setting of their formation.

Table 1

Click here to download Table: Table 1_Codegone et al_Rvsd2.doc

Mélange	Nature of blocks	Mesoscale feature	Block size	Process	Host Succession	Geodynamic setting
BrFm1	Intrabasinal (not-exotic)	Pinch-and-swell, boudinage, slumping ——— Tabular blocks randomly distributed in homogeneous sandy matrix (devoid of sedimentary structures)	few centimeters to decimeters	Soft-sediment deformation related to progressive deformation from slumping to debris flows ——— *In situ* liquefaction	upper Cambrian to late Lower Ordovician slope or toe of slope facies	"Microcontinent" – ocean transition
SedMé1a	Exotic	Huge blocks randomly distributed in a polymictic brecciated matrix	meter to hundreds of meters	Mass-transport processes (debris flows, slumps, slides, etc.)	Middle Ordovician slope facies	Subduction
SedMé1b	Mainly intrabasinal (not-exotic) and rarely exotic	Blocks randomly distributed in a polymictic brecciated matrix	few centimeters to tens of meters			
BrFm2	Intrabasinal (not-exotic)	Boudinage, pinch-and-swell, slumping	few centimeters to several meters	Layer-parallel extension related to submarine sliding	early Upper Ordovician trench-fill facies	Subduction
DpMé1	Intrabasinal (not-exotic)	Internal zonation of deformation from core to margins	few centimeters to a few meters (marginal zone) ——— up to tens of meters (core zone)	Extrusion of un to poorly consolidated sediments	Middle to Upper Ordovician trench-fill facies	Subduction
SedMé2	Exotic and intrabasinal (not-exotic)	Blocks randomly distributed in a polymictic brecciated matrix	centimeters to decimeters	Mass-transport processes (debris flows, slumps, slides, etc.)	Upper Ordovician foreland facies	Collision to intracontinental deformation
BrFm3	Intrabasinal (not-exotic)	Structurally ordered block-in-matrix fabric	few centimeters to decimeters	Thrusting and processes of thickening related to fault zones	Middle to Upper Ordovician trench-fill and foreland facies	Intracontinental deformation

Table 1 – Codegone et al.

