CATCHMENT EVOLUTION OF THE CONTINENTAL STRIKE-SLIP AS PONTES BASIN (TERTIARY, NW SPAIN): CONSTRAINTS FROM THE HEAVY MINERAL ANALYSIS

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Abstract: The Oligocene-Early Miocene As Pontes basin is a non-marine strike-slip basin, filled with small-sized alluvial fan deposits and related coal-bearing lacustrine-palustrine successions. The heavy mineral associations were determined in samples collected from two coal exploration wells, which cut the whole basin infill succession. The resulting data enabled us to reconstruct the evolution of the relief in the source areas that supplied sediment to the basin. The source areas were small and located in Precambrian to Palaeozoic (Cambrian-Silurian) rocks belonging to a basement structured during the Variscan orogeny. The main factor controlling the final heavy mineral assemblage in the Tertiary sequences was the initial source area lithology. Climatic variations and transport do not seem to have played a role in modifying the resulting heavy mineral composition. The environmental conditions in the basin led to a pervasive, early diagenetic sulfide neoformation in the terrigenous facies, whereas other diagenetic processes were not significant. The catchment areas which fed the As Pontes basin were mainly controlled by the major Pedroso-As Pontes-Moiñonovo fault system. They reached their maximum extent eastward, whereas their areal extent was more restricted northward and westward. Source area uplift and relief rejuvenation are recorded in the sedimentary infill by an increase in contribution of detrital grains of ultrastable heavy mineral (mainly zircon and tourmaline) fed from the metamorphic Precambrian Ollo de Sapo domain. Moreover, the progressive incision and down cutting of the drainage networks are recorded by progressive variation in the relative metamorphic heavy mineral percentages (biotite, garnet, andalusite, staurolite, sillimanite and kyanite).

Key words: *Source area evolution, drainage network, provenance, heavy minerals, As Pontes Basin, Tertiary.*

Resumen: La cuenca de As Pontes es una cuenca continental de pequeñas dimensiones (2,5x7km) y asociada a una falla de salto en dirección, cuyo desarrollo durante el Oligoceno-Mioceno inferior se relaciona con los movimientos dextros del sistema de fallas transcurrentes de Pedroso-As Pontes-Moiñonovo. La cuenca se desarrolló sobre un basamento Precámbrico y Paleozoico, y su relleno sedimentario corresponde a depósitos de abanicos aluviales de pequeño radio que pasan distalmente a medios pantanosos donde se acumularon depósitos de carbón. Se han estudiado 56 muestras pertenecientes a dos sondeos que cortan el registro sedimentario completo de las dos subcuencas en las que se divide la cuenca de As Pontes.

A partir de las asociaciones de minerales pesados se ha podido reconstruir la evolución de las áreas fuente suministradoras de sedimento a la cuenca. Éstas fueron de pequeñas dimensiones, y se localizaron siempre sobre las rocas Precámbricas y Paleozoicas que constituían el orógeno Hercínico, no habiéndose detectado ningún tipo de contribución a partir de una hipotética cobertera Mesozoica. Se ha podido establecer que el principal factor que controló las asociaciones de minerales pesados presentes en el relleno Terciario de la cuenca fue la distinta litología de las áreas fuente y la evolución de su drenaje. Otros factores como las variaciones climáticas y el transporte parecen no haber producido variaciones significativas sobre las asociaciones iniciales de minerales pesados. En cambio, las condiciones del ambiente de depósito sí son reconocidas como un factor determinante en la introducción de modificaciones sustanciales, especialmente en lo que hace referencia a los procesos diagenéticos tempranos que produjeron, en relación con las turberas y paleosuelos sometidos a condiciones reductoras, la precipitación y neoformación de sulfuros metálicos.

La evolución de las áreas fuente estuvo tectónicamente controlada por la actuación del sistema de fallas transcurrentes. Su máxima extensión se produjo hacia el este hasta alcanzar, muy tempranamente, las rocas del Manto de Mondoñedo, mientras que hacia el norte y oeste su extensión fue claramente menor. La reactivación y exhumación de los relieves del área fuente quedó registrada en forma de un incremento en la contribución de granos detríticos de minerales ultraestables (principalmente circón y turmalina) procedentes de las rocas metamórficas del dominio del Ollo de

Sapo, mientras que el encajamiento de la red de drenaje y la incisión de los relieves sobre los que se generó ésta queda reflejada en forma de una progresiva variación en los porcentajes relativos de minerales metamórficos (biotita, granate, andalucita, estaurolita, silimanita y cianita).

Palabras clave: *Evolución de áreas fuente, procedencia, minerales pesados, Cuenca de As Pontes, Terciario.*

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Sediment provenance studies based on heavy mineral analysis have often been used to address palaeogeographic and palaeotectonic reconstructions (Morton, 1985). Heavy mineral data provide information about the nature of the source rocks. Nevertheless, the heavy mineral suite is also sensitive to the processes operating during erosion, transport and deposition of the sediment. These factors are weathering (a factor related to the climate), mechanical abrasion, physical sorting and burial diagenesis (Morton, 1985; Dill, 1998; Morton and Hallswort, 1999). Integrated heavy mineral and stratigraphic analysis of siliciclastic basin fills enable us to determine which mineral variation must be attributed either to climate changes (diagenesis and/or weathering changes) or to changes in the source area composition, by deciphering the source area evolution. Thus, one of the aims of provenance studies is to single out the different factors influencing the final sediment composition.

This study focuses on the heavy mineral analysis from sandstones and sandy mudstones in a non-marine strike-slip Tertiary basin, which was mostly filled with alluvial and lacustrine-palustrine, coal-bearing successions. This basin, whose coals have been commercially mined for a long time, has a closely spaced grid of exploration boreholes. As a consequence, the geometry, stratigraphy and sedimentology of the infilling sequences are well known. This enabled us to determine to what extent mineralogical variations reflect climatic versus physiographic variations in the source areas, and to improve our understanding of their extrabasinal relief evolution.

Geological setting

The northwestern margin of the Iberian micro-plate is mainly constituted by a Variscan basement, which includes several domains (Julivert *et al.*, 1972; Fig. 1A). During Mesozoic times, the structured Variscan basement experienced extension and rifting related to the opening of the North Atlantic Ocean (e.g. Srivastava *et al.*, 1990; Roest and Srivastava, 1991). This resulted in continental crust thinning and emplacement of mantle peridotites in the west Galicia margin (Boillot and Malod, 1988). This region was affected during the Tertiary by tectonic inversion and compressive deformation resulting from the convergence between the European and Iberian plates, which started in the latest Cretaceous. A limited subduction of the oceanic lithosphere of the Vizcaya Gulf along the northern Iberian continental margin resulted in the growth of an accretionary prism (e.g. Mauffret *et al.*, 1978; Boillot *et al.*, 1979; Boillot, 1986; Boillot and Malod, 1988; Alvarez-Marrón *et al.*, 1996; Pulgar *et al.*, 1996). The resulting north-south compression gave rise to reverse and strike-slip fault systems and their related basins in the offshore and onshore regions. The Pedroso-As Pontes-Moiñonovo and the Lendo-Meirama-Boimil strike-slip zones (with the As Pontes basin belonging to the former) can be distinguished in the NW Iberia onshore (Santanach *et a*l., 1988; Bacelar *et a*l., 1988; 1992; Cabrera *et a*l., 1996; Fig. 1A).

The Precambrian-Palaeozoic basement

The structured Precambrian-Palaeozoic basement was the source area of the As Pontes Tertiary infill. The major basement structure resulted from the Variscan orogeny, whereas the Alpine Tertiary deformation controlled the formation and evolution of the As Pontes basin and its catchment area. Bastida *et al.* (1984) divided this basement into several domains or zones: Mondoñedo nappe, Ollo de Sapo, mafic rock complexes, igneous rock plutons, and fault zones (Fig. 1B).

The Mondoñedo nappe domain consists of Precambrian schists and gneisses (with interbedded quartzites and amphibolic gneisses) and Cambrian quartzites (Arce *et a*l., 1975; Arce and Fernández-Tomás, 1976; Bastida *et al.*, 1984).

The Ollo de Sapo domain includes Precambrian gneisses, schists and wackes, as well as Ordovician quartzites, slates and schists and Silurian rhythmically interbedded sandstones and slates (turbidites), slates, and schists (Fernández-Pompa and Piera, 1975; Arce *et al.*, 1975; Arce and Fernández-Tomás, 1976; Fernández-Pompa and Monteserín, 1976; Bastida *et al.*, 1984).

Two complexes with mafic and related rocks have been distinguished by Bastida *et al.* (1984): Cabo Ortegal (located to the north and northwest) and Ordenes (located to the west) complexes. In the northern zone of Cabo Ortegal complex, there are gneisses, eclogites, amphibolites, granulites and serpentinised mafic rocks. In the southern zone, slates and amphibolites occur (Fernández-Pompa and Fernández-Martínez, 1977; Fernández-Pompa and Monteserín, 1976; Bastida *et al.*, 1984). In Ordenes Complex schists and graywackes are widespread (Fernández-Pompa and Monteserín, 1976).

