Sand composition changes across key boundaries of siliciclastic and hybrid depositional sequences

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A B S T R A C T

Sand composition of arenite successions is sensitive to a suite of factors operating between initial grain production and final diagenesis on a variety of spatial and temporal scales. Seven allogenic factors, the relative importance of which relies upon the complex interaction between tectonics, eustasy, and climate, play a decisive role in dictating petrofacies distribution within siliciclastic to hybrid depositional sequences. These factors include (i) tectonic exhumation, (ii) physical and chemical rock breakdown, (iii) change in sediment flux, (iv) change in source/basin physiography, (v) shelf colonization by organisms, (vi) generation of chemical grains, and (vii) volcanism. Autogenic processes may locally have a considerable influence on the type and amount of sediment supplied to the basin, thus interfering with the external control. Based upon literature data, a conceptual framework of expected compositional changes across the key surfaces for sequence-stratigraphic interpretation is outlined. Two case histories, from the Miocene shelf-to-turbidite deposits of the northern Apennines and the Quaternary alluvial-to-nearshore succession of the Adriatic coast, respectively, are used as references to illustrate how arenite petrofacies changes can be framed into a sequence-stratigraphic scheme on multiple timescales.

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1. Introduction

The interplay of tectonics, eustasy and climate – the three main driving forces related to lithosphere, hydrosphere, and atmosphere – governs weathering of hinterland source rocks and production of penecontemporaneous volcanic, chemical, and biogenic grains, in concert with erosion, transport, and depositional processes on the Earth’s surface. This interplay triggers a series of phenomena with a profound influence on stratral patterns and stratigraphic architecture, including qualitative and quantitative sand compositional changes (Zuffa, 1994).

A variety of techniques are commonly used in order to detect compositional changes within sedimentary successions in a sequence-stratigraphic framework. Among these, geochemical investigations have been successfully carried out by testing facies and stratigraphic units of different rank (De Boer, 1993; Weltje and Weltje et al., 1996; Garcia et al., 2004; Amorosi et al., 2007, 2008). Geochemistry is a rather quick analytical procedure for stratigraphic correlations compared to other methods, such as optical studies of major and accessory components of sands (Morton and Hallsworth, 1999). However, in many instances, separation of individual parasequences or systems tracts with statistical confidence is not possible from the geochemistry itself alone (North et al., 2005). Compositional changes can also be revealed by the mineralogy of shales that are commonly associated to arenite formations (Amorosi et al., 2002; Arribas et al., 2003).

Detailed sand petrography has traditionally been restricted to provenance studies and paleogeographic reconstructions. Although several studies indicate that sedimentary packages, bounded by unconformities of different rank, are frequently marked by identifiable compositional variations (e.g., De Rosa and Zuffa, 1979; Dickinson et al., 1986; Garzanti, 1991; Ingersoll and Cavazza, 1991; Ito, 1991; Amorosi, 1995; Zuffa et al., 1995; Spadafora, 1996; Marchesini et al., 2000; Cibin et al., 2001; Arribas et al., 2003, 2007; Lawton et al., 2003; Basu et al., 2009; Seyrafaan and Toraby, 2009), the assessment of this tool in sequence stratigraphy is still in a very early stage.

The relationship among factors controlling compositional changes within a sedimentary succession is intricate. However, well-conceived petrographic investigations may help to decipher internal anatomy of depositional sequences, adding new insight for the reconstruction of source-to-sink systems. To reach this target, grain types need to be classified by taking into consideration three basic attributes: composition (e.g., carbonate versus non carbonate grains), spatial relationships (intrabasinal versus extrabasinal grains), and time relationships (grains coeval versus non-coeval with respect to the considered unit) (Zuffa, 1980, 1985, 1987, 1991).

The aim of this paper is to integrate arenite petrography and sequence stratigraphy by investigating the relative importance of the allogenic factors that may determine changes in arenite composition across and within depositional sequences. Through the development

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of a conceptual model of petrofacies distribution within a sequence-stratigraphic framework, specific objective is to delineate where and under what conditions sand composition changes may take place at key boundaries of unconformity-bounded stratigraphic units. Autogenic processes able to produce compositional changes in arenites with no significant correlation potential across the basin are also considered.

Two case studies, from open-marine (shelf to turbidite) and onshore (alluvial to coastal) settings, respectively, are discussed to show how sand petrography can be used as a tool for fingerprinting the bounding surfaces of depositional sequences. Where depositional systems are particularly sensitive to changes in sediment dispersal patterns, such as in the case of nearshore systems, and where high-resolution chronologic control is available (Quaternary successions), we show how compositional changes can be used for the detection of systems tract bounding surfaces.

2. Allogenic factors controlling changes in arenite composition

Arenite petrography deals with multicomponent systems that may be affected by a number of factors on a variety of time scales (Johnsson, 1993; Weltje and von Eynhatten, 2004). In order to relate arenite petrographic changes to the development of the key surfaces for sequence-stratigraphic interpretation, the most important factors that may cause compositional modifications in the type and amount of sediment supply are plotted in proportion to the interaction among the three major allogenic controlling factors: tectonics, eustasy, and climate (Fig. 1).