Figure 1
Click here to download high resolution image

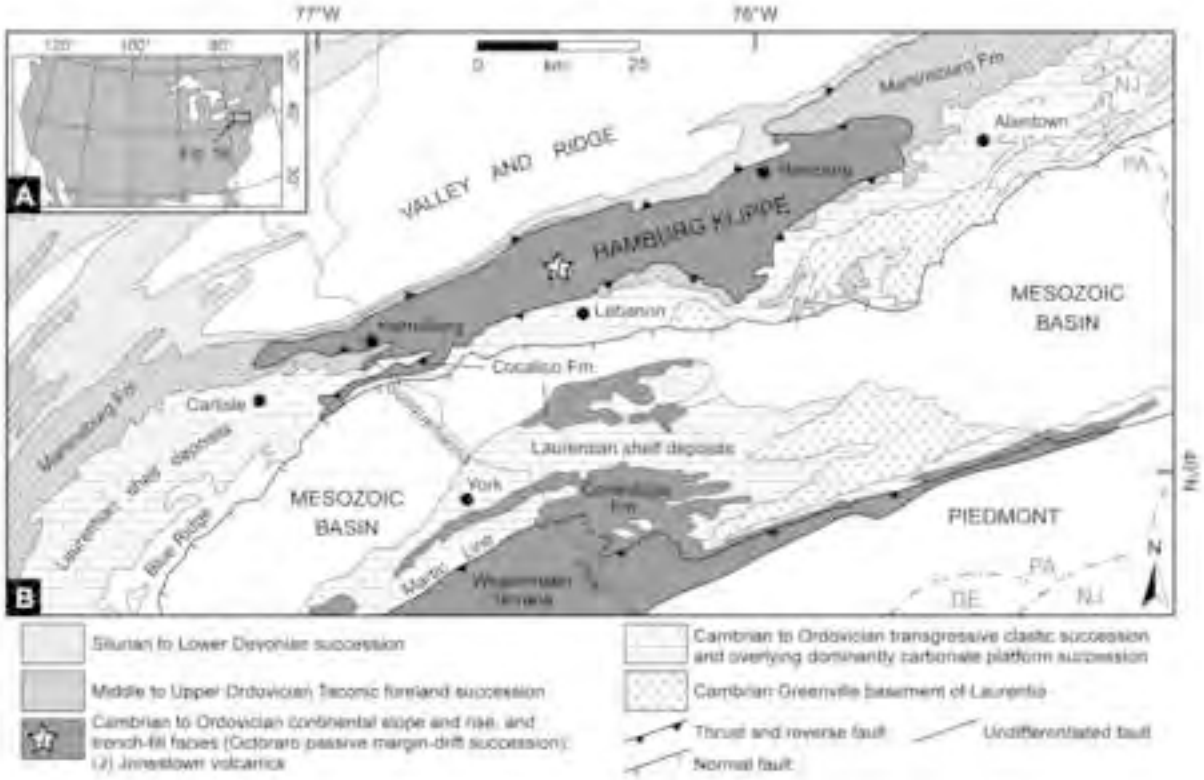

Figure 1 - Codegone et al.

Figure 2
Click here to download high resolution image

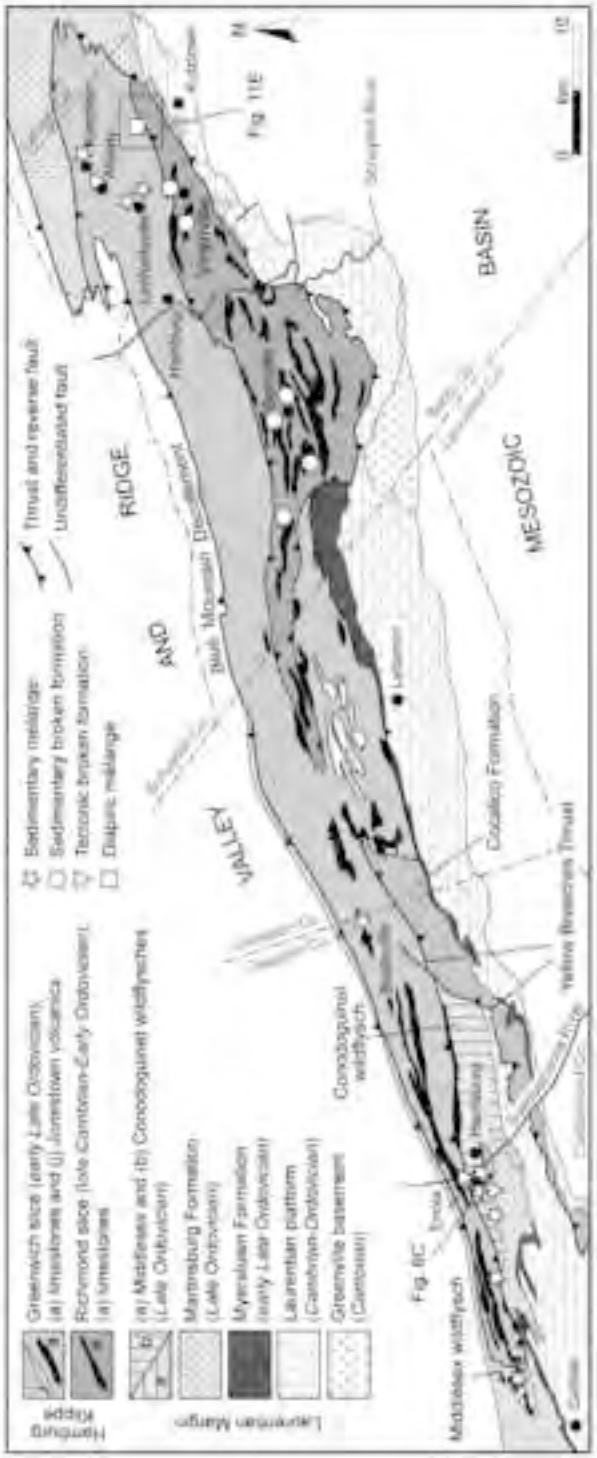

Figure 2 - Codegone et al.