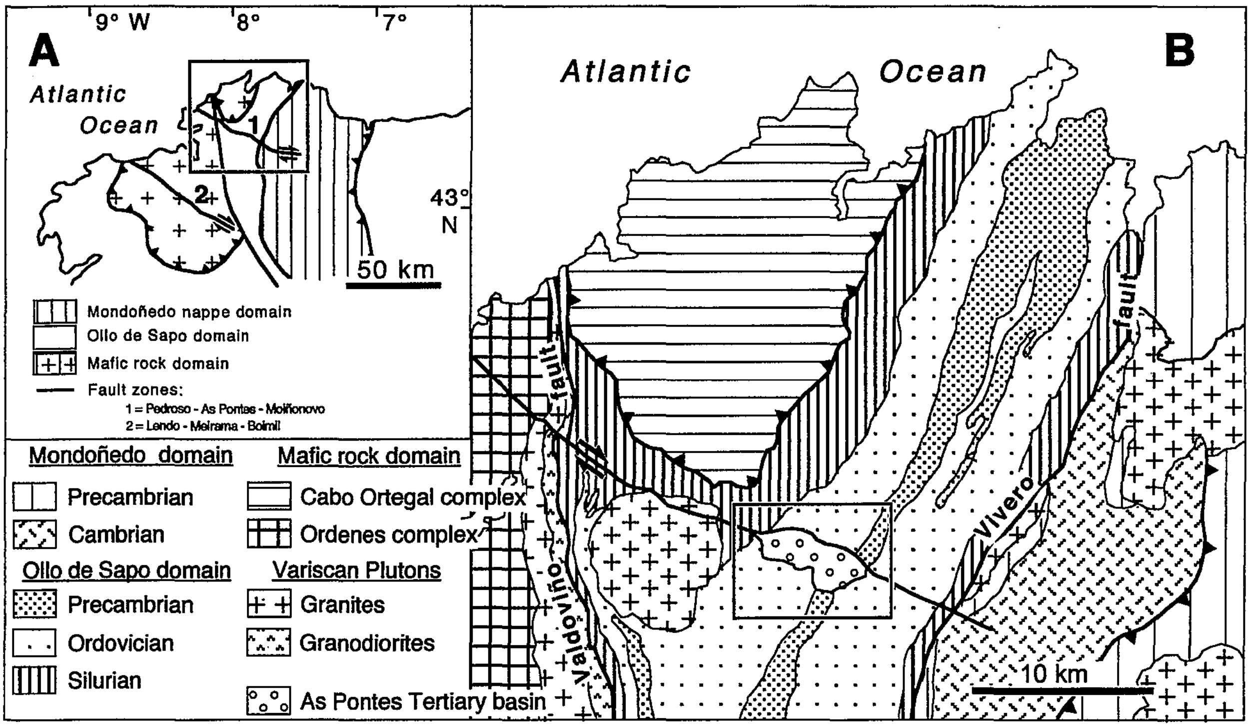

Figure 1.- A) Geological sketch of the NW Iberian micro plate, showing the major Variscan structural domains and the Tertiary strike-slip faults (modified from Julivert *et al.*, 1972). The inset indicates the detailed area in B. B) Geological sketch showing the As Pontes basin location and the main lithologies in the Precambrian-Palaeozoic basement. Inset indicates the area shown in Figure 2.

After Bastida *et a*l. (1984), two types of Variscan granitoids form plutons in the study area: alkaline granitoids or granites and calcalkaline granitoids or granodiorites.

The As Pontes basin

The As Pontes basin is located along a NW-SE dextral strike-slip major fault belonging to the Pedroso-As Pontes-Moiñonovo strike-slip zone (Fig. 1). This elongated and NW-SE oriented basin is about 7km long and less than 2.5km wide (Figure 2). Huerta et al. (1997) and Ferrús (1998) have recently studied its structure and sedimentary record.

Structure

The As Pontes basin is asymmetrical, with its substratum dipping gently towards the northern margins of the basin, where it attains maximum depth (up to 80 m below sea level datum). The northern margins of the basin are bounded by tectonic structures, whereas the southern edges consist of an unconformity between the base of the Tertiary basin fill and the substratum (Figure 2). The northeastern tectonic margins are defined by two distinctive kinds of tectonic structures. The observed E-W oriented boundaries are mainly related to low angle, gently dipping thrusts which in the subsurface attain up to 800m of horizontal displacement in the Cenozoic basin infill. The NNE-SSW edges of the basin are mainly related to the activity of reverse faults with a noticeable dextral component (Bacelar *et al.*, 1988, 1992; Cabrera *et al.*, 1996). The subsurface data demonstrate that the basin floor is affected by several compressional and extensional structures and that a basement ridge divides the basin into two subbasins (Fig. 3). This ridge is bounded to the west by a N-S oriented normal fault and to the south by an E-W oriented thrust.

The As Pontes basin structure resulted from a general N-S compression which controlled the tectonic evolution

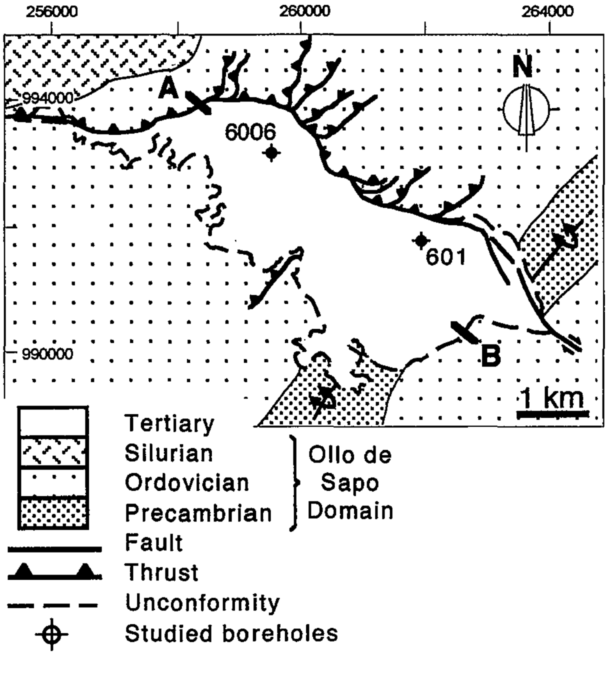

Figure 2.- Sketch of the surface structural features and boundaries of the As Pontes basin. Note the location of the studied boreholes 6006 and 601 (modified from Ferrús, 1998). A-B indicates the location of the cross-section shown in Figure 3. (UTM geographical coordinates).

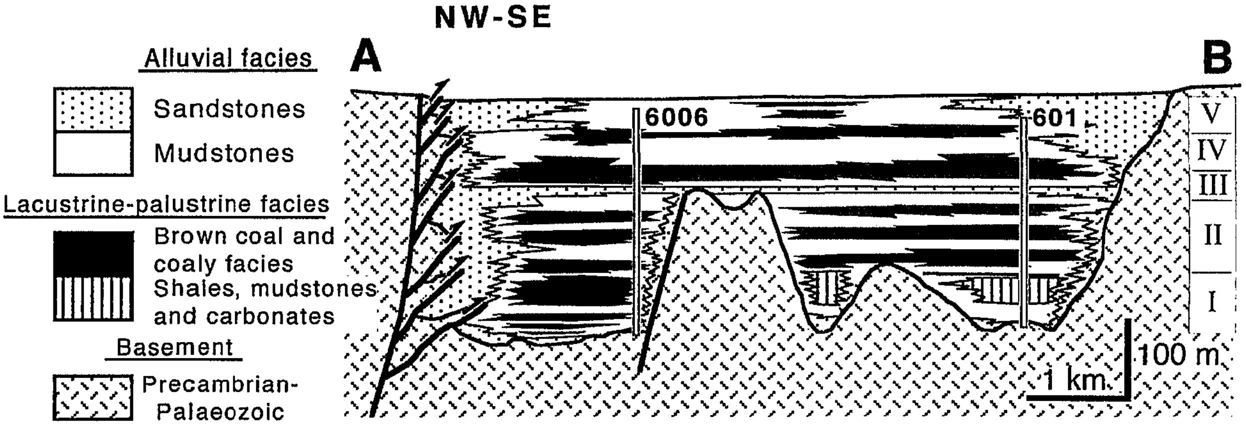

Figure 3.- Cross-section of the As Pontes basin showing its stratigraphical succession and the location of the studied boreholes detailed in Figure 4 (modified from Huerta, 1995). I to V indicate the main macrosequences in the As Pontes sedimentary infill (Ferrús, 1998). See location in Figure 2.

along a major NW-SE shear zone. The structures related to the early nucleation and further evolution of the major strike slip NNE-SSW oriented fault developed there and controlled the sedimentary evolution. Two main evolutionary stages have been distinguished (Ferrús, 1994; Ferrús and Santanach, 1994).

The first evolutionary stage (restraining overstep) resulted in the generation of several early compressional (thrusts and reverse faults) and extensional (normal faults) structures. During this early evolutionary stage, the normal fault and thrust activity resulted in the generation of two sub-basins (see Fig. 3) with distinct differences in their sedimentary record. These differences concern mainly the different development of terrigenous dominated alluvial and lacustrine assemblages versus organic matter dominated marsh to swamp ones.