Tectonics governs compositional changes (i) by making available hinterland source rocks and causing changes in basin accommodation through uplift, extension, and flexural loading of the lithosphere and, indirectly, (ii) by bringing about new pyroclastic products that may originate from coeval volcanism located in extrabasinal and/or intrabasinal areas. Eustasy takes into account variations of the ocean-water volume, which may cause sea-level change controlling, in turn, the type and quantity of intrabasinal and extrabasinal grain supply. Climate (pressure, temperature, and humidity) controls compositional changes of clastic grains generated by chemical and physical breakdown of source lithotypes and has power for generation of new chemical and biogenic grains. The interaction between these three driving forces activates factors that are able to produce compositional changes across stratigraphic unconformities over time spans of thousands to millions of years.

In this paper, we will focus on depositional cycles developed at two different timescales, i.e., 0.5–5 My (commonly referred to as “third-order sequences”—see Vail et al., 1977) and 0.01–0.5 My (sequences falling in the Milankovitch frequency band, including “fourth-order” and “fifth-order” cycles—see Vail et al., 1991), respectively (see triangles in Fig. 1).

Seven out of the major processes controlling changes in arenite composition are listed below. First, we discuss the factors that control accumulation of detrital grains (see factors 1, 2, and 3). Second, we illustrate the mechanisms that may lead to generation of newly formed grains (factors 5, 6, and 7). Factor 4 may involve both components. Given the different influence on sediment generation and supply exerted by tectonics, sea-level change and climate on different timescales, when moving from one triangle to the other some of the factors influencing sediment composition can be observed either to die out or shift toward a different position (Fig. 1).

2.1. Tectonic exhumation

Tectonic uplift of an orogenic wedge undergoing thrusting and block-faulting may cause erosional unroofing (exhumation) of different tectono-stratigraphic units and deposition of third-order sequences characterized by distinct detrital composition (Zuffa et al.,

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Fig. 1. Primary allogenic factors controlling arenite compositional changes, classified according to the relative influence of tectonics, climate, and eustasy. The triangles do not include autogenic factors, nor factors controlling petrofacies changes over timescales of >5 million years.
2.2. Physical and chemical rock breakdown

Chemical weathering and pedogenesis may represent an important control on the petrogenesis of siliciclastic sediments (e.g., Scarciglia et al., 2007). Weathering causes the depletion of unstable minerals, like feldspars and mafic minerals, and consequently comparatively stable minerals like quartz and zircon are enriched in detrital sediment (Weltje and von Eynhatten, 2004). Soils in watersheds with low relief ratio (maximum relief divided by the maximum length of the watershed) and high water discharge per unit area experience the most extensive chemical weathering, and sediments derived from these watersheds contain the lowest percentage of feldspars and rock fragments. Rock fragments may survive or not depending on their composition and humid versus arid climate conditions (Picard and McBride, 2007). The intensity of chemical weathering is directly related to climate via effective precipitation (stream discharge per watershed unit area) in individual sub-basins, whereas the duration of chemical weathering is inversely related to the relief ratio of the watershed (Grantham and Velbel, 1988). Intensely chemically weathered sands can be reincorporated into river bedload during channel migration, resulting in net dilution and replacement of newly deposited sand by older, compositionally more mature mineral grains, causing increase in ratios of quartz/lithic and monocrystalline/polycrystalline quartz (Johnson et al., 1981). Changes in maturation of sands due to weathering related to climate and relief occur mainly on timescales of tens to hundred thousand years. In this respect, rainfall, vegetation, and bulk composition of the bedrock act as major controlling factors (Nesbitt et al., 1997; Weltje et al., 1998).

2.3. Change in sediment flux

Sand composition is sensitive to several factors, including erosion, transport, and the delivery of sediment to the basin. Tectonic uplift and sea-level change, which control stream gradients, and climate, which governs river discharge, may interact according to a complex interplay, resulting in different sediment type/availability and efficiency of sediment transfer to the terminal sink. Change from low to high sediment flux owing to increased tectonic activity or favorable climate conditions will be marked by decreasing compositional maturity, concurrently with an increase in the lithic population. On the other hand, long periods of tectonic quiescence will be manifested as mature sand deposits. Changes in sand composition may be induced by disintegration of weathered grains from most labile rock types during subsequent transport (Picard and McBride, 2007). Changes in discharge regimes and sediment supply reflecting climatic controls may induce either sediment storage or sediment production, with direct influence on stratigraphic architecture, especially of fluvial deposits (Blum et al., 1994). A very evident example of climatic-induced change of sediment flux leading to prominent compositional changes is that observed across the Po Plain at the onset of major glaciations during the “Mid-Pleistocene Revolution” (Vezzoli and Garzanti, 2009).

2.4. Change in source/basin physiography

In collision margin settings, where tectonics dominates relative to eustatic changes, tectonic activity may cause source/basin reorganization, which modifies the drainage basins, source-rock types, and their relative proportions (e.g., Stow et al., 1984). This implies that important changes in arenite composition due to tectonic uplift, thrusting, or basin subsidence are likely to occur at bounding surfaces of depositional sequences (Dorsey, 1988; Cibin et al., 2001; Arribas et al., 2003; González-Acebrón et al., 2010). In comparatively deep-basin settings, however, where depositional sequences are bounded by correlative conformable surfaces, petrofacies changes within turbidite or gravity-flow deposits may be gradual across sequence boundaries.