Figure 3
Click here to download high resolution image

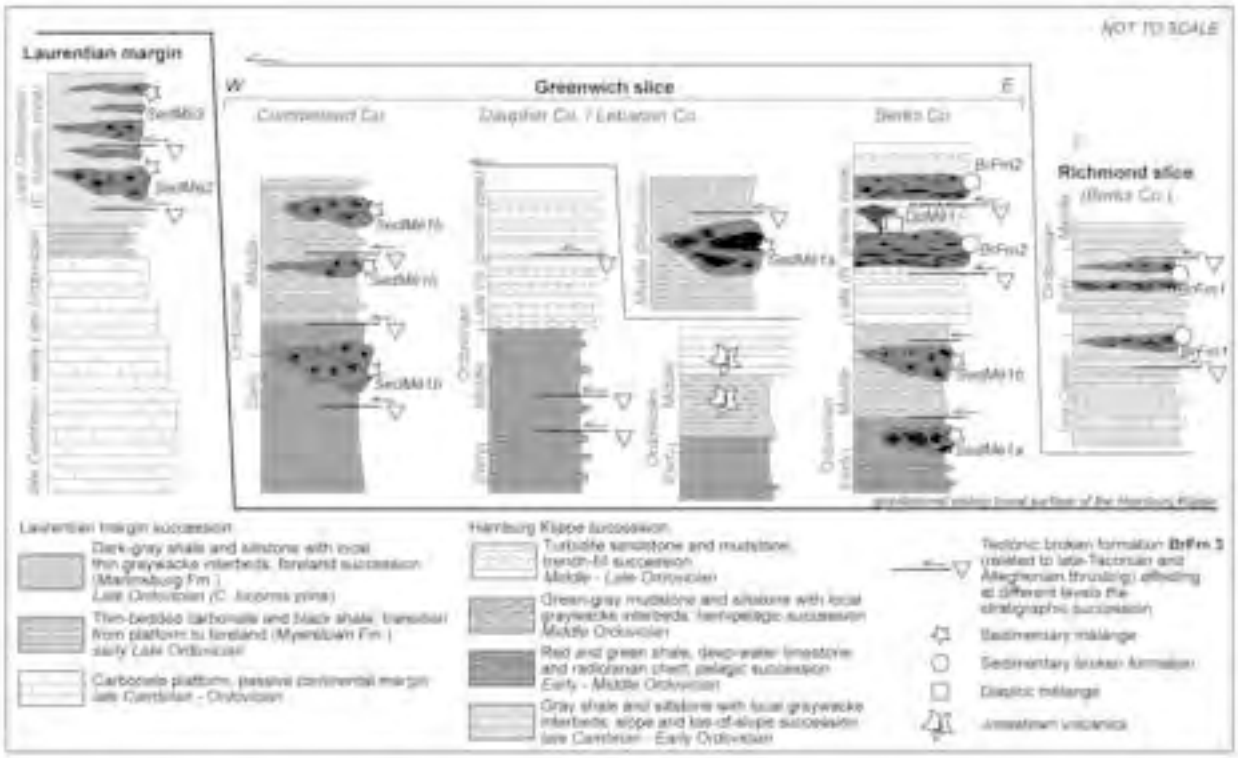

Figure 3 - Codegone et al.

Figure 4
Click here to download high resolution image

Figure 4 - Codegone et al.

