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Sandstone Petrology and Provenance in Fold Thrust Belt and Foreland Basin System

Salvatore Critelli and Sara Criniti

Abstract

The sandstone composition of foreland basin has a wide range of provenance signatures, reflecting the interplay between flexed underplate region and abrupt growth of the accreted upper plate region. The combination of contrasting detrital signatures reflects these dual plate interactions; indeed, several cases figure out that the earliest history of older foreland basin infilling is marked by quartz-rich sandstones, with cratonal or continental-block provenance of the flexed underplate flanks. As upper plate margin grows over the underplate, the nascent fold-and-thrust belt starts to be the main producer of grain particles, reflecting the space/time dependent progressive unroofing of the subjacent orogenic source terranes. The latter geodynamic processes are mainly reflected in the nature of sandstone compositions that become more lithic fragment-rich and feldspar-rich as the fold-thrust belt involves the progressive deepest portions of upper plate crustal terranes. In this context sandstone signatures reflect quartzolithic to quartzofeldspathic compositions.

Keywords: Sandstone, Petrostratigraphy, Convergent plate setting, Peripheral Foreland Basins, Sandstone Detrital Modes

1. Introduction

The evolutionary record of Earth's processes ascribed to sedimentary rocks has been pivotal in paleogeographical and paleotectonic reconstructions of source/basin systems. Compositional trends of clastic strata through space and time are used to frame the structural history of adjacent mountain belts and to monitor the key geodynamic changes during orogenic processes [1–5]. Clastic infilling of sedimentary basins, in orogenic systems, have been used as important indicators of tectonic activity and climatic changes. In the orogenic systems, clastic sedimentation may record the accretionary processes, the accommodation of the thrust units, and the flexural features of the foreland plate [5]. The chapter summarizes the close relations between source to sink in orogenic-derived sandstones. Foreland basin stratigraphy is intimately connected with the growth of orogenic systems. The derived sandstones reflect the changing nature of fold-thrust belts and the flexural features of the underplate. The main goal of this contribution is to discuss the changing sandstone petrofacies during infill of foreland basin systems using a petrological approach.

2. Fold-thrust belts in orogenic setting and Foreland Basin systems

The development of an orogenic wedge during continental collision points out a thickening of the crust. The excess of mass in this thickened crust acts like a load on the underthrust plate; that drag it to a flexure downwards close to the load, showing out a foreland basin framework [6, 7]. During plate convergence, the vertical load of the mountain belt migrates over the foreland plate, causing the migration of the associated foreland basin.

The foreland is the region between the front of a thrust belt and the adjacent craton [8–11]. Large volumes of clastic sediments derive from erosion of the thrust belt and subsequent deposition in the foreland basin. The foreland basin is generally defined as an elongate trough formed between a linear constructional orogenic belt and the stable craton, mainly in response to flexural subsidence caused by thrust-sheet loading in the orogen (**Figure 1**).

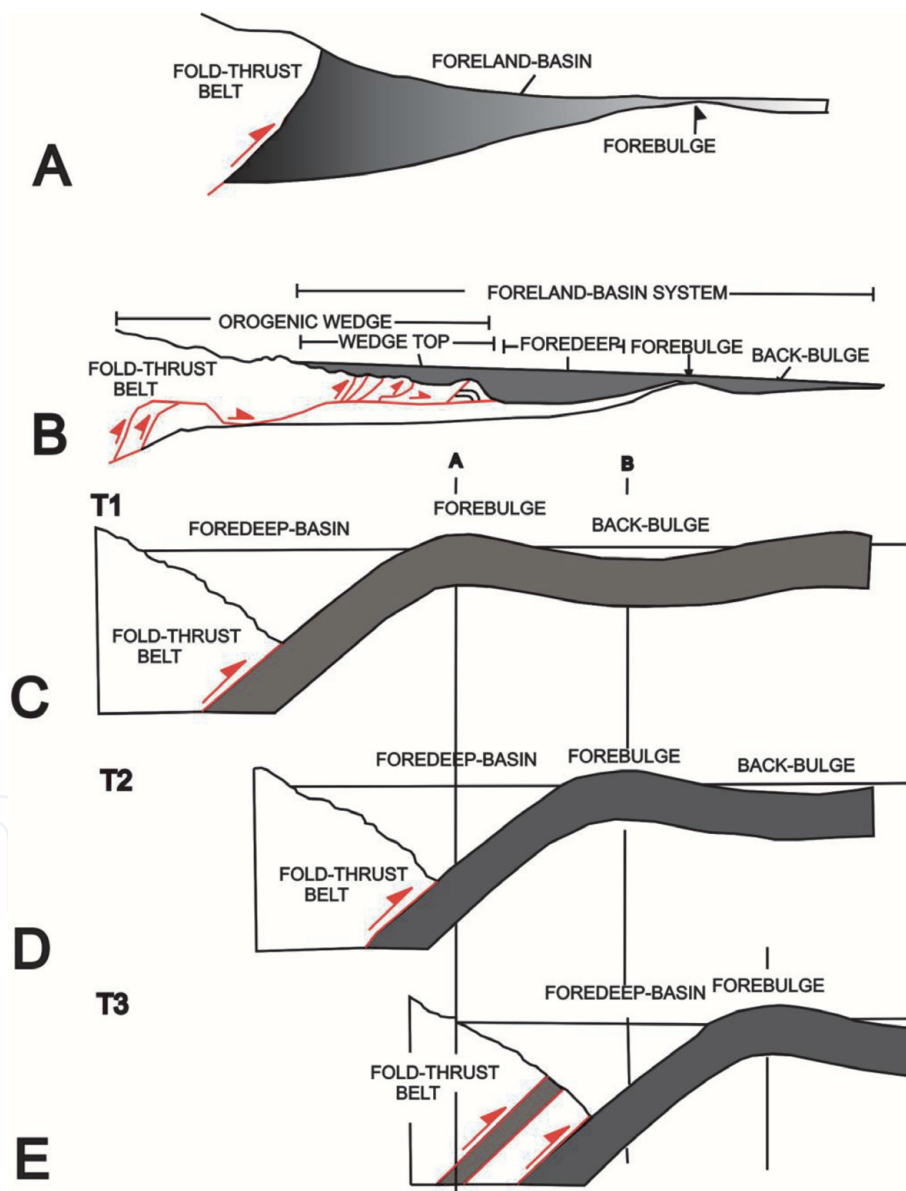


Figure 1.

Diagrammatic cross sections (from west to east) showing the general accepted notion of foreland-basin geometry (A, B) and the relationships between lithospheric flexure and accommodation space in foreland systems (C to E) [12–15]. A) General relationship between fold-thrust-belt, foreland basin and forebulge; B) foreland-basin geometry and depozones: Wedge-top, foredeep, forebulge and back-bulge depozones; C-E) relationship of the flexural features in times: c) initial (time 1) foreland system; D) foreland evolution during accretion of the fold-thrust-belt at time 2; forebulge migrated cratonward; E) previous forebulge assembled within the fold-thrust-belt. Modified after [4, 5, 12–15].