The second evolutionary stage (restraining bend) resulted in the final development of a major strike slip fault (the Pedroso-As Pontes-Moiñonovo) with two restraining bends (Bacelar *et al.*, 1988, 1992). The movement along this major fault, also caused by north-south shortening, resulted in the continuation of the compressional structure activity (thrusts and reverse faults) whereas the normal faults became inactive and they were finally overlapped by the basin infill. The initial subbasins became a single depositional zone. As a consequence, the alluvial, marsh-swamp sedimentary record, characterised by interbbeded terrigenous episodes and coal seams, spread all over the basin.

It should be pointed out that tectonics not only controlled the evolution of the structures which resulted in the basin generation, but also the evolution of relief and water catchment in the surrounding source areas.

Sedimentary infill

Fossil mammal data (López-Martínez *et al.*, 1993) and palaeomagnetic studies (Huerta, 1995; Huerta *et al.*, 1996) indicate a late Rupelian (Early Oligocene) to Aquitanian (Early Miocene) age for the sedimentary infill. Based on palynological studies, Médus (1965a, b) has proposed a palaeoclimatic evolution for the As Pontes basin, changing from humid and warm, tropical to subtropical climatic conditions in the middle of the sedimentary record to a more temperate and dry climate towards the upper part. These tropical to subtropical palaeoclimatic conditions are supported by additional palynological data (Cavagnetto, 2002) and by other fossil records (plant macrorests; mammals and reptiles; Menéndez-Amor, 1975; López-Martínez *et al.*, 1993; Cabrera *et al.*, 1994, 1995).

The sedimentary infill of the As Pontes basin is up to 325m in thickness (Fig. 3). It corresponds to 1) alluvial sedimentation ranging from proximal fine-grained, quartz-dominated conglomerates, wackes and coarse-grained sands to middle and distal fine-grained sandstones and siliciclastic siltstones and mudstones; and 2) mudstones, shales and carbonates related to lacustrine-palustrine sedimentation (Sáez and Cabrera, 2002). Small-sized alluvial fans constituted both axial and transverse depositional systems, whereas lacustrine systems developed in the low-lying basin zones.

The axial alluvial fans were the major sediment suppliers. These systems spread mainly towards the NW, and proximal, sand-dominated cohesive debris-flows and distal mudstone-dominated deposits have been recognised (Ferrús, 1998). Small-sized transverse alluvial fans spread basinward from the basin margins, towards the NE and SW. The development of lacustrine systems resulted in the deposition of inner basinal to marginal palustrine organic-rich matter sedimentation, including thick coal-bearing sequences.

The sedimentary record of the basin has been split into five macrosequences (I to V in Figs. 3, 4 and 5), which reflect major cycles of lacustrine-palustrine expansion-retraction and alluvial retrogradation-progradation (Ferrús, 1998). During deposition of macrosequences I and II, the As Pontes basin was subdivided by a tectonic threshold into two disconnected eastern and western subbasins. This depositional framework changed during deposition of macrosequence III, when the two earlier subbasins were filled-up and became a single, larger basin

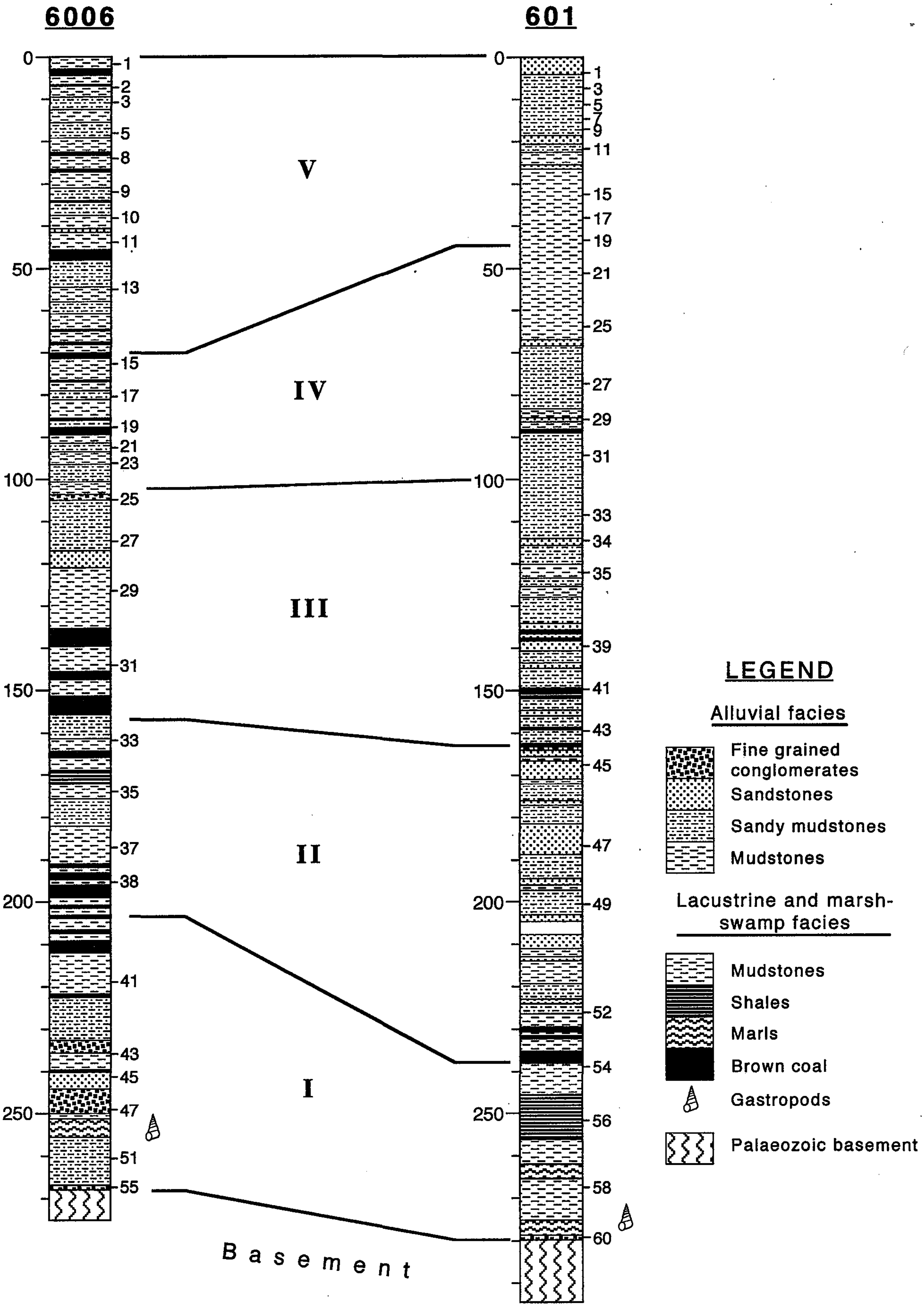

Figure 4.- Lithostratigraphical logs of boreholes 6006 and 601 and sample positions. I to V = macrosequences, as in Fig. 3.