Figure 5
Click here to download high resolution image

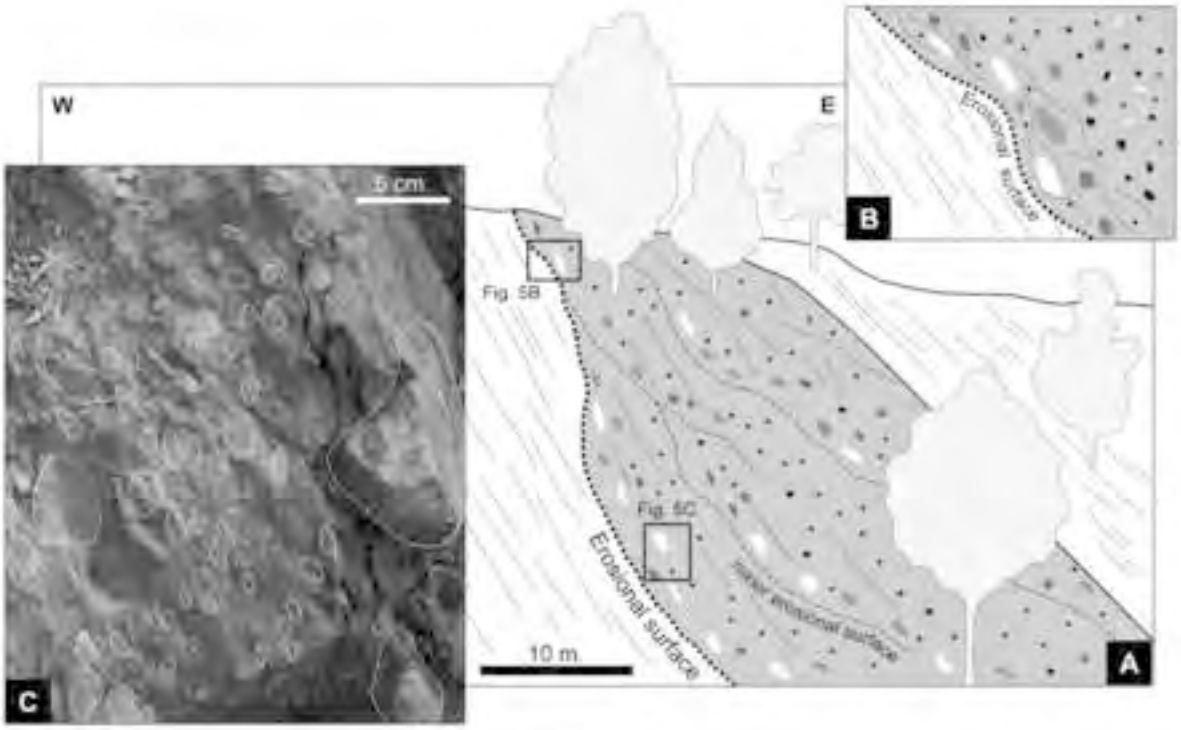

Figure 5 - Codegone et al.