On active shelves of passive continental margins, repeated cycles of shelf emergence and submergence due to sea-level fluctuations may cause changes in the type and proportion of lithologic units cropping out in the source areas, along with substantial modifications of sediment dispersal pathways. As an example, deep-water fans can be heading on the outer shelf at lowstand conditions during glacial periods, whereas shifts in sediment routing may take place during transgressive and subsequent highstand phases, when the shelf is submerged and sediment dispersal patterns have changed from direct to indirect river input (Normark, 1985). Compositional changes due to sea-level variations are a typical feature of Quaternary fourth-order and fifth-order depositional cycles.

2.5. Shelf colonization by organisms

In mixed siliciclastic-carbonate systems, where “foramol” (Lees and Buller, 1972) shelf-carbonate factories are active, sea-level changes may exert direct influence on the intra-/extrabasinal grain budget. Thus, various types of sand mixtures (intra-/extrabasinal grains) can be available for either deposition on shelves or reedimentation in deeper water areas, depending on rising or falling sea-level conditions, respectively. Such changes in sand composition may occur on multiple timescales, under appropriate climatic conditions that allow production of intrabasinal carbonate and chemical grains.

Shelf colonization by organisms can also be enhanced by changes in the shelf profile, which is in turn directly controlled by tectonics. A narrow shelf with steep depositional profile will display remarkably different production of intrabasinal grains and down-basin reedimentation relative to a wider shelf passing smoothly into a gentler depositional slope. Normal ramps and distally steepened ramps (Read, 1985) are crucial to make intrabasinal sources active in relation to the sea-level curve (Dolan, 1989). In these instances, changes in sand composition are likely to occur at sequence boundaries, although they have also been observed to characterize individual systems tracts (Fontana et al., 1989).

2.6. Generation of chemical grains

Changes in sea level and oceanic current regime, under specific climate conditions, may promote production of pedogenic grains, such as duriicretes (i.e., calcite, silcrete, and ferricrete) in the hinterland, and/or authigenic marine grains, such as glaucony and phosphate grains, the latter facilitated by upwelling, in shelf environments. Subaerial exposure due to sea-level fall causes pedogenesis and erosion of early deposited marine sediments, especially in coincidence of interfluvial sequence boundaries (Van Wagoner et al., 1990; Aitken and Flint, 1996; McCarthy and Plint, 1998; Roca and Nadon, 2007).

In fluvial systems draining carbonate sedimentary formations, microbial activity may generate carbonate buildups (tufa and stromatolites), which supply carbonate fragments during erosion. Single carbonate
grains, such as micritic, sparitic, coated, and penecontemporaneous bioclasts, may also be generated and provide significant contribution to fluvial sedimentation (Arribas and Arribas, 2007). In marine settings, the abrupt reduction in clastic influx during phases of rapid sea-level rise may lead to the formation of glaucony, the maturity of which is a function of its residence time at the sediment–water interface (Odin and Matter, 1981). Glaucous minerals form preferably at the first marine flooding surface and are widespread throughout the transgressive systems tract, showing maximum concentration and maturity close to the maximum flooding surface (Amorosi, 1995). The transgressive systems tract is also characterized by specific diagenetic features (Karim et al., 2010).

2.7. Volcanism

Supply from coeval volcanic activity may affect the sedimentary record by either (i) adding a significant penecontemporaneous volcanic epiclastic component to the non-coeval detritus or (ii) contributing discrete ash layers made up of pure volcanic grains emplaced through mechanisms of pyroclastic flow, fall, and surges (Zuffa, 1987). When volcanic activity is related to major phases of basin re-organization, transition from pre-eruptive to syn-eruptive and post-eruptive periods may be paralleled by important changes in arenite composition (e.g., Critelli and Ingersoll, 1995), which are likely to correspond to lower boundaries of third-order depositional sequences. Changes in sea level, however, may also influence the distribution of volcanic grains within depositional sequences. Specifically, the decrease in terrigenous supply within marine environments during transgressions, owing to sediment storage at river mouths, has been observed to determine increasing frequency of volcanic ash layers in the transgressive systems tracts (Ito, 1991).

3. Autogenic factors controlling changes in arenite composition

The role played by autogenic processes on petrofacies composition is a factor that requires special consideration when reconstructing sedimentary evolution of a given area. Unfortunately, the distinction between arenite compositional changes due to allogenic factors and those related to autogenic causes is very difficult to decipher, because it requires identification of regional-scale petrofacies changes as opposed to localized variations in sand composition. Autogenic factors act on a local scale only, producing changes in arenite composition that have no significant correlation potential across the basin, but that may reflect high-magnitude events (Schumm, 1981). Lacking a high-resolution stratigraphic framework, petrofacies variations due to local factors may be superposed on, and thus easily confused with, compositional changes taking place at major unconformities. The major autogenic processes affecting fluvial to deep-water sedimentation are summarized below.