Foreland basin stratigraphy records tectonic, eustatic, and climatic changes at convergent plate margins [11], where the formation of unconformities is the result of the interplay of temporal variations in the erosion and lateral progradation rates of the orogenic wedge, as well as tectonic and eustatic sea-level changes [6, 16–18].

In foreland settings, subsidence and uplift are profoundly affected by lithospheric flexure. Foreland basin subsidence is primarily controlled by downflexing of the lithosphere in response to thrust accommodation and loading [6, 16, 19]. Subsidence rate gradually decreases away from the thrust front, producing an asymmetrical depression. Flexure uplift (forebulge) occurs as an isostatic response to warping downward and forms the distal margin of the foreland basin. Cratonward the forebulge flexure, a broad shallow downwarp or intrashelf basin forms, named as back-bulge basin (**Figure 1**) [12, 20].

The dimension and amount of flexural subsidence and uplift produced by the flexural features (i.e., foreland basin, forebulge, back-bulge basin) primarily depend on the geometry and density of the tectonic load, rheology of the lithosphere, density and volume of the sediment infill, and amount of thrust wedge and forebulge erosion [5, 6, 12, 16, 21]. The interrelationships between lithospheric flexure, single thrust accommodation within the accretionary wedge structure and flexural subsidence creates geometrical complex bodies within the foreland region. The foreland basin system may be divided into four depozones, the wedge-top, the foredeep, the forebulge, and the back-bulge depozones [12] (**Figure 1**). Boundary between depozones may shift laterally through time following the deformation propagation. The longitudinal dimension of the foreland basin system is roughly equal to the length of the adjacent fold-thrust belt [12].

3. Concepts of compositional signatures

The petrographic signatures during the different ages of the foreland infill show a clear sign of the diverse provenance sands, related to the different steps of the uplift stages and strictly connected to nearby rock portions exposed during the tectonic events. The discrimination of the principal source than the secondary one will point out the whole petrographic composition. This approach gives the base to the building of provenance and regional scale models from sandstone petrography.

3.1 Provenance models

Foreland regions are one of the typical setting in which huge volumes of clastic sediments are rapidly accumulated. This peculiar feature became a key element in provenance studies of such tectonic setting, because it consequently reveals several issues as the framework of the basin evolution complex history, sediment dispersal pathways, dating of major thrust events and the thrust-belt unroofing history [2, 22–25]. In this kind of setting, the uplift-erosion-transport-deposition system is genetically and intimately related to the deformation style in thin-skinned thrust terranes. Transport of clastic sediment parallel to the tectonic shifting is the commonly assumed setting for the clastic-wedge/thrust association [23–25], named as «synthetic dispersal». However, opposite sediment dispersal pathways to the tectonic shifting is possible where hanging-wall beds dip toward the interior of the thrust belt, paleoslope, and therefore sediment dispersal, is opposite to tectonic transport. Such dispersal model, defined as «antithetic dispersal» [25], reveals a kind of inverted stratigraphy, reflecting unroofing in the source, or mixed compositions. As result of these assumptions, it follows that sediment dispersal pathways in foreland basin systems are controlled by geometries within the thrust sheet

system as frontal ramps, lateral ramps, and diverse hanging-wall beds dip. If distinct source-rock compositions are eroded sequentially, as in the case of predominantly vertical uplift of a stratigraphic section, «unroofing sequences» are commonly formed in the resultant anatomy of a clastic wedge [23, 25, 26].

This erosional inverted clast stratigraphy (unroofing history) can provide valuable information about the evolving sources and the identification of specific source areas [26–30]. In the case of thin-skinned thrustured terrains (where horizontal transport dominates), layered rocks with different lithologies are exposed to erosion as they pass over a ramp, providing a blended clastic dispersal pathways of the exposed rock types. The resulting clastics may show no unroofing sequences, but include the same blended clast composition for relatively great thickness. These blended clastics may indicate that the source rocks were formed by tectonic transport over a ramp [25]. In thin-skinned thrust belts, both «unroofing sequences» and «blended clastics» can result in combinations, due to the evolution of the entire orogenic system and foreland basin infill.

3.2 Large and regional-scale models based on sandstone Petrostratigraphy

Numerous studies have demonstrated that sand (stone) from foreland basins are characterized by high framework percentages of quartz and unstable sedimentary and metamorphic lithic fragments, and the mean composition is quartzolithic [1–3, 5, 30–32].

The foreland basin systems are a typical basin-setting in which multiple sources can be active at the same time, and the derivative sandstones may show mixed petrofacies [4, 5, 31, 33] (Figure 2). Schwab [31], in a general statement of