Figure 6
Click here to download high resolution image

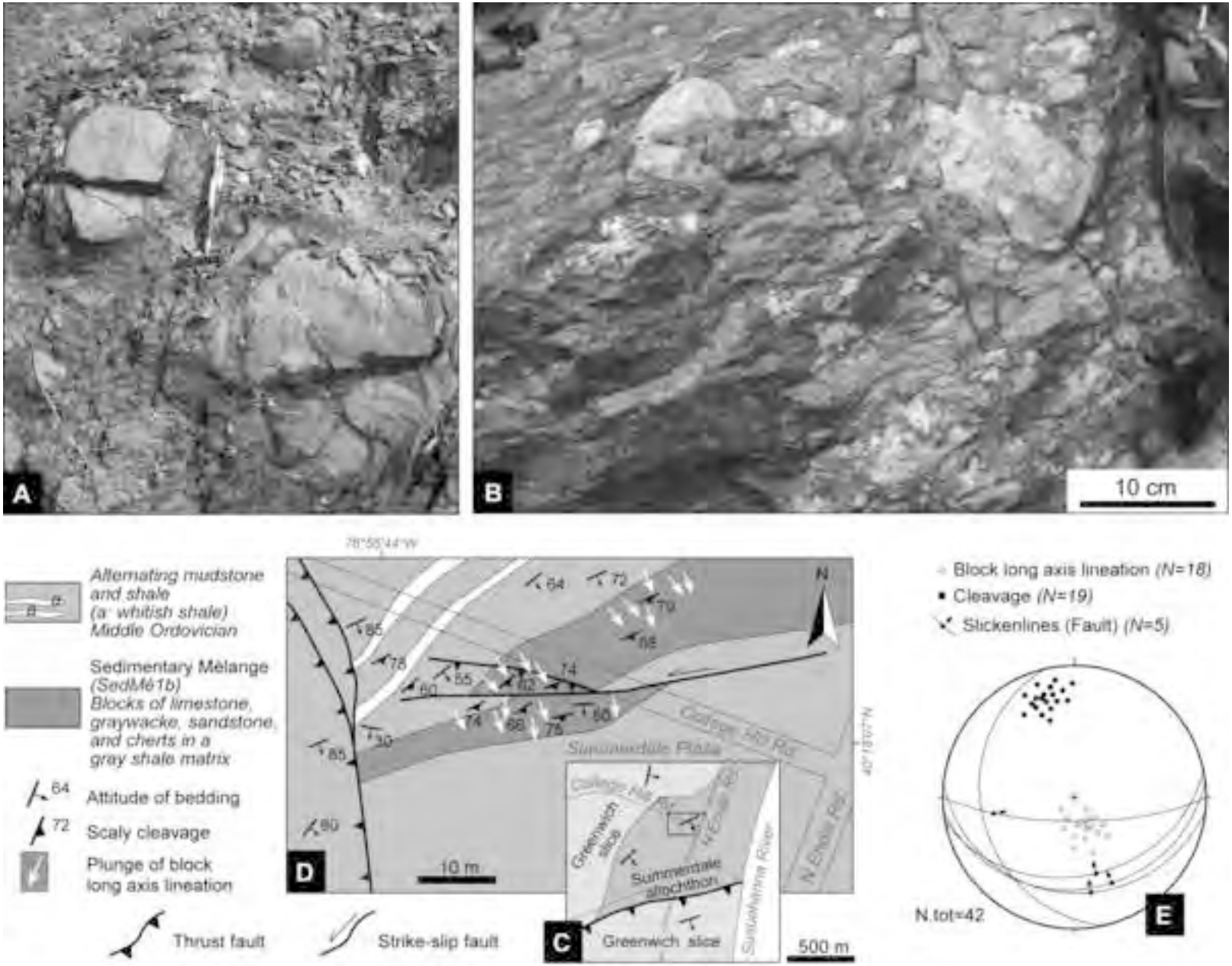

Figure 6 - Codegone et al

Figure 7
Click here to download high resolution image

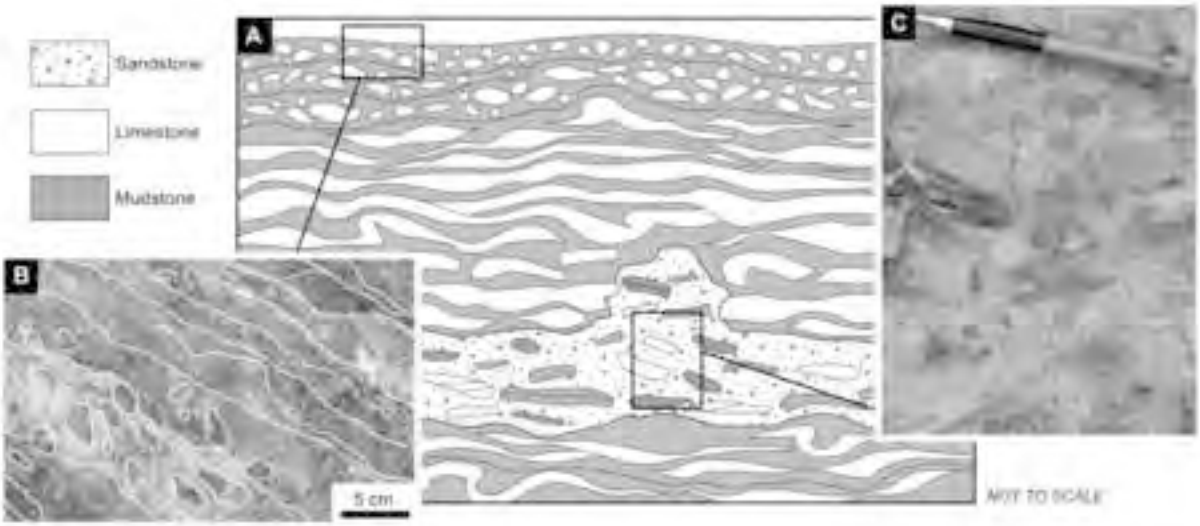

Figure 7 - Codegone et al.