3.1. Fluvial-channel avulsion and river capture

Fluvial-channel avulsion may have significant impact on sand composition of alluvial to deep-marine depositional systems, controlling paleoflow divergence and, ultimately, delta lobe abandonment and switching. Apart from relative sea-level rise, which may cause avulsions as a result of backfilling of fluvial valleys during transgressions, the location and shifting of avulsion sites are commonly related to autogenic factors. These include local tectonics, which may determine the formation of avulsion nodes along fault zones, increased discharge and within-channel sedimentation, which may lead to channel widening (Stouthamer and Berendsen, 2000). Avulsion sequences (Mackey and Bridge, 1995) generally occur on very short time scales and may take only a few centuries to form (Stouthamer and Berendsen, 2007). River capture, occurring when an active incising watercourse assimilates a drainage of a less active stream, may generate an increase of sediment flux and add new source rocks, thus changing sand composition (Stokes et al., 2002).

3.2. Sediment compaction and differential subsidence

Accommodation within delta-plain and coastal-plain depositional environments may be governed by a combination of regional base level and autocompaction of the peat (Davies et al., 2005). In such environments, local changes in sediment compaction may induce inundation with lagoonal or estuarine sediments or, conversely, subaerial exposure and oxidation. In these instances, changes in sand composition may occur in response to variations from continental to brackish and even shallow-marine depositional environments. Differential subsidence may preferentially draw channels into certain areas, inducing channel migration and resulting in considerable changes in the drainage network (Alexander and Leeder, 1987). Complex feedback systems can be generated by increasing sediment compaction, which may promote an increase in the frequency of avulsions, whereas avulsions can be lowered by peat growth and overbank deposition.

3.3. Provenance mixing and sediment dilution

The variety of processes (and transport directions) that normally characterize fluvial, nearshore, and even deep-marine systems may determine sediment dilution virtually in all depositional settings, making petrofacies schemes very difficult to decipher from the rock record. Rapid changes in sediment source and flow direction are common within coastal depositional environments, where individual processes (rivers, waves, marine, and tidal currents) may interact in a very complex manner, with active periods of just decades to centuries. Large oceanic currents also can contribute to this factor (Allen et al., 2008). Sediment delivery to the coastal area may be enhanced by delta progradation. Axial supply, however, can be replaced by longshore dispersal, if a shift in distributary channels leads to delta lobe abandonment. Given the delicate balance of sediment dispersal pathways in the littoral zone, shifts of paleoflow directions in coastal sub-environments may take place simply in response to small changes in accommodation/sediment supply or short-term variations in sediment load or river discharge. Sediment mixing is also a common feature of alluvial plains. In such environments, confluent drainage systems or convergence between tributary and trunk river systems may result in mixing of detritus from separate sources, leading to mixed compositions (Arribas et al., 2000; Garzanti et al., 2009).

3.4. Hydraulic sorting

Compositional changes associated with textural effects and hydraulic sorting during sediment transport may cause systematic distortion in quantitative provenance analysis (Garzanti et al., 2009). Differences in grain size, density, and shape may determine textural-dependent petrofacies modifications within alluvial to deep-marine depositional systems. Such size-dependent compositional variability may be the result of either downcurrent sediment variations (see Fontana et al., 1989) or segregation of detrital grains into facies associations reflecting separate energy levels (Garzanti et al., 2008).

Interpretation of petrofacies changes in depositional basins with multiple sources and complex dispersal patterns requires a careful approach, since changes in composition from a layer to another may (i) either reveal the presence of different sources active approximately at the same time (autogenic control) (ii) or reflect modifications through time of source/basin physiography in response to the interplay of tectonics and sea-level changes (allogenic control). In multisourced foreland basin systems, flat, elongate foredeeps commonly promote unidirectional, bipolar patterns of turbidite sedimentation, fed by both longitudinal and
transversal sources, resulting in vertically stacked turbidites of significantly different composition, which reflect a pure autogenic control (Gandolfi et al., 1983; Ricci Lucchi, 1986; Stefani et al., 2007).

4. Compositional changes in a sequence-stratigraphic framework

Of the range of stratigraphic indicators, petrofacies changes commonly provide a clear and widely correlatable tool between multiple sampled sections. As shown in the previous sections, petrographic procedures for discriminating compositional changes across bounding surfaces of lithostratigraphic units and sedimentary bodies have been successfully used in several provenance studies. The role of this tool in sequence stratigraphy, however, remains largely to be assessed mainly because (i) comparatively few petrographic studies have been associated with sequence-stratigraphic interpretation of sedimentary successions and (ii) intricate feedback relationships among sedimentary processes acting on continental, coastal, shallow-, and deep-marine environments do not allow unequivocal source-basin relationships to be established (Zuffa, 1987).

Changes in accommodation (Jervey, 1988) and sediment supply represent the major factors in shaping stratigraphic architecture (Thorne and Swift, 1991; Dreyer, 1993; Martinson, et al., 1999). While several papers have focused on the analysis of sequence geometry in response to changes in accommodation (Posamentier and Vail, 1988; Wright and Marriott, 1993; Howell and Flint, 1996; Neal and Abreu, 2009), comparatively few studies have attempted to address on a numerical basis the climatic-physiographic control of sediment production and supply, which governs a significant fraction of the observed petrofacies changes (see simulation experiments by Wolde, 1998). Although detailed combined analysis of sediment composition and sequence geometry is beyond the scope of this paper, we document in the following sections how accurate analysis of compositional and textural properties of sediments across sequence boundaries and within depositional sequences may help to disentangle the relative influence of tectonism, sea-level change, and climate on sequence development, leading to an appropriate interpretation of petrofacies changes.