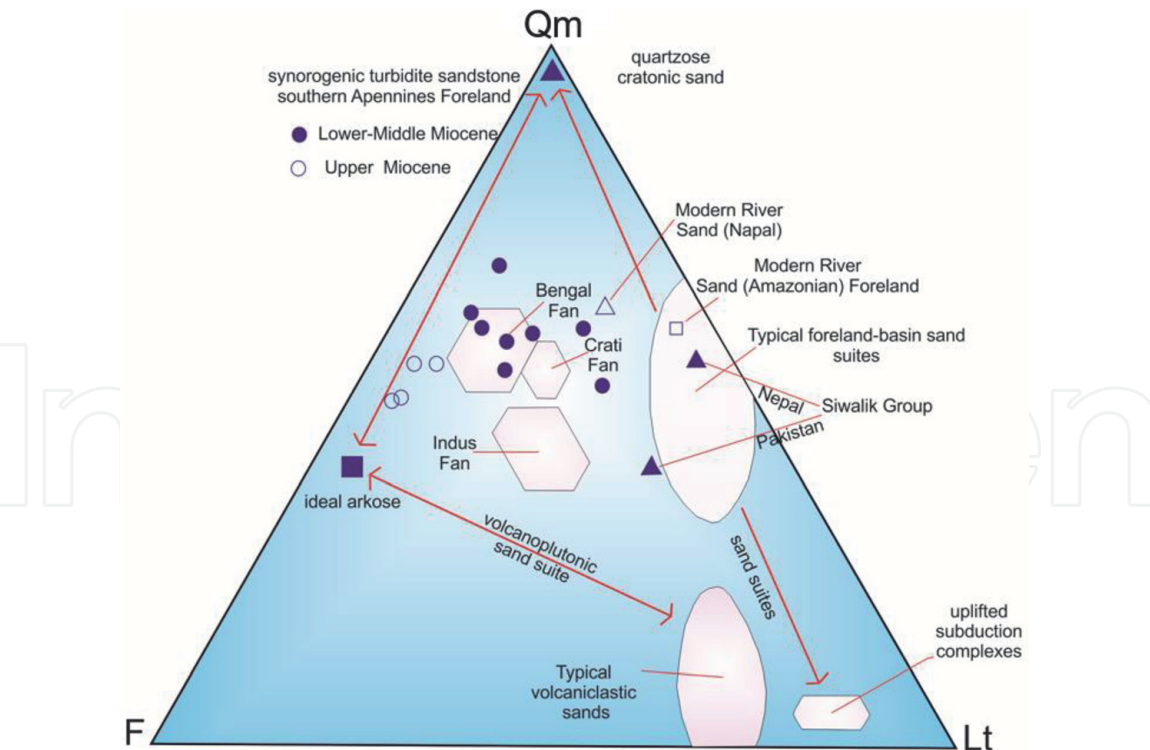


Figure 2. QmFLt (Qm = monocrystalline quartz, F = feldspars, Lt = aphanitic lithic fragments) diagram illustrate the concept of mixing detritus from different provenance types that produce detrital modes reflecting mixed provenance [2]. Typical foreland-basin sand suites were derived from uplifted fold-thrust belts exposing sedimentary and metasedimentary strata. The mixed provenance relations are also typical of some foreland basin systems and remnant ocean basins (i.e. southern Apennines foreland, Indus and Bengal fans of the Himalayan belt). During early stage of foreland infill, sand may derive from cratonal areas, generating quartzose sand. Subsequent petrofacies is quartzolithic, and during final foreland infill (foreland uplift), petrofacies may be mixed and quartzofeldspathic. Modified after [4, 15].

foreland-basin sandstone petrofacies, testifies the complex pattern of provenance relationships during the foreland basin evolution. Quartzose sand is typical during the early stage of foreland infill, when the thrust-belt has low elevation and consequently supplies low amounts of detritus, while cratonal region is flexing and provides more amounts [33, 34]. The subsequent petrofacies is typical quartzolithic, when the thrust-belt is growing and show up its roots. Local nearby provenances from magmatic arcs, uplifted subduction complexes or uplifted carbonate rocks of the forebulge represent just small amounts of the clastic record within foreland basin system. Only if the thrust belt shows severe uplift rates, in a way to expose the crustal basement, petrofacies can evolve to quartzofeldspathic sand during the late stage of “Foreland Uplift” [3–5, 35–37].

4. Provenance and setting: Sandstone detrital modes and orogenic provenance

Foreland basins adjacent to orogenic wedges experience drastic changes in provenance during their sedimentary history due to the high stressed event. In general models, arkosic petrofacies of rift phases lie at the base of the foreland successions, followed up by quartzose petrofacies of the passive margin or cratonal regions. These pre-orogenic strata are then succeeded by quartzolithic petrofacies derived from upper crust thrust units of the nascent orogenic system. Detrital modes in foreland setting are the combination of two main key sources located on the thrust and uplifted upper plate, and on the underplate. These issues are crucial in the definition of key tectonostratigraphic sources that grow up from the deformational pattern of the plate convergence, closely revealed in the clastic stratigraphy of the resulting foreland basin system. Sandstone petrology is a key tool for unveiling the close relation between source to sink and the spatial and temporal significance of the whole detrital budget.

4.1 Key tectonostratigraphic sources

4.1.1 Upper plate sources

Thin-skinned thrust terranes. - Such terranes are mainly made up of metasedimentary bedrocks and sedimentary successions directly covering their basement rock suites; other thrust units are composed by ophiolitic sources of ancient consuming oceanic basins, including oceanic crust rocks of both metavolcanic and subvolcanic fragments and their oceanic sedimentary cover of chert-rich, pelagic shale and limeclasts (**Figure 3**).

Foreland Uplift terranes. - Mid-crustal deformed and thrust terranes, including mid-high-grade metamorphic rocks (micaschist, gneiss, granulite) and plutonic suites (mainly tonalite-to-granite) are involved in the plate convergence and rapidly exhumed and uplifted. These thick-skinned thrust terranes are high producer of sand, indeed, phaneritic crustal terranes are able to generate huge volumes of feldspar-rich clastic material, and they are responsible of detrital mode shifting toward more quartzofeldspathic sandstone suites within the orogenic provenance field. Many examples along the stratigraphic record testify the changing nature of foreland sandstone petrofacies from quartzolithic to quartzofeldspathic sand suites [5, 29, 30] (**Figure 4**).

Remnant Volcanic arc. - Persistent active volcanic sources, as remnants of pre-collisional history, may contribute to the sedimentary budget of the foreland basin system when volcanic activity continues during the early stages of foreland evolution. Signatures from active volcanic sources may be diluted with other detrital