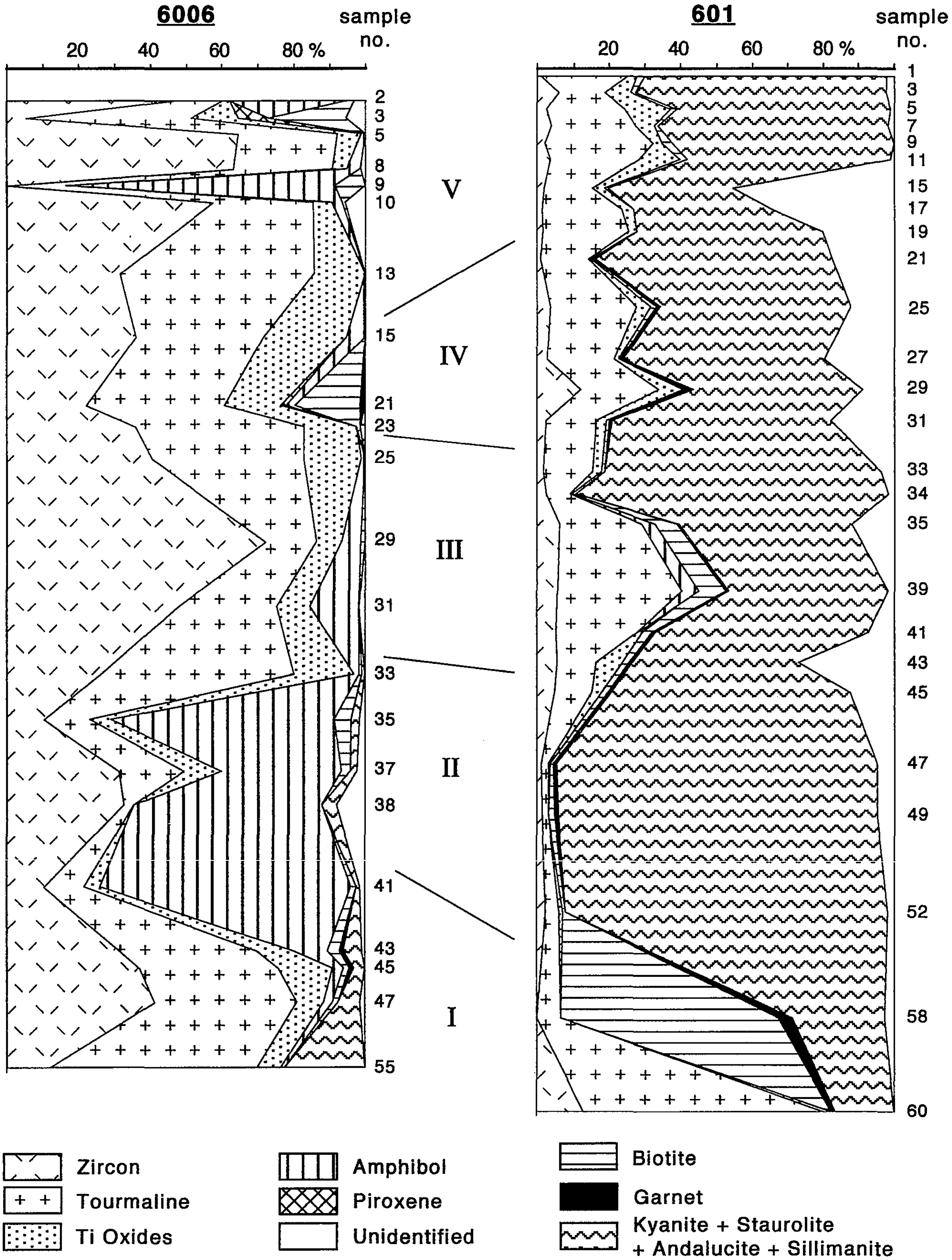

Figure 5.- Heavy mineral frequencies and vertical evolution in boreholes 6006 and 601. Samples containing more than 97% in opaque heavy minerals were not plotted. See values in Tables II and III.

parent rock samples

		lithology	Sample	Zrn		Tur		Rt	Ant			Brk	Ol	Px	Aph	Chl	Bt	Gar	Ky	St	And	Sil	Ap
				(ro)	(eu)	(ro)	(eu)		(oc)	(ta)	(a)												
Mondoñedo nappe domain	Precambrian	schists & gneisses	MN.1	4.0	—	**29.9**	**46.0**	1.6	—	—	—	—	—	—	0.8	—	6.4	**11.3**	—	—	—	—	—
		schists	MN.2	5.8	—	**12.4**	**81.8**	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
		quartzites	MN.3	**37.5**	0.9	3.5	**27.1**	**29.8**	—	—	—	—	—	—	0.6	—	0.6	—	—	—	—	—	—
	Cambrian	quartzites	MN.4	0.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	**75.8**	0.3	0.9	**22.7**	—
Ollo de Sapo domain	Precambr.	schists	OS.1	**82.6**	2.9	—	—	—	0.4	3.3	2.5	—	—	—	2.9	0.4	4.6	0.4	—	—	—	—	—
	Ordovician	quartzites	OS.2	4.3	3.2	—	—	—	0.5	—	—	0.3	—	—	0.8	**84.9**	0.3	5.4	—	—	—	0.3	—
		quartzites	OS.3	**69.3**	0.8	—	0.8	2.6	—	4.3	1.7	—	—	—	2.6	**13.7**	3.4	0.8	—	—	—	—	—
		slates	OS.4	—	—	0.7	0.7	—	—	—	—	—	—	—	**18.1**	0.7	1.4	**75.6**	1.4	1.4	—	—	—
		slates	OS.5	6.0	7.8	—	**11.8**	—	5.9	—	1.9	—	—	—	7.8	**51.0**	5.9	1.9	—	—	—	—	—
	Silurian	turbidites	OS.6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	**100.0**	—	—	—	—	—
		slates	OS.7	7.1	1.4	0.7	2.1	0.7	**75.2**	9.3	2.8	—	—	—	0.7	—	—	—	—	—	—	—	—
Ortegal Cape complex	North	gneisses	CO.1	**34.4**	—	6.8	2.5	8.0	—	—	—	—	—	—	2.5	—	**14.8**	**31.0**	—	—	—	—	—
		eclogites	CO.2	—	—	—	—	4.7	—	—	—	—	—	4.7	**42.7**	0.5	0.5	**46.9**	—	—	—	—	—
		serpentenized mafic rocks	CO.3	—	—	—	0.4	—	—	—	—	—	**90.2**	9.0	0.4	—	—	—	—	—	—	—	—
	South	slates	CO.4	1.2	—	—	—	—	—	—	—	—	—	—	**26.0**	**72.4**	0.4	—	—	—	—	—	—
Variscan plutons		granites	PL.1	—	0.3	—	0.3	—	—	—	—	—	—	—	—	—	**98.9**	0.1	—	—	0.1	—	0.3
		granodiorites	PL.2	—	0.1	—	4.5	—	—	—	—	—	—	—	—	0.4	**94.9**	—	—	—	—	—	0.1

Table I.- Heavy mineral percentages of the source rock samples from the Precambrian and Palaeozoic basement Zrn(ro) = rounded zircon. Zrn(eu) = euhedral zircon. Tur(ro) = rounded tourmaline. Tur(eu) = euhedral tourmaline. Rt = rutile. Ant(oc) = octahedral anatase. Ant(ta) = tabular anatase. Ant(a) = anhedral anatase. Brk= brookite. Ol = olivine. Px = pyroxene. Aph = amphibole. Chl = chlorite. Bt = biotite. Gar = garnet. Ky = kyanite. St = staurolite. And = andalusite, Sil = sillimanite and Ap = Apatite.

during deposition of macrosequences IV and V (Ferrús, 1998). Macrosequence I records a widespread development of lacustrine versus alluvial environments. Deep lacustrine sediments were developed in the eastern subbasin while shallow lacustrine-palustrine coal-dominated sediments were deposited in the western subbasin (Figs. 3, 4). Axial alluvial fans were not developed, and only short radius, transverse alluvial fans were active from the basin margins. Macrosequence II records increase in the terrigenous alluvial fan sedimentation. The axial alluvial system started its activity in the eastern subbasin, whereas transverse alluvial fan systems were active in the two subbasins. Both axial and transverse alluvial fan systems prograded basinward, originating the retraction of the lacustrine and palustrine environments. Macrosequence III records the filling of the two subbasins, resulting in a single basin. A major alluvial fan expansion has been pointed out originating both axial and transverse alluvial fan progradations over the retreating palustrine-lacustrine environments (Ferrús, 1998). Macrosequences IV and V record an increase in the detrital alluvial sedimentation versus lacustrine deposition. In fact, the upper Macrosequence V, which constitutes the top of the basin fill, is entirely siliciclastic, resulting in coal accumulation decay.

Sampling and procedure

Two kinds of sampling were carried out in the studied area: one related to the As Pontes basin sedimentary infill and the other related to the potential source rocks. For the former, two well cores (wells 601 and 6006) were selected. These wells cut the whole sedimentary infill of both As Pontes subbasins and reached the Palaeozoic basement. The borehole 601 cuts a 294.5m thick succession in the eastern subbasin, whereas borehole 6006 cuts a 273.5m thick succession in the western subbasin (Figs. 2, 3 and 4). Sampling included poorly consolidated, sandstone and sandy mudstone beds, covering the mentioned macrosequences.

A total of 73 samples, 17 from the source area rocks, and 28 from each borehole supports heavy mineral studies, by using the 0.063-0.250mm-size fraction. Heavy-mineral separation was made by gravity-settling by using high density liquid (bromoform). Slides of heavy fraction were mounted by using Canada balsam and were identified under a polarising microscope. A minimum of 300 opaque and nonopaque detrital grains was counted in each slide (Mange and Maurer, 1992).

Results

Heavy minerals from possible source rocks

In the studied samples, zircon, tourmaline, anatase, brookite, rutile, biotite, pyroxene, amphibole, garnet, kyanite, staurolite, andalusite, sillimanite, olivine apatite and chlorite occur (Table I). Both colourless zircon and green-brown tourmaline appear euhedral (prismatic and bipyramidal for zircon and prismatic for tourmaline) or rounded in shape. Octahedral, tabular and anhedral anatase habits were differentiated. Brookite is present with anhedral shape and reddish-brown coloured rutile grains are rounded. Kyanite is present as euhedral elongated prismatic crystals, sometimes altered, whereas staurolite and andalusite are present as anhedral grains. Colourless sillimanite is present with fibrous and/or rectangular habit. Pyroxenes frequently show prismatic habit, whereas amphiboles appear as crystals prismatic or laminar in shape, occasionally very altered. Chlorite frequently occurs as altered pseudohexagonal plates. Garnets and olivines are present as crystals commonly with an anhedral habit.

The Precambrian schists and gneisses of the Mondoñedo nappe (samples MN.1 and 2, Table I) provide a high tourmaline and minor garnet contribution, whereas the interbedded quartzites (sample MN.3) show a high content in ultrastable minerals. By contrast, Cambrian quartzites (MN.4) have a high content of metamorphic minerals, mainly kyanite and sillimanite.