Figure 8
Click here to download high resolution image

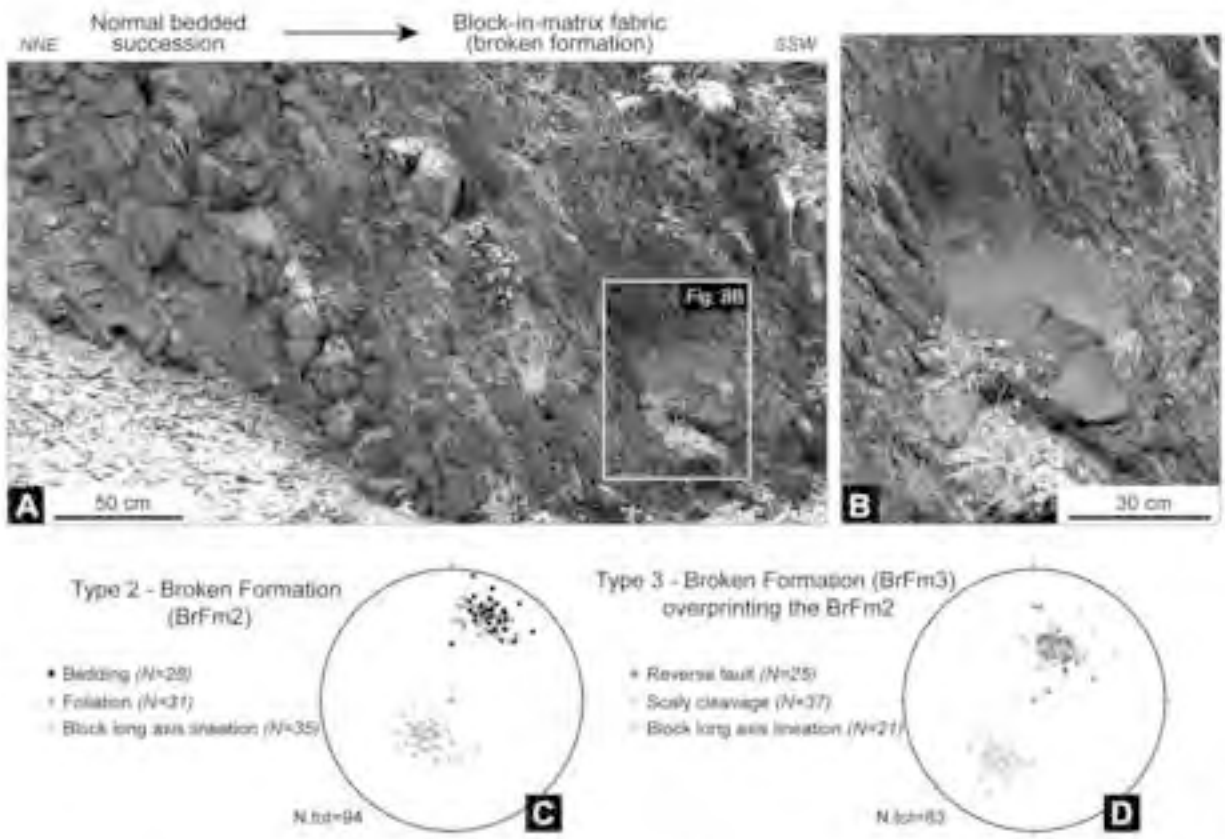

Figure 8 - Codegone et al

Figure 9
Click here to download high resolution image

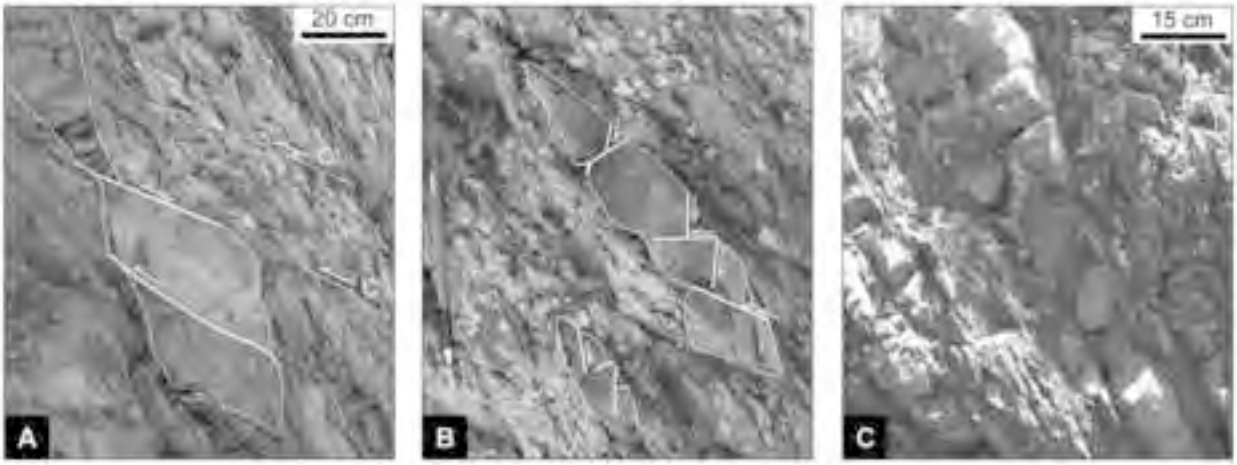

Figure 9 - Codegone et al.