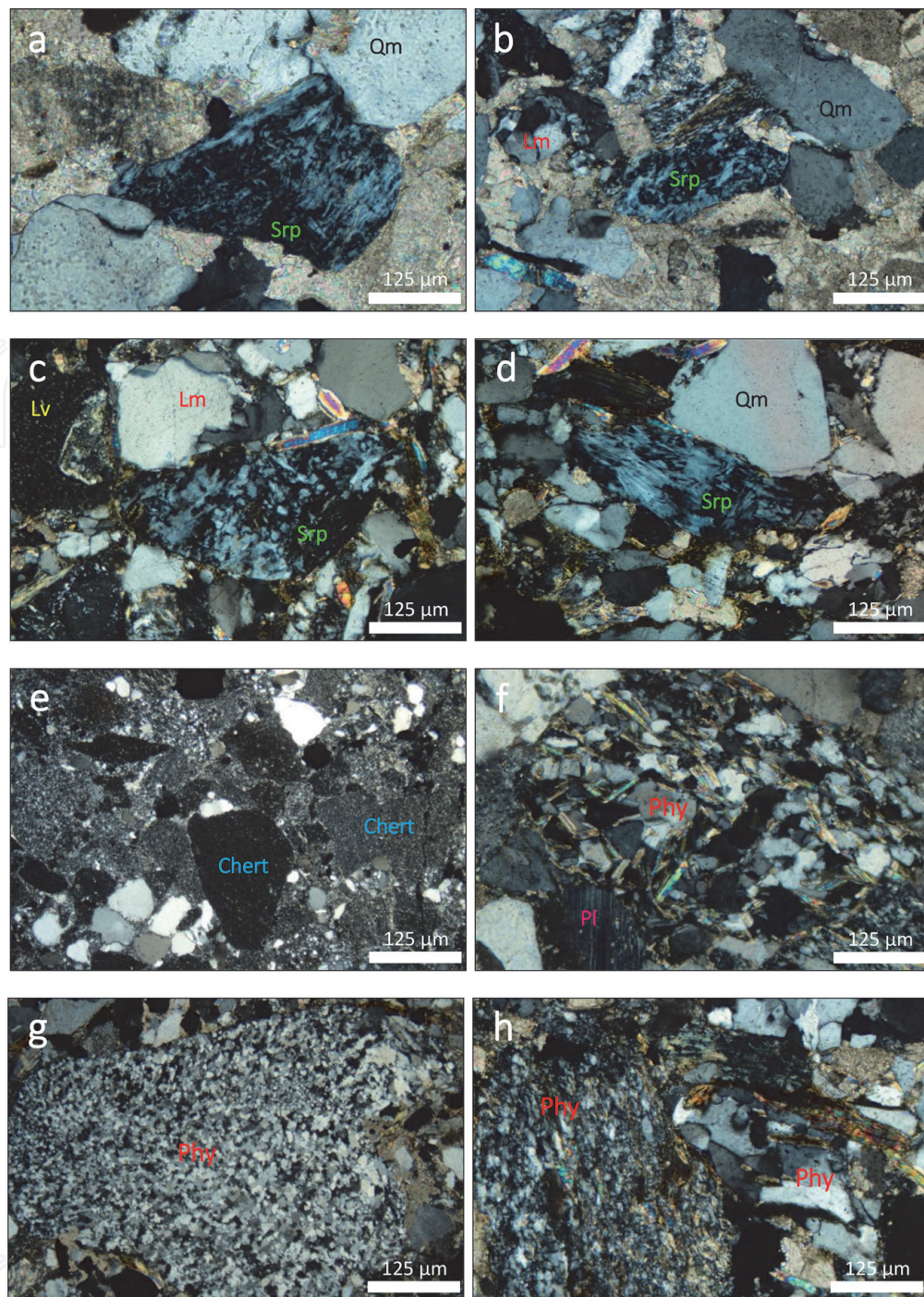


Figure 3. Key photomicrographs of upper plate source terranes. The source terranes include: (a-to-f) obducted remnant ocean terranes of (a-b) cellular serpentinite and (c-d) serpentinite-schist and eroded oceanic sedimentary cover of impure chert and argillaceous chert (e) and quartzite (f), and (g-h) folded, foliated and thrustured upper crust rock suites of low-grade metamorphic rocks of phyllite (g and h). All photos are crossed polars. Mineral abbreviations: Qm = quartz monocrystalline, Srp = serpentine schist, Lm = metamorphic lithic, Lv = volcanic lithic, Phy = phyllite, Pl = plagioclase.

budget or they can represent distinctive volcanoclastic layers interbedded within the foreland clastic wedge (Figure 5).

4.1.2 Underplate sources

Thrustured underplate margin. - Portions of the underplate continental margin may be involved in flexure and in underthrust, and then assembled within the orogenic wedge. Usually they include sedimentary cover and upper crust stratigraphy of the underplate. Shallow-water to deep-water strata and upper crust low-grade

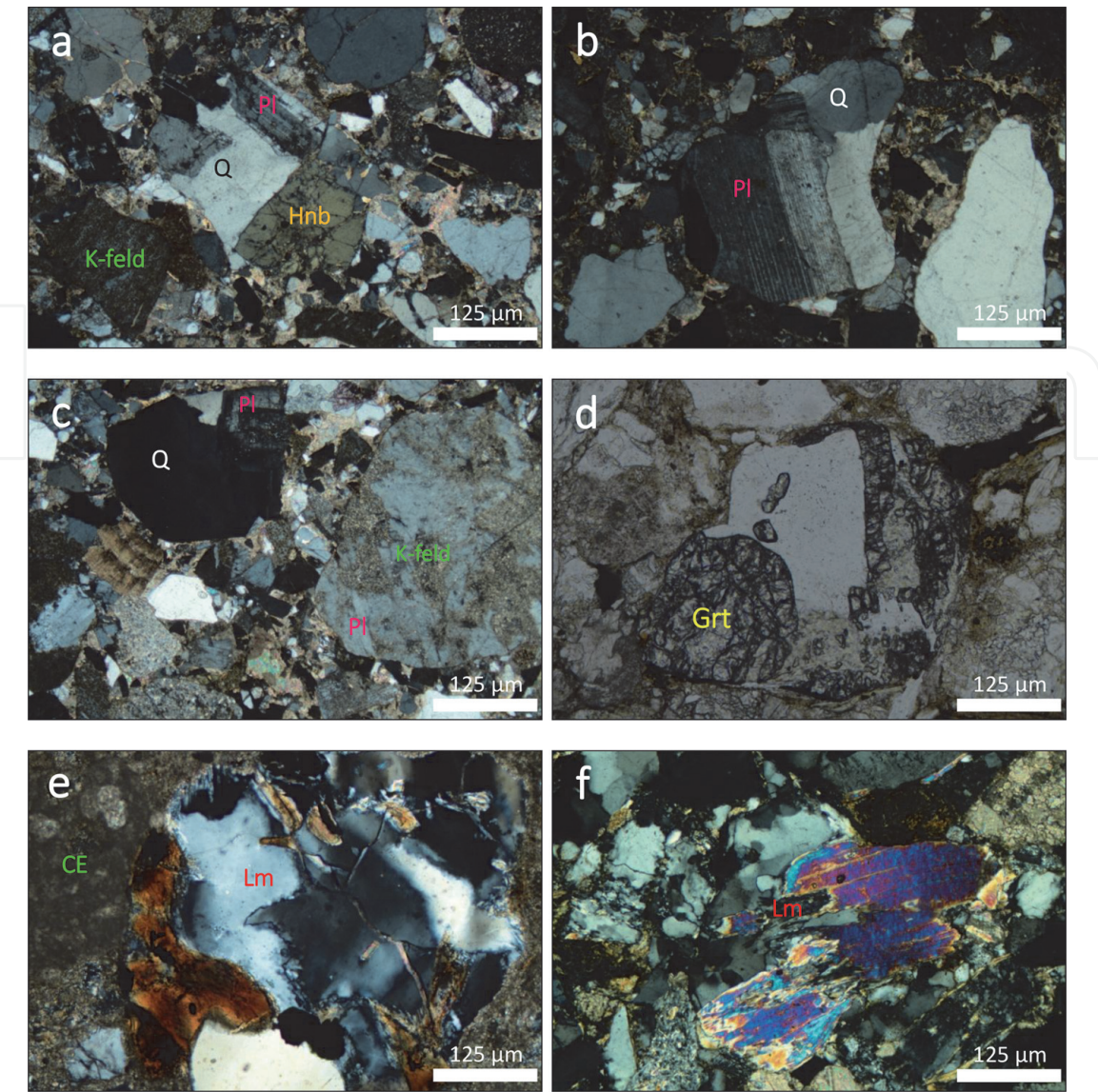


Figure 4. Key photomicrographs of deeper crustal rock suites of the upper plate source terranes. The source terranes include: (a-to-c) exhumed plutonic rock suites, mainly from intermediate tonalite (a) to granodiorite (b) and granite (c), and (d-to-f) medium-high grade metamorphic rocks of garnet-bearing gneiss (d), and paragneiss (e-f). A, b, c, e, f photos are crossed polars, (e) is plane-polarized light. Mineral abbreviations: Q = quartz, Pl = plagioclase, Hnb = hornblende, K-feld = K-feldspar, Grt = garnet, lm = metamorphic lithic, CE = extrabasinal carbonate.

metamorphic rocks of the underplate continental margin generate sedimentary and metasedimentary lithic fragments within the puzzle of the foreland sandstone suites.