The conceptual framework of compositional changes versus stratigraphic units and their boundaries illustrated in Fig. 2 is aimed at facilitating the construction of a rationale useful for predicting if, where, and under what conditions compositional changes across sequence boundaries of different rank can be expected. This scheme, however, should be used very cautiously, and not as a template or a paradigm, since none of the cases listed below bears unambiguous, conclusive evidence for the cause of the observed petrofacies change.

Because the scale plays a fundamental role in relating sand compositional changes with sequence stratigraphy, the “third-order depositional sequence”, i.e., sedimentary packages formed during time intervals of about 0.5–5 My (see Fig. 1), was chosen as stratigraphic unit of reference. The term “depositional sequence” is used here in the sense of both Mitchum et al. (1977) and Posamentier et al. (1988). Finally, the term petrofacies is used in the sense of Dickinson and Rich (1972) “to imply rocks of similar petrology” with respect to the quality and quantity of their components.

4.1. Lack of compositional change across sequence boundary

Continental settings include depositional environments that are relatively less sensitive than the coastal and marine zones to changes in basin configuration (Blum and Törnqvist, 2000). Within the alluvial realm, variations of sea level or accommodation may not necessarily produce significant changes in draining directions, and thus compositional variations at sequence boundaries (Vezzoli and Garzanti, 2009). In these instances, fluvial sheets or channel belts may be petrographically indistinguishable from the overlying and underlying strata, a phenomenon known as “congruence” (Lawton et al., 2003).

Congruent sequence boundaries are more likely to record episodes of sea-level fall rather than tectonically driven base-level changes. The latter, by exerting direct influence on basin shape, are likely to cause significant changes in sediment dispersal patterns, and thus petrofacies changes at sequence boundaries (Fig. 2a).

4.2. Compositional change across sequence boundary

An intimate relationship between detrital sand composition and tectonic activity has been documented by a variety of papers (e.g., Ingersoll, 1978; Dickinson et al., 1998; Critelli, 1999; Garzanti et al., 2001; Miall and Arush, 2001; Arribas et al., 2003, 2007; Weissheimer de Borba et al., 2004; Critelli et al., 2007). The development of basin-wide unconformities due to active tectonics is commonly accompanied by deposition of sand units that differ markedly in composition, and different petrofacies may permit the characterization of each sequence in terms of both clastic constituents and provenance (Arribas et al., 2003). Compositional changes at sequence-boundary unconformities generally mark abrupt paleodrainage reorganization in response to tectonic uplift (Ryu and Niem, 1999; Roca and Nadon, 2007; Vezzoli and Garzanti, 2009). In terms of sequence stratigraphy, changes in arenite composition at sequence boundaries are likely to be recorded (i) at the basin margin, by sharp petrofacies changes within fluvial and transgressive estuarine to littoral and shelfal sand bodies directly overlying the subaerial unconformity, (ii) in deep-water settings, at the base of thick successions of falling-stage turbidites (correlative conformity), in association with diagnostic changes in lithofacies patterns (e.g., abrupt increase in the sandstone to shale ratio). Petrographic change across the sequence boundary within turbidite deposits is more likely to be a gradual and continuous process, not episodic, which may take place along a considerably long period of time (Fig. 2b).

4.3. Different compositional changes across the same sequence boundary

Arenites in the basal portion of a depositional sequence can be architecturally similar, but their compositional and dispersal characteristics may be different, if petrologically different detritus is derived at the same time from separate sources (Lawton et al., 2003). This implies that distinct petrofacies may occur simultaneously in different parts of the basin across the same sequence boundary (Spadafora, 1996). The occurrence of synchronous compositional variations is a feature commonly observed where basin readjustment in response to tectonic activity may lead to basin partitioning, with abrupt changes in drainage basin development. Variable inputs from different watersheds are likely to influence the coeval onset of different petrofacies above the sequence boundary in different parts of the basin (Fig. 2c).

4.4. Similar compositional change across different sequence boundaries

Within thrust-and-fold belts, compositional evolution through time may lead to the occurrence of the same petrofacies change across non-coeval sequence boundaries. This particular feature, which is strictly related to sediment recycling and cannibalization, is observed when the same lithostratigraphic unit is involved in uplifting and thrusting events in successive times, according to fault position and activation. As a consequence, the same unit may act as sediment source in different phases of basin evolution, and the same petrofacies change can be recorded in different parts of the system with different ages (Spadafora, 1996) (Fig. 2d).