Figure 10
Click here to download high resolution image

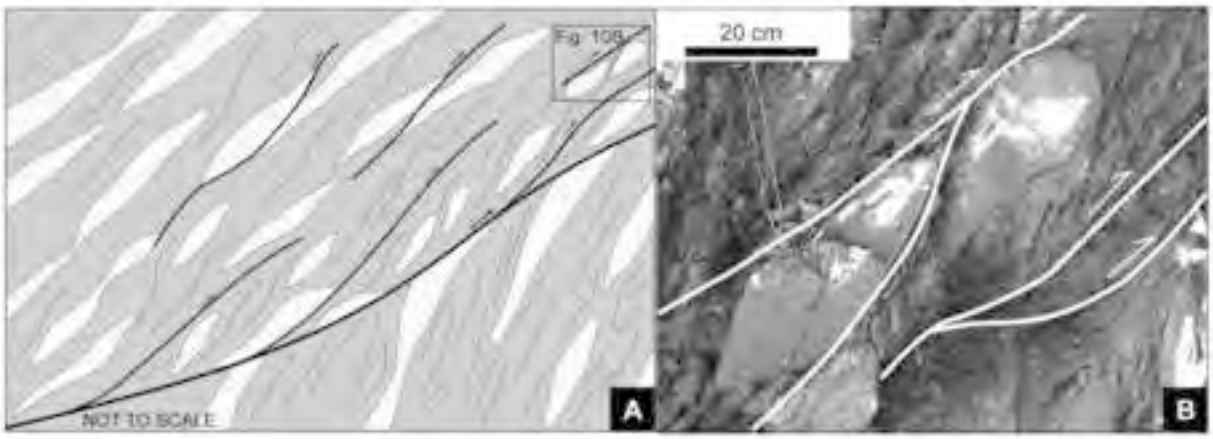

Fig. 10 - Codegone et al.