Forebulge. - It is the region of potential flexure uplift along the craton side of the foredeep. Because of forebulge is a positive and potentially migratory feature, which may be eroded, its potential of preservation is low. A signal of the presence of ancient forebulge may be the erosional unconformity surface. The forebulge is generally considered a zone of nondeposition or erosion, or a condensed succession, and the resulting unconformity may be used to mark its location through time. In subaerial foreland basins the forebulge is a region of erosion, with streams draining both toward and away from the orogenic belt. In submarine foreland basin systems, local carbonate patch may be developed; extensive forebulge carbonate strata can connect the foredeep with the back-bulge depozone [13]. Forebulge is a producer of sediments for the foredeep in terms of delivering detrital grains and huge gravity flow deposits. The nature of the detrital budget is in response of the underplate stratigraphic record (**Figure 6**).

Internal stable foreland. - Craton interior region of the underplate widely contributes to the initial stages of foreland generation, and usually discharge huge

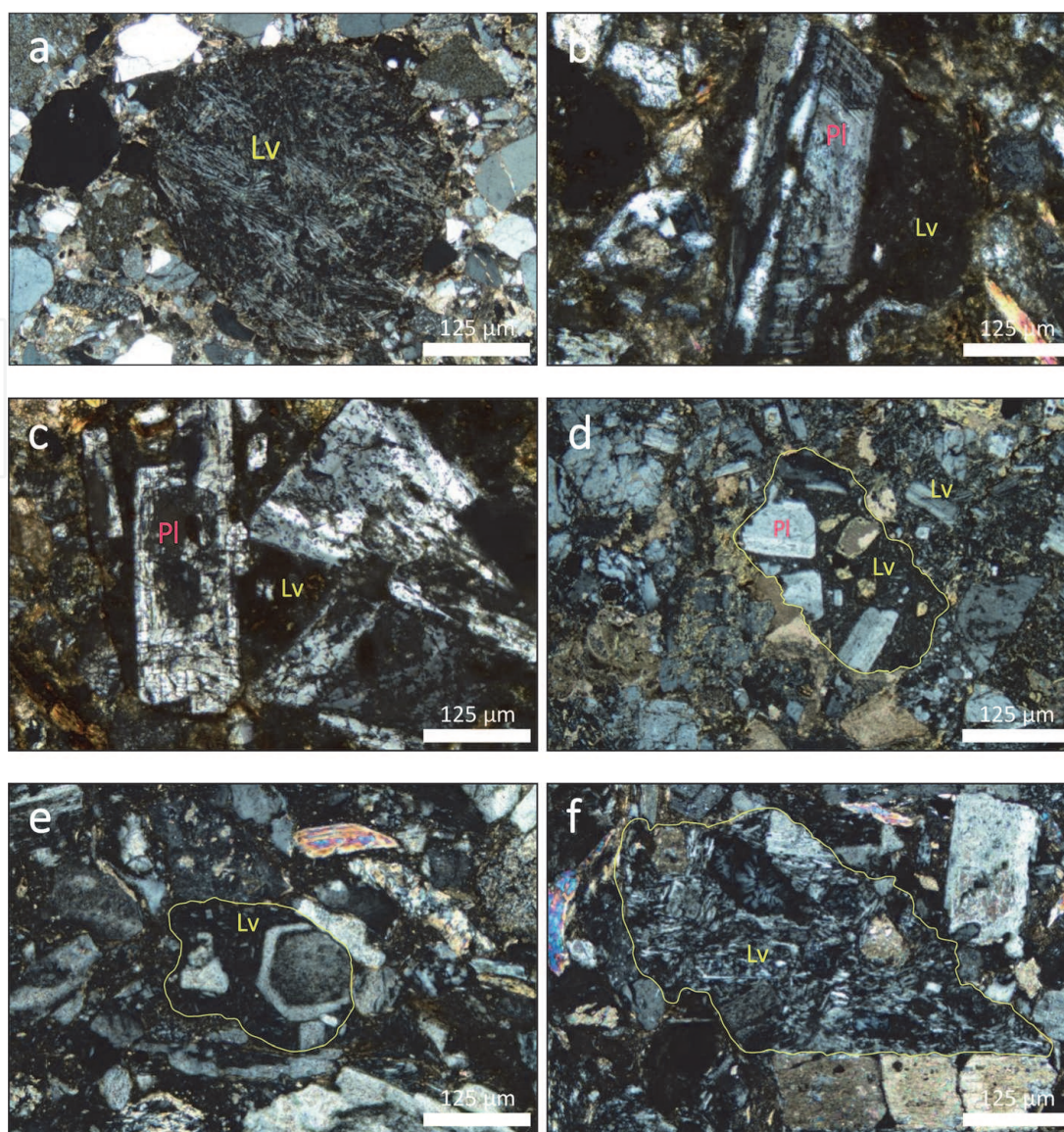


Figure 5. Key photomicrographs of volcaniclastic signatures in foreland basins. The source terranes include: Volcanoclastic lithic rock fragment with microlithic texture (a, f) and felsitic seriate structure (b-e). All photos are crossed polars. Mineral abbreviations: Lv = volcanic lithic, Pl = plagioclase.

volumes of supermature quartzose detritus into the foreland infill. Local limeclasts and intrabasinal carbonates are an adding source (**Figure 7**).

4.2 Key sandstone petrofacies filling foreland basin

Key sandstone petrofacies reflects the changing nature of the orogenic evolution and related filling of foreland basin. Quartzose, quartzolithic, quartzofeldspathic, and hybrid sandstones are the main signatures in foreland setting (**Figure 8**). Local calcilithite and volcaniclastic sandstones may also occur in this tectonic setting. Optical analysis of modal point count in sandstone is hardly suggested for the best fitting of the whole composition trying to recognize the temporal and spatial significance of the identified petrographic classes (**Table 1**).

4.2.1 Quartzose petrofacies

Quartz-rich sandstones reflect provenance from stable craton and lowlands reflecting abundance of rounded quartz grains, mainly monocrystalline. The stratigraphic record testifies occurrence of quartzose petrofacies as the main signatures