4.5. Compositional change across systems tract boundary

Patterns of arenite composition may be strongly affected by changes in sea level, and thus record systematic variations within depositional sequences, from a systems tract to another (Ryu and Niem, 1999; Marchesini et al., 2000). This implies that laterally
extensive petrofacies changes are not expected uniquely as markers of the sequence boundary. Sediment dispersal, and thus sand composition, may evolve up section with sequence architecture, in response to changes in accommodation (Lawton et al., 2003). For instance, as a function of sedimentary evolution during relative sea-level cycles, falling-stage (turbidite) sandstones may be texturally immature and contain more chemically unstable grains, because of rapid burial and lack of further reworking. In contrast, highstand sandstones, of deltaic origin, are likely to be characterized by higher proportion of abrasion-resistant grains, due to continuing action of waves, longshore currents and tides related to shoreline progradation. Petrofacies changes are also expected at the initial transgressive surface (maximum regressive surface of Catuneanu et al., 2009), reflecting the abrupt facies change from fluviol to transgressive estuarine and shoreface arenites (Marchesini et al., 2000). Regionally extensive flooding surfaces, including the maximum flooding surface, may host remarkable amounts of non-carbonate intrabasinal grains, such as glaucony and phosphates. Glaucony characteristics may vary consistently within the transgressive systems tract, with maximum abundance and maturity marking maxima of sediment starvation (Loutit et al., 1988; Amorosi, 1995; Amorosi and Centineo, 1997). Sediment composition within depositional sequences can be influenced by climate change (e.g., glacial/interglacial variations), leading to alternation of soil formation with dense vegetation cover and marked denudation. In these instances, shifts in composition across systems tracts reflect the different extent of weathering with changing climate conditions (Weltje et al., 1998; Lugli et al., 2007) (Fig. 2e).

4.6. Compositional change across facies tract boundary

Although on vertical sections (outcrops or cores) individual systems tracts may be fingerprinted by diagnostic petrofacies changes (see Fig. 2e), simple, one-to-one relationships between petrofacies and systems tracts should not be expected in a three-dimensional sequence-stratigraphic framework. Specifically, facies variability internal to systems tracts may lead to downcurrent petrofacies changes within coeval deposits (i.e., facies tract). Maximum facies (and compositional) variability is likely to be observed within the lowstand systems tract (LST) and highstand systems tract (HST), where conditions of sea-level stillstand promote extensive delta and coastal progradation, with marked activation of autogenic processes. Remarkable petrofacies changes within HST have been reported by Ryu and Niem (1999) and Marchesini et al. (2000). On the other hand, minor compositional change is expected within facies tracts of the falling-stage systems tract (FST) and transgressive systems tract (TST). Here, the influence of sea-level forcing on wide portions of the basin, in terms of fluviol incision and generalized drowning, respectively, strongly reduces the relative importance of autogenic factors, favoring the development of more laterally extensive petrofacies (Fig. 2f).

5. Case studies

In order to address some of the conceptual points discussed in the previous sections, two case histories from stratigraphically well-constrained units in Italy are described below. The first case study, through an example from the Miocene of the Northern Apennines (Bismantova Group), focuses on petrofacies distribution within shelf to deep-marine deposits in a tectonically dominated setting (Fig. 3). Compositional changes are discussed in this example to the scale of third-order depositional sequences, with no specific systems tract connotation. On the other hand, the second case history, from the late Quaternary alluvial–coastal succession of the Adriatic coastal plain, illustrates petrofacies changes to the scale of depositional cycles...
falling in the Milankovitch frequency band, with special emphasis on compositional variations across systems tracts and their bounding surfaces (Fig. 4). This latter case study emphasizes sand petrography as an important tool in studying the internal architecture of sandy clastic depositional units on high-resolution spatial scales and in deciphering the depositional history of complex sedimentary successions.

5.1. Shelf to deep-marine deposits: the Miocene epi-Ligurian succession of the Northern Apennines

The northern Apennines are a complex thrust belt consisting mainly of tectonically superposed and juxtaposed units, elongated parallel to present tectonic axes (Boccaletti et al., 1990). The bulk of the thrust belt consists of turbidite deposits, representing the infilling of foreland basins that migrated stepwise during the successive phases of the Apennines tectogenesis. The foredeeps were coupled with minor substrate (epi-Ligurian) basins, carried passively piggyback on top of the allochthonous “Ligurian” thrust sheet, between Eocene and Pliocene (Ricci Lucchi, 1986). The epi-Ligurian succession, dismembered by compressional tectonic activity, crops out in the Apennines as scattered slabs, with moderate preservation of the original stratigraphic relationships. Miocene deposits are made up of three major lithostratigraphic units, namely Pantano Fm. and Cigarello Fm. (forming Bismantova Group), and overlying Termina Fm. (Fig. 3).

The sequence-stratigraphic analysis of this succession (Amorosi, 1997) has led to identification of four depositional sequences (S1–S4) sensu Mitchum et al. (1977) (Fig. 3). The onset of nearshore and shelf sedimentation (sequence S1) took place during the late Burdigalian in response to a phase of generalized tectonic uplift, which led to the development of a regional basal unconformity. The unconformable lower boundary of sequence S2 (lower Langhian) represents the base of transgressive, glaucony-rich, tide- and storm-influenced nearshore arenites. Generalized drowning of the shelves during the late Langhian–early Serravallian is documented by the rapid upward transition to turbidite coarse-grained siliciclastic deposits and deep-water marls (sequence S3). The fourth sequence boundary (S4) is marked by renewed turbidite sedimentation within strongly channelized slope and base-of-slope environments. Tectonics is thought to have exerted a major control on sequence architecture, especially at lower boundaries of sequences S1, S3, and S4. In contrast, a possible eustatic control has been hypothesized for sequence S2 (Amorosi, 1997).