Related to the Ollo de Sapo domain (samples OS.1 to 7 in Table I), the Precambrian schists provided a high zircon contribution; Ordovician quartzites are characterised as major chlorite and/or zircon suppliers and minor contributors of metamorphic minerals (biotite, garnet), whereas Ordovician slates contributed

bore-hole 6006

Seq.	Sample	OP	TR	Zrn		Tur		Rt	Ant			Brk	Px	Aph	Bt	Gar	Ky	St	And	Sil	Un
				(ro)	(eu)	(ro)	(eu)		(oc)	(ta)	(a)										
V	1	99.6	0.4	—	—	20.0	20.0	—	—	—	—	—	20.0	—	40.0	—	—	—	—	—	—
	2	89.3	10.7	**37.8**	8.2	4.9	9.8	—	—	1.6	—	—	—	**32.8**	—	1.6	—	—	—	—	3.3
	3	96.8	3.2	5.4	—	**24.4**	**21.6**	—	5.4	2.7	2.7	2.7	8.1	—	**21.6**	—	—	—	—	—	5.4
	5	85.4	14.6	**37.6**	**26.7**	**14.8**	**12.9**	—	4.0	—	2.0	1.0	—	1.0	—	—	—	—	—	—	—
	8	84.4	15.6	**42.0**	**21.0**	**18.5**	9.2	—	1.7	—	2.5	—	—	3.4	—	—	—	—	—	—	1.7
	9	91.0	9.0	—	—	—	16.7	—	—	—	—	—	—	**75.0**	8.3	—	—	—	—	—	—
	10	86.7	13.3	**44.8**	**12.8**	**19.1**	9.2	—	2.8	0.7	1.4	—	—	2.8	—	—	—	0.7	—	—	5.7
	11	99.9	0.1	—	—	—	—	—	—	—	—	—	—	—	100.0	—	—	—	—	—	—
	13	87.9	12.1	**23.6**	7.6	**33.7**	**21.1**	1.5	1.5	1.0	9.0	1.0	—	—	—	—	—	—	—	—	—
IV	15	91.7	8.3	**23.1**	**12.8**	**20.5**	**15.4**	—	7.7	—	**15.4**	—	—	5.1	—	—	—	—	—	—	—
	17	98.8	1.2	—	—	33.3	—	—	—	—	—	—	—	66.7	—	—	—	—	—	—	—
	19	99.9	0.1	50.0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	50.0
	21	85.6	14.4	**18.2**	3.9	**29.8**	9.1	1.3	2.6	1.3	9.1	1.3	1.3	2.6	**18.2**	1.3	—	—	—	—	—
	23	94.1	5.9	**29.6**	6.1	**28.4**	**18.9**	—	1.4	—	**12.8**	0.7	—	—	0.7	—	—	0.7	0.7	—	—
III	25	95.1	4.9	**25.0**	**15.2**	**29.4**	**13.4**	—	3.6	0.9	**10.7**	0.9	—	0.9	—	—	—	—	—	—	—
	27	99.7	0.3	—	—	20.0	20.0	—	20.0	—	40.0	—	—	—	—	—	—	—	—	—	—
	29	89.2	10.8	**63.2**	**8.8**	4.0	**10.4**	—	—	4.0	3.2	—	—	5.6	0.8	—	—	—	—	—	—
	31	86.2	13.8	**40.5**	6.9	7.5	**20.5**	—	0.7	2.0	6.9	—	—	13.7	—	—	—	—	—	—	1.3
II	33	85.0	15.0	**21.6**	4.8	**17.8**	**36.5**	1.0	2.4	1.0	10.1	1.9	—	1.9	0.5	—	0.5	—	—	—	—
	35	62.7	37.3	8.1	2.0	2.0	**10.6**	—	0.5	0.5	3.5	0.5	—	**67.8**	1.0	—	0.5	1.5	—	—	1.5
	37	77.9	22.1	**26.2**	5.5	8.4	9.9	—	0.5	0.5	8.9	1.0	—	**33.1**	2.0	—	0.5	1.0	—	—	2.5
	38	93.5	6.5	**29.3**	2.4	2.4	2.4	—	—	—	—	—	—	**51.4**	—	—	—	2.4	—	—	9.7
I	41	69.3	30.7	9.3	2.9	2.4	6.8	1.0	—	—	2.4	0.5	—	**71.2**	1.5	—	0.5	—	—	—	1.5
	43	71.8	28.2	**27.1**	4.3	**12.2**	**26.2**	2.0	1.1	0.6	6.5	0.3	—	9.1	3.7	0.3	4.0	0.6	0.3	—	1.7
	45	76.1	23.9	**32.9**	4.2	9.3	**29.6**	1.8	1.5	2.7	9.3	0.6	—	3.9	0.3	0.3	2.4	0.3	0.3	—	0.6
	47	68.1	31.9	**35.2**	6.1	7.8	**32.1**	2.6	—	—	4.9	0.3	—	3.5	0.3	—	4.0	0.9	0.9	—	1.4
	51	98.6	1.4	13.6	—	4.6	63.6	4.6	—	—	—	—	—	—	—	—	13.6	—	—	—	—
	55	88.8	11.2	4.1	7.2	2.1	**56.6**	—	—	2.6	4.1	—	—	0.5	—	—	22.3	0.5	—	—	—
	X	87.6	12.4	22.6	7.7	13.6	18.1	0.5	1.7	1.0	5.7	0.6	0.4	17.5	2.7	0.2	1.6	0.4	0.1	—	1.6

Table II.- Heavy mineral percentages from borehole 6006 samples. OP= opaques. TR= translucents. Un=unrecognised minerals. The remaining heavy mineral legend as in Table I. X= mean. X values of OP and TR columns were calculated using the entire sample values. X values of the rest of the heavy mineral columns were calculated by using only samples with TR> 3%.

mainly garnet and/or chlorite and minor amphibole and tourmaline grains. The only heavy mineral contributions provided by the Silurian turbidite rocks are garnet crystals, whereas Silurian slates are rich in anatase.

The potential heavy mineral contribution from the northern part of the Cabo Ortegal Complex was determined in samples CO.1 to 3 (Table I). The Cabo Ortegal gneisses can provide a high zircon and garnet contribution and minor biotite; eclogite contribution is characterised by high amphibole and garnet percentages, whereas the serpentinised mafic rocks are rich in olivine. The southward slates (sample CO.4, Table I) would supply high chlorite and minor amphibole contributions.

Both Variscan granites and granodiorites (PL.1 and 2, Table I) mainly provided biotite crystals, and minor zircon, tourmaline, apatite, chlorite, garnet and andalusite.

Heavy minerals from sedimentary infill

The heavy minerals found were zircon, tourmaline, anatase, brookite, rutile, biotite, pyroxene, amphibole, garnet, kyanite, staurolite, andalusite and sillimanite. However, neither chlorites nor olivines were found. Euhedral versus rounded shapes in zircon and tourmaline as well as octahedral, tabular or anhedral habits in anatase were differentiated (Tables II and III).

Tourmaline grains show a wide range of colours (brown, green, blue, pink and rarely, black and colourless). Brookite occurs frequently with pyramidal habits. Rutile is reddish-brown coloured and frequently rounded. Grains of euhedral colourless kyanite, staurolite and andalusite, the last two with an anhedral habit, showing inclusions of carbonaceous matter, are recognised. Colourless sillimanite with both prismatic and fibrous habits also occur. Finally, pyroxene (prismatic), amphibole (laminar), and garnet varieties were not differentiated.

Heavy mineral percentages are given in Tables II and III. The vertical evolution of the heavy mineral frequencies for each borehole is shown in Fig. 5, where samples with a translucent mineral percentage less than 3% were not plotted.

Borehole 6006 has a high proportion of opaque versus translucent minerals (OP/TR = 7.06, see Table II). The most abundant constituents are the ultrastable mineral zircon and tourmaline, but rutile content is low. The contribution of titanium oxides is higher than in borehole 601, but the most abundant mineral is anhedral anatase. Brookite is frequent but scarce. Pyroxene and amphibole are present (pyroxene occurs as an occasional mineral but amphiboles are relatively abundant). The contribution of the metamorphic minerals is small, just about 2% (4.91% if we include biotite), and their relative proportions are biotite> kyanite> staurolite> garnet> andalusite. The metamorphic mineral occurrence is mainly concentrated in the lower third of the succession. Only 1.65% of the counted heavy minerals was classified as unrecognised.

The borehole 601 has a lower ratio of opaque versus translucent heavy mineral composition (OP/TR = 0.99, see Table III). Its content of ultrastable minerals is lower than borehole 6006 (it is about 23.6% because its zircon content decay and only tourmaline grains appear as a significant constituent). The content of titanium oxides is lower, but in this case, the contribution of both rutile and anhedral-tabular anatase is similar, whereas that of brookite is negligible. Pyroxene grains were not recognised and amphibole contribution was scarce to negligible. The most characteristic feature of the heavy mineral asociation of borehole 601 is its high content of metamorphic minerals. It reaches up to more than 60% and include staurolite> andalusite> kyanite> biotite> sillimanite> garnet. Since metamorphic mineral grains are frequently altered, about 10.3% of them were classified as unrecognised.

Discussion

Heavy mineral provenance

Mondoñedo nappe source rocks: According to Arce *et al.* (1975), Arce and Fernández-Tomás (1976) and Bastida *et al.* (1984) the Mondoñedo nappe domain has undergone diverse grades of metamorphism, which ranges from E to W from the chlorite to the andalusite and sillimanite metamorphic zones. Therefore, sediment delivered from this domain would contain a metamorphic mineral association consisting of chlorite, biotite, garnet, staurolite, andalusite or sillimanite. According to these authors, the Precambrian rocks also contain amphibole, zircon and tourmaline as accessory minerals. The heavy mineral suites in the 0.063-0.250mm size fraction of the Mondoñedo nappe samples (Table I) are in agreement with this. Thus, Precambrian schists, gneisses and quartzites have a high zircon and/or tourmaline content and locally rutile. Small proportions of amphibole and metamorphic biotite and garnet also occur. Moreover, the Cambrian quartzites are characterised by a major occurrence of metamorphic heavy minerals (Table IV).