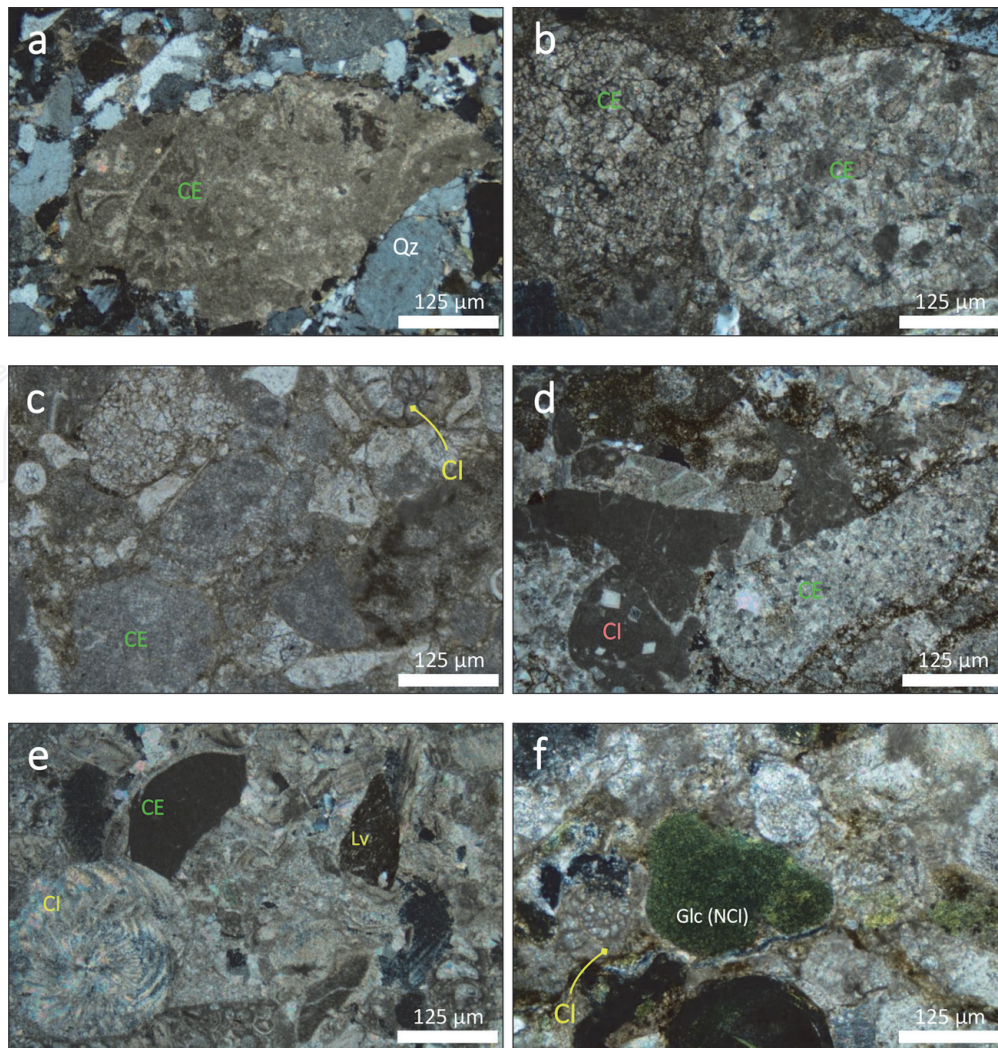


Figure 6.

Key photomicrographs of underplate source terranes. The source terranes include: (a-to-d) folded and thrust continental margin rock suites of sedimentary cover and eventually metasedimentary bedrocks and undeformed forebulge sources. A-to-d extrabasinal carbonate grains (CE or limeclasts) in quartzolitic sandstone, calcilithite and hybrid arenites. Hybrid arenites having abundant intrabasinal carbonate of bioclasts (e) and non-carbonate particles of glaucony and phosphates (f) are useful in foreland setting as related to signatures of sea-level change and underplate setting. All photos are crossed polars. A, e, f photos are crossed polars, b, c, d are in plane-polarized light. Mineral abbreviations: CE = extrabasinal carbonate, Qm = quartz, CI = intrabasinal carbonate, Lv = volcanic lithic, Glc = glaucony, noncarbonate intrabasinal (NCl).

of early stage of foreland infill [31]. Quartzose sandstone is mainly in response of downdip flexed continental margins of underplate when it represented ancient passive margins or stable craton. Great volumes of mature quartz sand can travel around the slow topography of the underplate and lay in subsiding regions of the various depozones of the foreland basin system. Circum-Mediterranean orogenic belts are a clear example of huge volumes of quartzarenite occurrence with a wide dispersal pathways all around the main orogenic fronts that accommodate more than 4,000 m of supermature quartzarenite turbidites of the Numidian Sandstone ([5] and bibliography therein). Other examples include the Carboniferous coastal quartzarenite related to the collision of Siberia with Laurussia [36], and so many others examples in the stratigraphic record and in modern setting [40, 41].

4.2.2 Quartzolitic petrofacies

Elongated Q-L plotted quartzolitic suites is the main composition of foreland sandstones reflects the growing orogen of thin-skinned thrust belt of accreted plate. Large occurrence of metasedimentary and sedimentary lithic fragments, such as

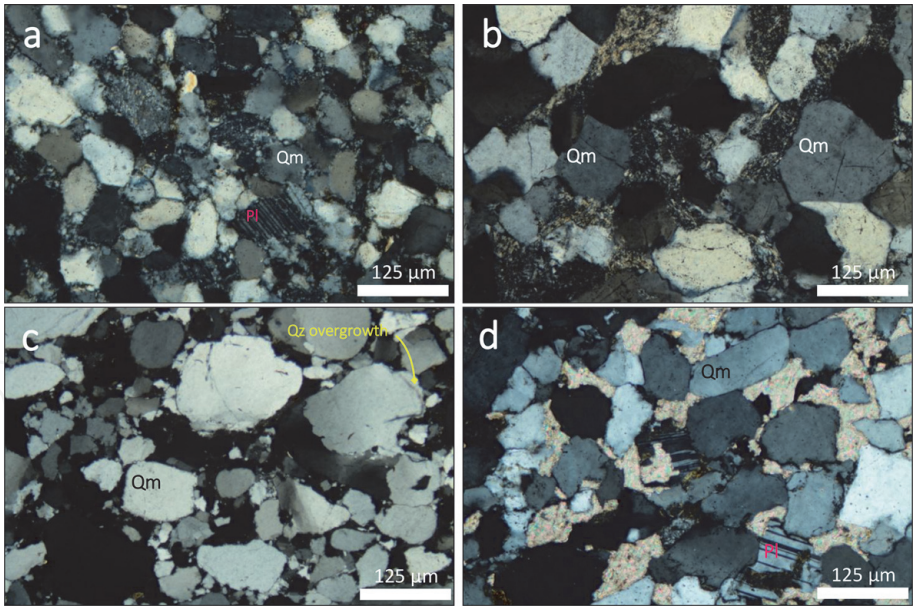


Figure 7. Key photomicrographs of craton interior underplate provenance. The source terranes include dominant quartzose grains of internal stable foreland. (a) Quartzarenite of the antler flysch, Idaho, (b) carboniferous quartzarenite, Svalbard Island, (c) and (d) well-rounded quartzarenite of the Numidian sandstone in the circum-Mediterranean orogenic region. All photos are crossed polars.