Petrofacies distribution (Amorosi and Spadafora, 1995; Spadafora, 1996; Spadafora et al., 1998) closely reflects this hierarchy of depositional cycles (Fig. 3). Homogeneous hybrid composition (petrofacies P1), with relative abundance of carbonate material and non-carbonate intrabasinal grains (e.g., glaucony), characterizes shelf arenites throughout sequences S1 and S2. Sequence S3 marks the abrupt shift to siliciclastic sedimentation, although three different source areas for the detritus are documented by the development of distinct petrofacies (P2a, P2b, and P2c). Sequence S4 is preserved in the Bologna Apennines only, where arenites display the same petrofacies (P2a, P2b, and P2c) observed in the Parma-Reggio Emilia Apennines at S2/S3 sequence boundary.

Several out of the examples of petrofacies distribution in a sequence-stratigraphic framework shown in Fig. 2 are summarized by the Bismantova arenites: (i) lack of compositional change (see Fig. 2a) is recorded at S1/S2 sequence boundary, suggesting that sediment dispersal patterns on the shelf did not change significantly in response to sea-level fluctuations. (ii) Abrupt shifts in arenite composition (see Fig. 2b) are invariably observed where the sequence bounding unconformities developed in response to tectonic activity.

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### Fig. 2a

Sequence-stratigraphic interpretation of Miocene Bismantova Group, with arenite composition and petrofacies distribution. Compositional triangles show the petrofacies (P1, P2a, P2b, P2c) that characterize sequences S1 to S4. First-order diagram (total sand fraction) (Zuffa, 1980): NCE, non-carbonate extrabasinal grains; CE, carbonate extrabasinal grains; NCI, non-carbonate intrabasinal grains; CI, carbonate intrabasinal grains. Second-order diagram (terrigenous grains only): Q, Quartz; F, feldspars; L + CE, fine-grained rock fragments, including limestone and dolostone. Third-order diagram (fine-grained rock fragments): Lm, metamorphic; Lv, volcanic; Ls + CE, sedimentary (including limestone and dolostone). Petrographic data after Amorosi and Spadafora (1995) and Spadafora (1996).

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### Fig. 3

Sequence-stratigraphic framework shown in Fig. 2 are summarized by the Bismantova arenites: (i) lack of compositional change (see Fig. 2a) is recorded at S1/S2 sequence boundary, suggesting that sediment dispersal patterns on the shelf did not change significantly in response to sea-level fluctuations. (ii) Abrupt shifts in arenite composition (see Fig. 2b) are invariably observed where the sequence bounding unconformities developed in response to tectonic activity.
(iii) A multiple compositional change (see Fig. 2c), given by the synchronous onset of petrofacies P2a, P2b, and P2c, is observed at S2/S3 boundary across different sectors of the study area, suggesting substantial basin re-organization and dismembering of the epi-Ligurian basins due to tectonic activity. (iv) Finally, a delayed compositional change (see Fig. 2d), marked by local return to petrofacies P2a, is observed at the base of sequence S4 in the Bologna Apennines.

Fig. 4. The late Quaternary succession of the Adriatic coastal plain. (a) Study area (rectangle), with indication of the three sediment sources (i, ii, iii) feeding the present Adriatic coast. (b) Schematic cross-section with sequence-stratigraphic interpretation (LST, lowstand systems tract; TST, transgressive systems tract; HST, highstand systems tract; RS, ravinement surface; MFS, maximum flooding surface) and petrofacies (Pa, Pb, Pc) distribution across systems tracts. (c) Paleogeographic evolution of the study area during the last 18 ka. The present-day coastline of step 4 is shown as a dashed line in steps 1, 2, and 3. Modified after Marchesini et al. (2000). (d) Variation of the most distinctive compositional parameters used for petrofacies distinction. Dots indicate arithmetic averages for each of specimen subgroup, and bars indicate the range of values. (e) Ternary plots showing bulk composition of the samples studied. NCE, non-carbonate extrabasinal grains; CE, carbonate intrabasinal grains; CI+NCI carbonate intrabasinal and non-carbonate intrabasinal grains. Q, quartz, F, feldspars, L, fine-grained rock fragments, including carbonate.
5.2. Alluvial to nearshore deposits: the late Quaternary succession of the Adriatic coastal plain

Sediment supplied to the Adriatic coastal plain can be related to three main source areas (Fig. 4a):

(i) Rivers draining the Northern Apennines. Catchment basins in this part of the chain include mostly Upper Jurassic and Cretaceous deep-marine strata and Tertiary siliciclastic turbidites.

(ii) Rivers draining the Eastern Alps, between Piave and Adige rivers. Catchment basins include large areas of South-Alpine Mesozoic carbonate rocks (such as the Dolomites), igneous rocks and Permian Triassic acidic and intermediate volcanic rocks.

(iii) The Po River catchment basin, which extends from the central and western Alps up to the western side of the northern Apennines. The high-pressure/low-temperature rocks of the western Alpine Penninic units represent one of the more distinctive markers of this wide and heterogeneous sediment source area.