Ollo de Sapo Domain source rocks: Earlier studies have suggested the presence of chlorite, biotite and garnet in this domain given the low to medium grade metamorphism. Moreover, zircon, tourmaline and apatite could be present as accessory heavy minerals in the Precambrian and Silurian rocks, whereas zircon, tourmaline and rutile could be supplied by the Ordovician rocks (Fernández-Pompa and Piera, 1975; Arce *et al.*, 1975; Arce and Fernández-Tomás, 1976; Fernández-Pompa and Monteserín, 1976; Bastida *et al.*, 1984).

These data partially agree with our data from source rock samples (Table I), i.e. the low to medium grade bore-hole 601

Sec.	Sample	OP	TR	Zrn		Tur		Rt	Ant			Brk	Px	Aph	Bt	Gar	Ky	St	And	Sil	Un
				(ro)	(eu)	(ro)	(eu)		(oc)	(ta)	(a)										
V	1	46.3	53.7	0.9	—	2.7	**21.6**	1.5	—	0.3	0.9	—	—	—	2.1	—	8.7	**46.3**	**12.9**	—	2.1
	3	48.4	51.6	4.5	0.9	1.2	**12.2**	4.5	0.3	2.1	0.3	0.3	—	—	0.9	—	**12.8**	**47.2**	**10.4**	—	2.4
	5	57.1	42.9	0.9	1.3	3.5	**18.9**	6.0	—	1.3	**5.7**	—	—	—	1.6	—	**9.7**	**43.8**	**5.7**	0.3	1.3
	7	44.8	55.2	3.3	0.5	6.5	**17.3**	3.7	—	0.5	0.9	—	—	—	0.9	—	**12.6**	**30.9**	**21.0**	—	1.9
	9	49.7	50.3	2.0	—	3.3	**27.3**	2.0	—	0.7	—	—	—	—	2.6	—	6.5	**33.5**	**22.1**	—	—
	11	37.8	62.2	3.6	—	4.5	**20.5**	6.3	—	0.9	4.5	—	—	—	1.8	—	8.9	**30.2**	**17.9**	—	0.9
	15	36.7	63.3	1.3	0.3	1.7	**11.9**	1.7	—	0.7	1.3	—	—	—	0.3	—	7.6	**23.5**	3.6	0.3	*45.8*
	17	30.5	69.5	0.6	0.6	3.1	**19.1**	0.8	—	0.8	1.4	0.3	—	—	—	—	4.2	**24.2**	**10.4**	—	*34.5*
	19	41.0	59.0	0.4	0.4	6.0	**18.7**	1.2	—	—	1.2	—	—	—	—	—	4.8	**33.2**	**13.1**	0.4	*20.6*
IV	21	35.3	64.7	0.4	—	3.0	**10.9**	—	0.4	0.4	—	—	—	—	0.4	0.4	1.9	**45.5**	**18.7**	0.4	*17.6*
	25	54.5	45.5	1.1	2.5	6.1	**18.2**	2.9	—	0.7	0.7	—	—	—	1.4	0.4	5.7	**32.9**	**14.2**	0.7	12.5
	27	49.2	50.8	1.8	0.4	8.4	**11.4**	0.4	—	0.4	0.4	—	—	—	0.4	0.4	3.7	**35.6**	**16.9**	—	*19.8*
	29	51.2	48.8	9.9	2.0	1.5	**20.7**	3.0	0.5	2.5	1.0	—	—	—	0.5	2.0	7.9	**34.7**	3.9	—	9.9
	31	38.9	61.1	1.5	0.4	3.0	**11.9**	1.1	0.4	0.7	0.4	—	—	—	0.7	0.4	1.5	**41.4**	**18.1**	0.4	*18.1*
III	33	39.3	60.7	0.5	0.9	5.4	8.6	1.8	—	0.5	0.5	—	—	—	0.5	—	6.8	**51.9**	**18.0**	0.5	4.1
	34	47.3	52.7	1.1	0.6	0.9	6.6	0.3	—	—	—	—	—	—	0.9	—	8.9	**66.7**	**12.3**	—	1.7
	35	53.5	46.5	4.4	1.6	6.1	**16.9**	1.6	0.8	0.4	0.4	—	—	0.4	6.5	0.4	6.1	**30.6**	**11.3**	0.4	12.1
	39	42.2	57.8	4.7	0.5	3.8	**31.3**	1.9	—	1.9	0.5	—	—	0.5	7.6	0.5	**12.3**	**30.2**	1.9	0.5	1.9
	41	43.3	56.7	3.6	1.4	5.4	**17.7**	0.5	—	0.9	—	—	—	—	2.7	0.5	3.6	**52.4**	4.1	—	7.2
	43	40.0	60.0	2.9	2.2	3.2	8.2	3.9	—	1.8	1.8	—	—	—	1.8	0.4	5.4	**34.3**	6.5	—	*27.6*
II	45	32.1	67.9	3.7	0.8	2.1	8.6	2.5	—	0.4	—	—	—	—	1.7	0.4	6.2	**54.2**	6.2	0.4	12.8
	47	31.6	68.4	0.4	0.4	1.3	0.9	0.4	—	—	—	—	—	—	0.9	0.4	6.7	**78.9**	4.4	0.4	4.9
	49	31.9	68.1	0.4	0.4	1.3	0.9	—	—	—	—	—	—	—	1.8	0.4	5.3	**82.0**	2.2	0.4	4.9
	52	39.0	61.0	0.9	0.9	1.2	3.0	1.2	—	—	—	—	—	—	0.3	—	**16.3**	**66.9**	0.6	6.9	1.8
I	54	100.0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	56	99.0	1.0	14.3	—	—	7.1	—	—	—	—	—	—	—	7.1	—	35.8	28.6	—	—	7.1
	58	95.0	5.0	—	—	2.5	3.7	—	—	—	—	—	—	—	**61.4**	3.7	1.2	**18.8**	3.7	2.5	2.5
	60	78.8	21.2	**12.3**	0.5	—	**68.4**	0.5	—	0.9	—	—	—	—	0.9	—	1.9	**11.8**	2.8	—	—
	X	49.8	50.2	2.6	0.8	3.4	16.0	1.9	0.1	0.7	0.8	—	—	—	3.9	0.4	6.8	41.6	10.1	0.6	10.3

Table III.- Heavy mineral percentages from borehole 601 samples. Legend as in Tables I and II. X values of OP and TR columns were calculated using the entire sample values. X values of the rest of the heavy mineral columns were calculated by using only samples with TR >3%.

metamorphic minerals (chlorite, biotite and garnet) is widely present, and the schists and quartzites also contain high proportions of zircons. However, some heavy minerals described by the previous workers were not found in our source rock samples. These minerals are: apatite and tourmaline in Precambrian schist samples; chlorite, biotite, zircon, tourmaline and rutile in Silurian turbidites; and chlorite, biotite and garnet in Silurian slates (Table I). By contrast, anatase and amphibole occur in the studied source rock samples but were not cited by the aforementioned authors (see Table I).

Given the considerations discussed above we assume that 1) the Precambrian schists of the Ollo de Sapo domain contributed with major zircon and scarce chlorite, biotite and garnet content. Although anatase and amphibole have not been documented and tourmaline and apatite have been documented but not found in our source rock samples, all these minerals could have been supplied by the Ollo de Sapo domain rocks; 2) the Ordovician rocks provided abundant, although variable zircon, chlorite and garnet proportions, minor and variable tourmaline and scarce biotite and rutile (see Table IV). Moreover, anatase and amphibole (heavy minerals found in our source area samples but not previously documented) are probably some of the heavy minerals which could have been incorporated (Table IV). 3) The Silurian rocks provided variable (from very high to non-existent) garnet and/or anatase contents and variable (from low

			Abundant	Frequent	Scarce	Probable
Mondoñedo nappe domain		Precambrian	**Zrn, Tur**	Rt	Aph, Bt, Gar	
		Cambrian		Chl, Bt, Gar, St, And, Sil		
Ollo de Sapo domain		Precambrian	**Zrn**		Chl, Bt, Gar	Tur, Ant, Ap, Aph
		Ordovician	**Zrn, Chl, Gar**	Tur	Rt, Bt	Ant, Brk, Aph, Ky, St, Sil
		Silurian	**Gar, Ant**		Zrn, Tur, Rt, Aph	Chl, Bt
Ortegal Cape complex	N	Gneisses	**Zrn, Bt, Gar**	Tur	Aph	Rt, Ap, Cpx, Chl, Ky, St
		Eclogites	**Aph, Gar**		Rt, Px	Zrn, Ap, Chl, Bt, Ky
		Serpentenized mafic rocks	**Ol**	Px	Aph	Tur, Chl, Gar
	S	Slates	**Chl**	Aph	Zrn, Bt	
Variscan Plutons		Granites	**Bt**	Zrn, Tur, Ap	Gar, And	Rt, Sil
		Granodiorites	**Bt**	Zrn, Tur, Ap, Chl		Gar, Aph

Table IV.- Proposed source areas and their relative heavy mineral contribution to the As Pontes basin. The column "probable" refers to minerals cited in previous petrographic works but that they were not found in our samples. See text for discussion. Cpx= clinopyroxene. Legend for the rest of heavy minerals as in Table I

to non-existent) zircon, tourmaline, rutile and amphibole contents. Other heavy minerals could have been chlorite and biotite. Although these minerals have been previously cited, they were not found in the source rock samples (Table IV).