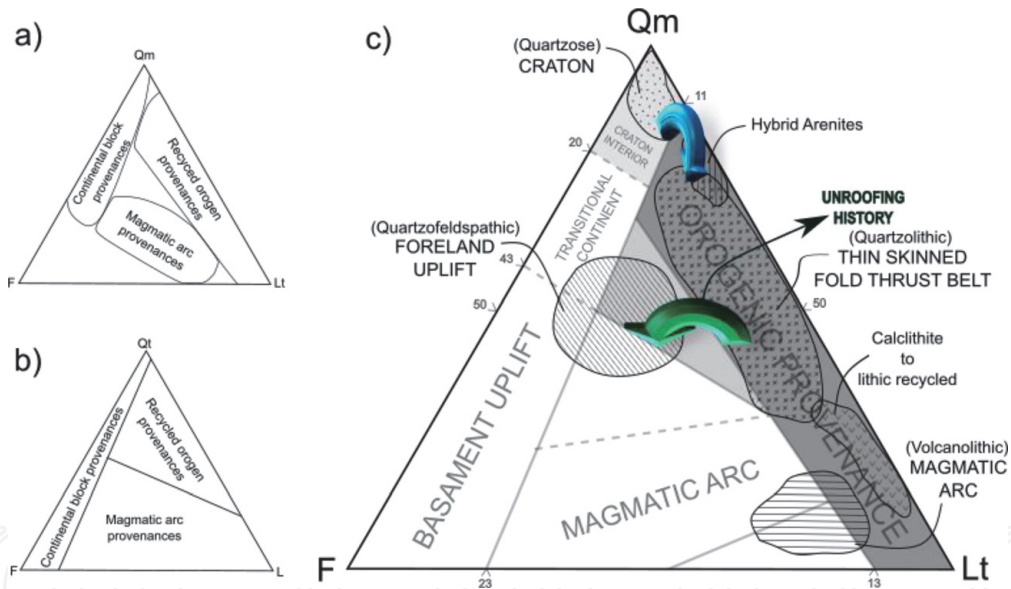


Figure 8. QmFLt (Qm = monocrystalline quartz, F = feldspars, Lt = aphanitic lithic fragments) diagram used for illustrate the concept of different provenance types in relation to tectonic setting. (a) Sources for original conception of plate tectonic setting and sandstone composition by Dickinson and Suczek [38], and (b) later refinement by Dickinson [1]. (c) Typical foreland-basin sand suites were derived during early to late stages from: (i) craton interior, (ii) upper crust thrust (iii) interbedded volcanoclastic suites from remnant magmatic arc, and (iv) uplifted mid-crustal fold-thrust belts. During early stage of foreland infill, sand may derive from cratonal areas, generating quartzose sand. Subsequent petrofacies is quartzolitic, and during final foreland infill (foreland uplift), petrofacies may be mixed and quartzofeldspathic testifying the unroofing history of the Orogenic Belt and related foreland infill (arrow).

abundant quartz, are the main detrital supply to the foreland basin. Nice examples are quartzolitic sandstones of the Eocene-to-Pliocene foreland basins of the Himalayan thrust-belt [3, 35], as such as many other sandstone examples of Paleozoic through Pleistocene orogens [5, 11, 15]. On both ancient and recent foreland sand (stone), the main detrital component is the abundance of quartz and aphanitic lithic fragments. The latter are mainly represented by (i) low-to-medium grade

Petrographic classes					
Quartz (Qt=Qm+Qp)			Extrabasinal Carbonates (CE)		
NCE	Qm	Quartz (single crystals)	CE Ls	Dolostone	
	Qp	Polycrystalline quartz with tectonic fabric		Micritic Limestone	
		Polycrystalline quartz without tectonic fabric		Sparitic Limestone	
	Qm	Quartz in metamorphic r.f.		Microsparitic Limestone	
		Quartz in volcanic r.f.		Biomicritic Limestone	
		Quartz in plutonic or gneissic r.f.		Biosparitic Limestone	
		Calcite replacement on quartz		Fossil (single skeleton)	
				Fossil in Limestone-Dolostone	
	Feldspars (F=K+P)			Single spar (calcite)	
	K	K-feldspar (single crystals)		Single spar (dolomite)	
K-feldspar in plutonic r.f.		Fe-Oxid concretions			
Calcite replacement in k-feldspar			Intrabasinal Carbonates (CI) and noncarbonates (NCI)		
P		Plagioclase (single crystals)	CI	Bioclast	
		Plagioclase in metamorphic r.f.		Peloids	
		Plagioclase in plutonic r.f.	NCI	Glauconite	
		Plagioclase in plutonic or gneissic r.f.		Oxide-Fe	
		Plagioclase in sandstone		Rip-Up clasts	
		Plagioclase in volcanic r.f.			
	Calcite replacement in Plagioclase		Interstitial components (Matrix and cements)		
			Siliciclastic matrix		
	Micas		Carbonate matrix (micrite)		
	Micas and clorite (single crystals)		Carbonate cement (pore-filling)		
	Micas in volcanic r.f.		Carbonate cement (patchy calcite)		
	Micas in plutonic r.f.		Calcite replacement on underterm. grain		
	Micas in metamorphic r.f.		Siliceous cement		
			Albite cement		
	Lithic fragments (L=Lm+Lv +Lv)		Phyllosilicate cement		
	Lv	Volcanic lithic with microlithic fabric		Oxid-Fe cement	
		Volcanic lithic with felsitic granular texture		Quartz overgrowth	
		Volcanic lithic with felsitic seriate texture		Clay and Clay grain coats	
Volcanic lithic with lathwork texture		Alterites (indeterm.alterite grain)			
Volcanic lithic with vitric texture					

Petrographic classes	
	Quartz (Qt=Qm+Qp)
	Extrabasinal Carbonates (CE)
	Serpentinite
	Serpentine-schist
	Phyllite
Lm	Fine-grained Schist
	Slate
	Siltstone
	Impure Chert
Ls	Shale
	Dense minerals
	Dense mineral (single crystal)
	Dense mineral in plutonic r.f.
	Dense mineral in volcanic r.f.
	Dense mineral in metamorphic r.f.
	Opaque minerals

Table 1.
Optical petrographic classes for modal analysis of arenites by using temporal and spatial criterion of the various modal classes [39–41]. NCE: noncarbonate extrabasinal grains; CE: carbonate extrabasinal grains; NCI: noncarbonate intrabasinal grains; CI: carbonate intrabasinal grains.

metamorphic lithic fragments of phyllite, quartzite, micaschist, and metavolcanics; (ii) ophiolitiferous detritus of obducted oceanic crust, including serpentinite and serpentine schist, lathwork textures of volcanic fragments of basalts, sedimentary chert, argillaceous chert and pelagic limestone; (iii) sedimentary lithic fragments of sedimentary strata involved in the orogenic wedge, including siliciclastics (siltstone, shale), chert, and extrabasinal carbonate grains; (iv) volcanic lithic fragments of both older volcanic suites and coeval volcanic sources (see section 4.2.4).