Figure 11
Click here to download high resolution image

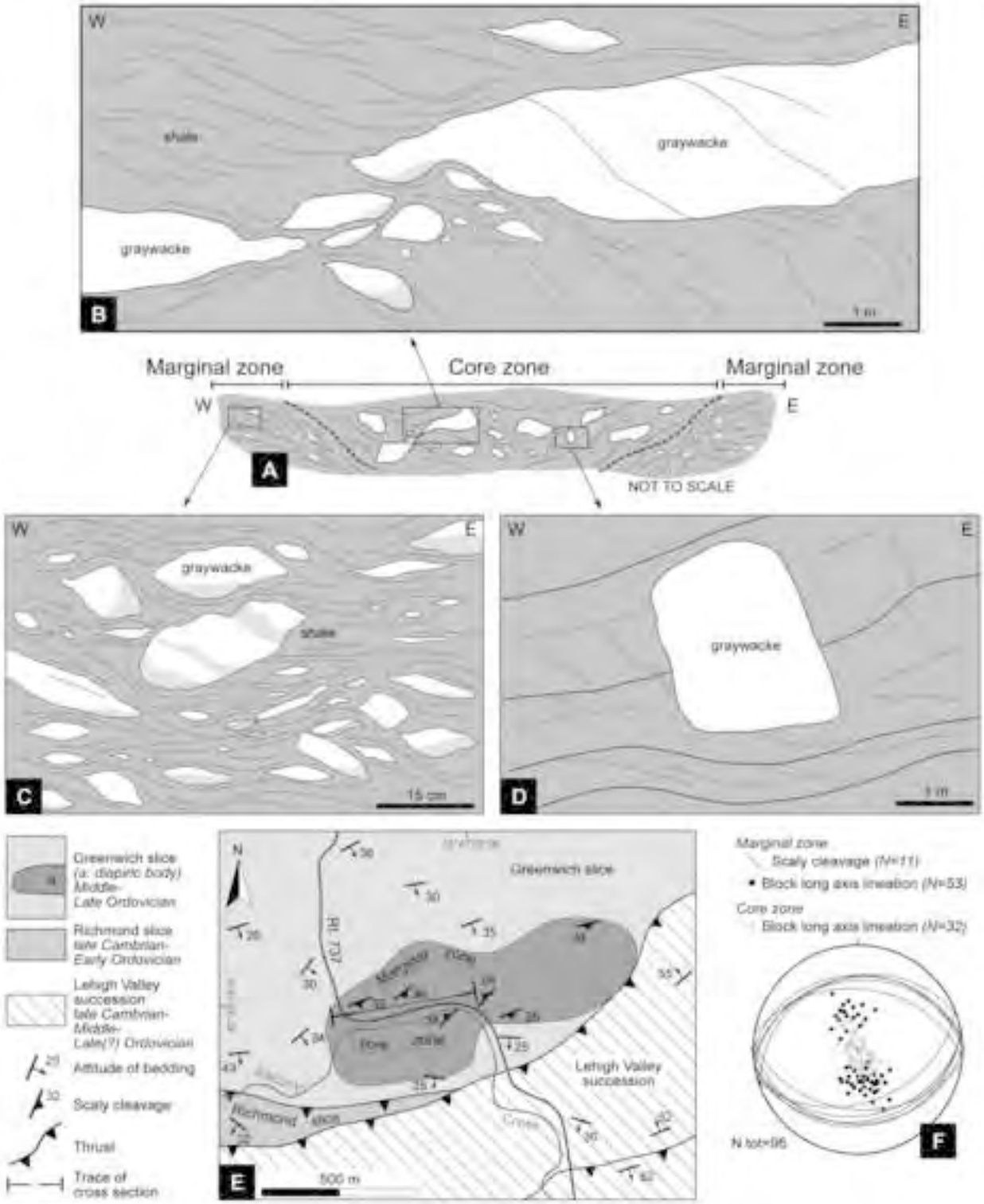

Figure 11 - Codegone et al.

Figure 12
Click here to download high resolution image

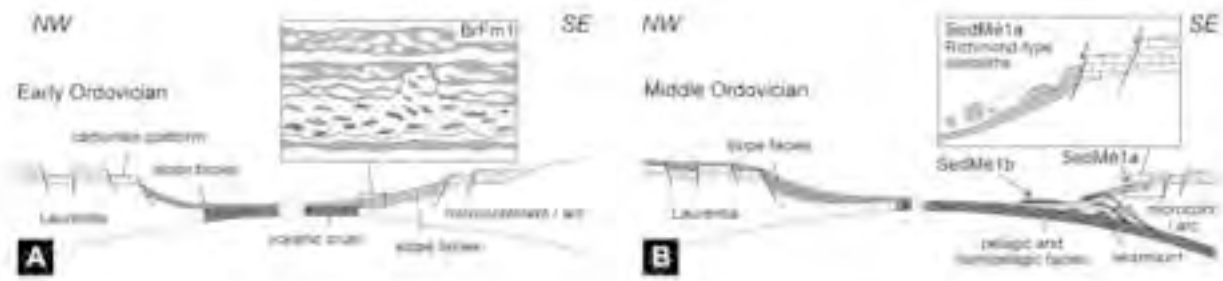

Figure 12 - Codegone et al.

Figure 13
Click here to download high resolution image

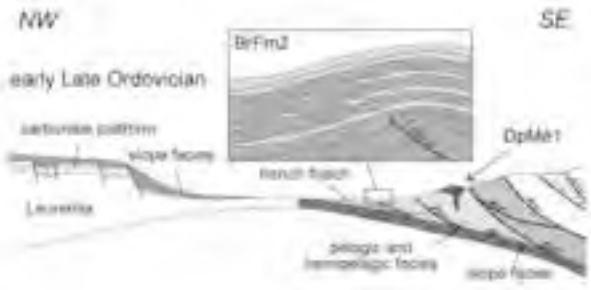

Figure 13 - Codegone et al.

Figure 14
Click here to download high resolution image

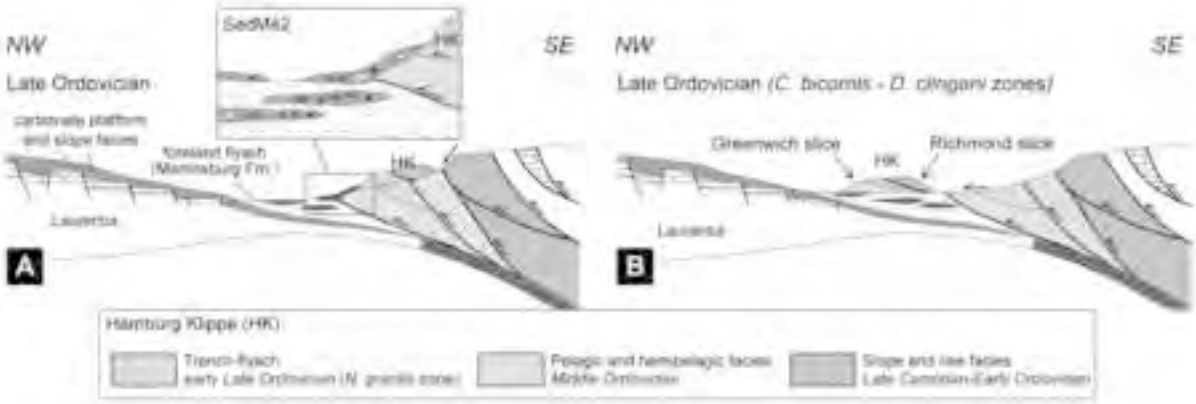

Figure 14 - Codegone et al.