Mafic source rocks: In the northern part of the Cabo Ortegal complex, gneisses contain major garnet and biotite metamorphic minerals, and minor zircon, apatite, tourmaline, clinopyroxene, amphibole, kyanite, staurolite and chlorite (Fernández-Pompa and Fernández-Martínez, 1977; Bastida *et al.*, 1984). Eclogites have high garnet and amphibole contents, whereas kyanite can be frequent and apatite, rutile and zircon are accessory minerals. Serpentinised mafic rocks contain olivine, ortopyroxene, clinopyroxene, amphibole, garnet and chlorite.

In the southern Cabo Ortegal complex, Fernández-Pompa and Monteserín (1976) and Bastida *et al.* (1984) indicate that slates contain chlorite and zircon, whereas amphibolites are rich in amphiboles.

The heavy mineral content described above agrees with data obtained from our studied source rock samples (Table I). Thus, in the northern Cabo Ortegal samples, gneisses are rich in zircon, garnet and biotite, with minor tourmaline and scarce amphibole; eclogites have a high amphibole and garnet content, with minor rutile and the serpentinised mafic rocks have high olivine and minor pyroxene and amphibole contents. In the southern Cabo Ortegal samples, slates are rich in chlorite and amphibole, with scarce zircon and biotite (Table IV).

No contribution of schists and graywackes from the western Órdenes complex to the As Pontes basin fill has been detected.

Igneous source rocks: Both granites and granodiorites have a high biotite content. Granodiorites can also contain tourmaline and/or garnet, and apatite, zircon and amphibole as accessory heavy minerals, whereas accessory minerals in granites are apatite, zircon, tourmaline, rutile, andalusite and sillimanite (Arps, 1970; Capdevila and Floor, 1970; Bastida *et al.*, 1984). This mainly agrees with heavy mineral content in granite and granodiorite samples (PL.1 and 2, Table I).

Thus, we assume (Table IV) that both granites and granodiorites provided a high proportion of biotite grains. However, granites could also contribute with scarce zircon, tourmaline, apatite, andalusite and sillimanite grains whereas granodiorites could contribute with scarce zircon, tourmaline, apatite, garnet and amphibole grains.

Factors controlling the heavy mineral assemblage

It must be considered that the final composition of sediment results from a set of factors that influenced the sedimentary cycle. The most important of these factors are the source rock composition, transport and depositional processes (diagenesis and authigenic inputs). The tectonic environment and the climate simultaneously influence these factors. Johnsson (1993) and Morton and Hallsworth (1999) have discussed the influence of these factors on the heavy mineral content of a sediment.

In order to assess the climatic influence, the ZTR index to estimate the maturity of the heavy mineral assemblages was calculated. This index was proposed by Hubert (1962) by calculating ultrastable versus unstable heavy mineral ratio. The ZTR index evolution for the 6006 and 601 boreholes is shown in Fig. 6. It can be observed that there is no agreement between both 6006 and 601 ZTR index evolutions, bearing in mind that the deposits recorded in both boreholes were deposited under the same palaeoclimatic conditions. The greater value for ZTR index of borehole 6006 would indicate a larger textural maturity for its mineral assemblages. As a consequence, the main heavy mineral composition and vertical evolution recorded by the basin infill would be mainly related to lithological differences in the source rocks affected by the catchment evolution in the evolving source area. Moreover, owing to the relatively small areal extension of the drainage basin, modification in the final mineral association due to transport could be considered minor. This also agrees with the fact that the heavy mineral content and the vertical evolution of the mineral assemblages differ considerably from one borehole to the other (Fig. 5).

Early diagenetic processes related to the sedimentary environment (acid water flows and mineral neoformation) could be another factor of change in the mineral assemblage and could provide major modifications in the final sediment composition. Acid underground water flows related to the marsh-swamp peat-forming environments could have dissolved the unstable minerals. This could account for the absence of apatite, chlorite and olivine in the studied assemblages, and for the higher ZTR index in 6006 borehole samples, where coal and coaly facies beds are more widespread than in 601 one. Nevertheless, some samples of borehole 6006 related to coaly facies beds have a high content in other unstable minerals (eg., amphibole), whereas some samples belonging to the lower part of the well 601, which are related to coaly facies, have a lower content of ultrastable heavy minerals. This suggests that unstable mineral dissolution by acidic waters was not always a major process controlling the final heavy mineral association even though a certain control cannot ruled out.

Finally, mineral neoformation in the sedimentary basin could modify the final sediment composition, resulting in a relative decrease in the detrital content. In fact, the anoxic environments related to coal accumulation favour neomorphic sulfide (Gerritse, 1999) and siderite (Mozley, 1989) precipitation. Some of the studied samples have a high opaque mineral content, which in some cases reach 100%. This high content of opaque heavy minerals could be related to sulfide and/or siderite precipitation since samples with the highest opaque mineral percentage are those closely related to coaly facies. In order to isolate the effect of authigenic mineral formation, samples with or more than 97% of opaque heavy minerals were considered without statistical value, and their data were not plotted in Fig. 5.

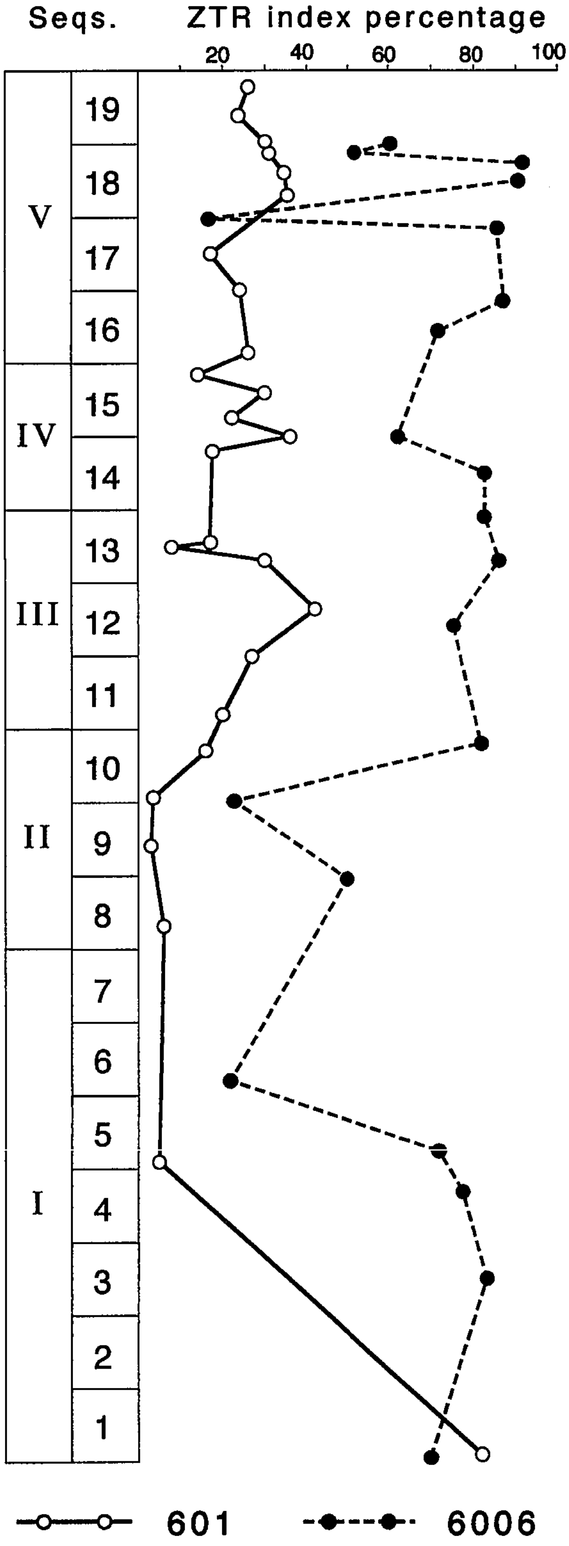

Figure 6.- ZTR index percentage evolution for boreholes 6006 and 601. The diverse stratigraphic units of the basin infill (sequences and macrosequences) at the vertical axis are represented not to scale to facilitate the comparison of samples in the same stratigraphical position.