The late Quaternary depositional history of the Adriatic coastal plain south of Po River delta, reconstructed in terms of sequence stratigraphy by Amorosi et al. (1999, 2003) (Fig. 4b), has been summarized by Marchesini et al. (2000) as follows (Fig. 4b, c). An alluvial plain developed in the study area (grey rectangle in Fig. 4c) during the Last Glacial Maximum (about 20 ky BP). At that time, sedimentation was restricted to channelized areas (LST), whereas paleosol development took place on the interfluves. The post-glacial sea-level rise, between 18 and 6 ky BP resulted in the rapid landward migration of a barrier-lagoon–estuary system, which reached the study area about 8.8 ky BP (TST). At peak transgression, approximately 5.5 ka, the coastline was located about 20 km landward of its present position. During the subsequent highstand phase, progradation of an early Po delta lobe took place in the study area (lower HST). Finally, in the 13th century AD, the abrupt northward shift of Po River due to an avulsion event caused the abandonment of the formerly active Po Delta lobe and the construction of the modern delta in its present position (upper HST).

Cross composition and heavy minerals of sands from cores and surface samples (in particular, dolostone rock fragments, pyroxene, and amphibole contents) allow recognition of three different petrofacies (Pa, Pb, and Pc), which have been interpreted as being of Apenninic (Pa), mixed Eastern Alps/Po River basin (Pb), and Po River catchment basin (Pc) provenance, respectively (Fig. 4d and e). The distribution of these petrofacies changed through time, in response to shoreline migration (Fig. 4b). In the late Pleistocene, the lowstand alluvial plain was characterized by deposition of detritus supplied from Apenninic rivers (Petrofacies Pa). During the Holocene transgression, when the shoreline migrated tens of kilometers west of its present position, coastal deposits were fed by a mixed Po River–Eastern Alpine contribution (Petrofacies Pb), the latter probably as a result of southward transport by the littoral drift. The turnaround from transgressive to highstand conditions related to the progradation of the early Po River delta, promoted a gradual cut off of the Alpine detritus, leading to the establishment of a pure Po River provenance (Petrofacies Pc). The abrupt change in composition of the youngest beach–ridge sands marks the northward shifting of River Po, with subsequent abandonment of the early Po Delta, and testifies to the re-establishment of a coastal system fed by rivers draining the Apennines (Petrofacies Pa).

This case study shows that detailed sand petrography may be used as a major tool for unraveling the high-resolution depositional history of transitional and shallow-marine stratigraphic units on a scale at which standard arenite petrography is generally not applied. Of special interest is the characterization of individual systems tracts (LST, TST, HST) in terms of arenite composition (Fig. 2e), showing that sea-level fluctuations exerted a major control on changes in sediment dispersal in the coastal system. The complex pattern of compositional changes recorded within HST shows that autogenic processes may lead to important petrofacies variations within an individual systems tract (Fig. 2f), on temporal scales of just few thousands of years. In this instance, prompt interpretation of petrofacies distribution is possible uniquely due to the well-established relationship between facies architecture and easily datable (even historical) Holocene events. A direct implication of this example is that when dealing with ancient successions, for which high-resolution temporal constraints are not available, superposition of autogenic processes onto external forcing mechanisms can make proper reconstruction of sediment dispersal patterns in the coastal system (and thus interpretation of compositional changes in a sequence-stratigraphic framework) very difficult or even impossible.

6. Conclusions

A conceptual framework of sand compositional changes versus stratigraphic units and their boundaries is proposed based on seven allogenic factors relied upon the complex interaction among tectonics, eustasy, and climate, which dictates petrofacies distribution within siliciclastic to hybrid depositional sequences. Autogenic processes able to produce compositional changes in arenites, with low correlation potential across the basin, are also evaluated. In this analysis, sediment generation not only is seen as a product of weathering but takes also into account penecontemporaneous pyroclastic activity and chemical–biogenic processes that may operate during sequence formation, adding important coeval supply to the non-coeval detrital component. The resulting scheme makes possible the construction of a rationale useful for predicting if, where, and under what conditions compositional changes across sequence boundaries of different ranks can be expected. Specifically, it may prove particularly useful in designing appropriate sampling strategies for detecting compositional changes that may facilitate the reading of strata in terms of sequence stratigraphy and reinforce paleogeographic reconstructions.

However, this scheme should be used very cautiously, and not as a template or a paradigm. Not all the factors that influence sand composition are applicable to all cases, and they may have different weights in different scenarios. Whereas we can understand and evaluate genetic factors that would cause petrographic changes across third-order sequence boundaries, we can hardly list changes that identify lower rank stratigraphic surfaces. This study shows that autogenic processes may lead to notable compositional variations even within individual systems tracts, on temporal scales of just few thousands of years, thus making the picture of petrofacies distribution very difficult to decipher. However, when dealing with stratigraphic successions for which accurate chronologic control of facies architecture is available (e.g., Quaternary), interpretation of compositional changes and sand dispersal patterns in a sequence-stratigraphic framework may be possible to the scale of depositional cycles falling in the Milankovitch frequency band.

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