4.2.3 Quartzofeldspathic petrofacies

Plotted in the intermediate portions of the QFL diagram, sandstones having abundance of quartz and feldspar and minor lithic fragments are quartzofeldspathic sandstone suites. They reflect the uplift foreland stage of late orogenic phases when mid-crustal rocks (dominantly high-grade metamorphic and plutonic suites) are involved in thrusting, exhumation and uplift. Key lithostratigraphic units in the geological record have quartzofeldspathic sandstone suites as Old Red Sandstone of the Caledonian orogen [36] or New Red Sandstone of the Variscan orogen (e.g. Val Gardena Fm.) [42], as such as late petrofacies units of many other orogens [5, 35].

4.2.4 Interbedded volcanoclastic petrofacies

Coeval volcanoclastic sandstones may accommodate in foreland region due to persistent volcanism, related to the subduction during closure of remnant ocean basins and early foreland stage. Dominantly arc-derived volcanoclastic sandstones occur in foreland setting as important detrital contribution in quartzolithic suites and as interbedded volcanoclastic suites, related to the coeval volcanism with

sedimentation. Volcanic debris is represented mainly as abundance of vitric fragments (ash shards) in ash turbidites or as occurrence of typical textural attributes in volcanic lithic fragments [3]. The most typical volcanic textures in foreland strata are vitric, felsitic granular, felsitic seriate and microlithic reflecting typical silicic volcanism from trachite-andesite to rhyodacite and rhyolite.

4.2.5 Hybrid arenite petrofacies

Hybrid arenites are defined by Zuffa [39, 43–45] as the mixing of extrabasinal detrital grains, both siliciclastics and carbonate, and intrabasinal detrital grains, both noncarbonate and carbonate. In many submarine foreland settings, the mixing of intrabasinal and extrabasinal detrital grains reflects hybrid arenite suites. Mostly is the combination of siliciclastic particles together with the main allochemical grains [46] or intrabasinal carbonate grains. These signatures are in response of remobilized intrabasinal grains during huge arrival of subaerial clastics, temporally stored in shallow water. Deep-water turbidite systems in foreland basins include large occurrence of hybrid arenites suggesting the active roles of shallow-marine environment. Also, non-carbonate -rich (mainly glaucony and phosphatic) hybrid arenite signatures testify maximum flooding during sea-level changes [47].

4.2.6 Calclithite petrofacies

Limeclasts [38] and extrabasinal carbonate grains [39, 43, 44] signatures are typical in foreland settings [48, 49]. Ancient carbonate grains derive from eroded older carbonate strata and reflect, in foreland setting, diverse but interfingered dispersal pathways drained from the fold-thrust belt, intrabasinal structural highs, forebulge and the stable foreland. Distinguishing the nature and location of older carbonate detritus is crucial for detailed paleogeographic reconstructions. Older carbonate source rocks may occur as both (i) subaerial exposed carbonate strata interbedded within the fold-thrust belt, and as (ii) intrabasinal structural highs within wedge-top and foredeep depozones, that can result as base-of-slope carbonate breccia and related turbidite sandstones. Within the circum-Mediterranean region, ancient foreland sandstone strata reflect important contributions from older carbonate detritus in the Pyrenees [50], Betic Cordillera [40, 51], Iberian Range [52, 53], Alps and Apennines [5, 48, 49, 54], due to large abundance of Mesozoic-to-Cenozoic carbonate platform/to basinal successions related to the Neo-Tethyan oceanic rifting.

4.3 Spatial and temporal significance of sand grains

More refined compositional signatures of sand (stone) in foreland setting include temporal (coeval vs. noncoeval) and spatial (extrabasinal vs. intrabasinal) decoding of clastic particles [39, 44]. The large spectrum of detrital grains in sand (stone) has high value in inferring the spatial/temporal constraints. Carbonate and volcanic detrital grains are particularly sensitive of these discriminant subdivisions if the ultimate goal is the correct palaeogeographic reconstructions. For instance, carbonate grains can be spatially generated in extrabasinal and intrabasinal environments, and can be noncoeval (paleo) or coeval (neo) with sedimentation: (i) noncoeval extrabasinal carbonate grains are eroded and grains generate carbonate lithic fragments (dolostone and limestone); (ii) coeval extrabasinal carbonate grains are fragments of newly formed carbonate concretions in soils (calcrete, caliche) or travertine fragments; (iii) coeval intrabasinal carbonate grains are the typical allochemical particles [46] including ooids, bioclasts, intraclasts and peloid; (iv)

noncoeval intrabasinal carbonate grains include older carbonate strata in structural-related intrabasinal highs that can deliver large blocks and sand at the base of slope.

Volcanic particles represent the most intricate task in optical analysis for the discrimination between grains eroded from ancient volcanic rocks (paleovolcanic or noncoeval grains) and grains generated by intrabasinal or extrabasinal active volcanism during sedimentation (neovolcanic, coeval grains) [39, 44, 55]. Apart the contributions from older eroded volcanic rocks that refine the general puzzle of source areas, the coeval volcanoclastic contribution represent a well-defined marker in the sedimentary record. Volcanic particles can reveal important constraints on deciphering spatial (extrabasinal vs. intrabasinal) and temporal relationships of neovolcanic events (pre-, syn-, inter- and post-eruptive periods).

5. Summary

The whole chapter tries to summarize the typical fold thrust belt and foreland basin system settings from the petrological point of view of the key sandstone suites. This kind of reasoning permits to point out all the evolutionary events of these tectonic frameworks. After explaining the theoretical key concepts of the tectonic structures involved and the main provenance models, the discussion points out to the key sandstone petrofacies that commonly represent the infilling of the basin settings. The early stage of the foreland usually reflects quartzose sandstone suites derived from cratonic area. The huge volumes of the foreland infill has quartzolithic sandstone suits, derived from the growing orogenic belt. Finally quartzofeldspathic sandstone compositions are mainly derived from uplifted thrust belt. Local volcanoclastic and hybrid arenites can also occur during the foreland history.

6. Conclusions

In foreland settings, subsidence and uplift are profoundly affected by lithospheric flexure. Foreland basin subsidence is primarily controlled by downflexing of the lithosphere in response to thrust accommodation and loading. The interrelationships between lithospheric flexure, single thrust accommodation within the accretionary wedge and flexural subsidence experiences geometrically complex entities within the foreland region [4, 5]. Sandstone signatures of foreland-related basins reflect the close changing nature of detrital composition during the growth of the orogenic belt and the flexure of the underplate. Quartzolithic sand (stone) suites are the main composition of foreland sandstones during syntectonic evolution of foreland infill. However, quartzose suites occur during the early stage of foreland infill, as such as quartzofeldspathic sandstones during the later foreland uplift. Local contributions of volcanolithic sandstones from magmatic arc may occur as remnant arc activity continues during initial orogenic processes. Finally, carbonate-rich strata derived from both erosion of ancient carbonate successions and coeval carbonate/noncarbonate detritus are typical in many marine foreland infill.

In conclusions, close relations between regional sandstone petrofacies and major unconformities may contribute to the more precise paleogeographic and paleotectonic reconstructions.

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