As Pontes basin fill trend and erosional history of the source areas

On the basis of the characterization of the heavy mineral assemblages of the source rocks which fed the basin (Tables I and IV), and bearing in mind that other factors (i.e climate, diagenetic changes) did not substantially modify the sediment composition, the vertical heavy mineral assemblage evolution in the studied successions (Fig. 5) would reflect the catchment area evolution and the erosional history of the source areas. The heavy mineral associations differ from one borehole to the other. Drillhole 6006 has high zircon and tourmaline percentages, resulting in a very high ZTR index, as well as variable amphibole and biotite contents, although other metamorphic minerals are scarce. By contrast, drillhole 601 has a relatively lower zircon and tourmaline presence, but their metamorphic mineral content is higher than in borehole 6006. The high ZTR index in drillhole 6006 must probably be related to a permanent contribution from the Ollo de Sapo domain, where variable amounts of biotite, pyroxene and garnet grains could also be supplied (see Table IV). Leaving aside the high zircon and tourmaline content in its bottom levels, the succession drilled by the borehole 601 records a high metamorphic mineral content (Table IV). Biotite and garnet are dominant in the lower part of this succession, whereas andalusite, staurolite, sillimanite and kyanite become widespread in the overlying units and probably indicate significant contribution from the Mondoñedo nappe domain. The possible contributions from plutons to the sedimentary infill cannot be confirmed since the most diagnostic apatite mineral is not recorded (Table IV).

Source area evolution of the As Pontes basin, as deduced from the heavy mineral analysis is shown in Fig. 7. This evolution is divided into four stages. The first stage (Fig. 7 A and B) corresponds to the deposition of the Macrosequence I. It records the basin initiation and the earlier settling in of the relatively restricted catchment areas which fed the northern transverse alluvial fans. During this stage, sedimentation took place in two isolated subbasins; in both subbasins the sedimentation resulted from the evolution of small sized transverse alluvial fans and the development of lacustrine zones in the eastern subbasin. This earlier basin fill stage (Fig. 7A) was characterised by alluvial sediment supplied from source areas mainly constituted by Ordovician quartzites and Precambrian schists of the Ollo de Sapo domain. This domain could provide the high zircon and tourmaline and relatively low metamorphic mineral contents recorded at the base of both successions (Figs. 5 and 6). However, the successions in both subbasins display different upward trends. Thus, the western subbasin fill succession (borehole 6006) shows the earlier input and subsequent increase in unstable amphibole grains. On the contrary, the eastern subbasin fill succession (hole 601) displays 1) an increase in opaque heavy minerals (probably related to sulfide and/or siderite neoformation in the peat-forming environments); and 2) a translucent heavy mineral assemblage characterised by the rise in the metamorphic mineral content (biotite, garnet, staurolite and andalusite, among others).

These vertical changes must reflect the progressive unroofing of each differentiated source area in the Ollo de Sapo domain rocks. The increase in amphibole grains in the western subbasin must be interpreted as a consequence of the down cutting of the catchment area eroding Ordovician slates. In the eastern subbasin, the increase in metamorphic minerals with major contribution of biotite and staurolite, but also garnets, andalusite, sillimanite and kyanite could be interpreted as the result of the headward erosion of the catchment area. This suggests a progressive eastward drainage incision in the Ordovician slates and Silurian turbidites of the Ollo de Sapo domain. This incision finally reached the metamorphic rocks of the Mondoñedo nappe domain, which contains different metamorphic zones (Fig. 7B).

The second evolutionary stage in the source areas (Fig. 7C) corresponds to the deposition of macrosequence II. It is characterised in the western subbasin (borehole 6006) by an increase in opaque heavy minerals and the maintenance of a high percentage of amphibole grains as translucent components (Fig. 5 and Table III). In the eastern subbasin (bore 601) the opaque heavy mineral content decay and the major contribution is made up of metamorphic mineral grains (Fig. 5 and Table III).

These vertical changes could reflect the predominance of marsh-swamp peat-forming environments, with major sulfide and minor carbonate precipitation, in the western subbasin versus their lesser persistence in the eastern subbasin. Moreover, the detrital heavy minerals indicate that the catchment area that fed the transversal alluvial fans in the western subbasin developed over the amphibole-rich Ordovician slates of the Ollo de Sapo domain (Fig. 7C). In the eastern subbasin, the heavy mineral content of this second stage shows a higher contribution of a wide spectrum of metamorphic minerals (see Table III). This must be interpreted as the consequence of progradation of alluvial fans fed from a source area that spread over the Cambrian metamorphic rocks of the Mondoñedo nappe domain (Fig. 7C).

The third stage in the evolution of the catchment areas (Fig. 7D) corresponds to the sedimentation of macrosequence III. During this period, the two subbasins were filled-up and the As Pontes basin became a single depocentre (Ferrús, 1998). The ratio between opaque and translucent heavy minerals still shows differences related to the major peat-forming environment development in the western part of the basin. At the same time, the detrital translucent heavy mineral content has a high proportion of metamorphic minerals in the eastern borehole 601 and abundant

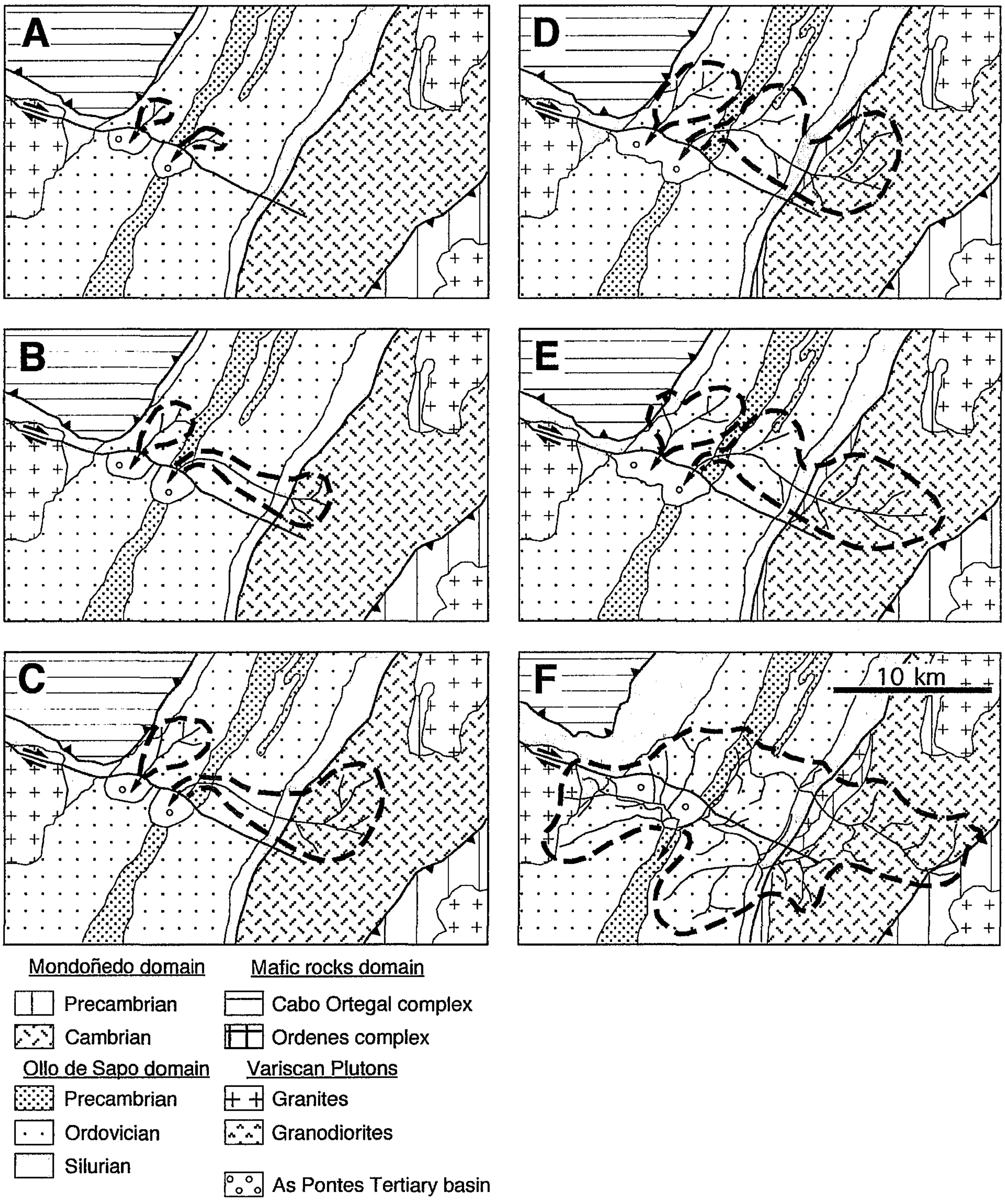

Figure 7.- Unroofing history of the Precambrian-Palaeozoic catchment areas of the As Pontes basin based on heavy mineral analysis. The figure only shows the catchment areas developed over the tectonically active northern source areas. No data are available about the southern source areas and their catchment evolution. From stages A to E the basin was endhorreic, whereas the present-day drainage (F) is open. See text for further explanations. Legend for units as in Figure 1.

amphibole grains in the western drillhole 6006. However, the main feature of this third stage is that both successions show an increase in ultrastable minerals, mainly zircon and/or tourmaline. These variations must be interpreted as a consequence of the catchment areas down cutting over the Precambrian schists and the Ordovician quartzites of the Ollo de Sapo domain. This synchronism in the down cutting for both source areas in the same parent rocks suggests a tectonic uplift of the area occupied by -at least- the Precambrian schists and the Ordovician quartzites of the Ollo de Sapo domain, and a later headward erosion affecting both source areas where the relief had been rejuvenated (Fig. 7D). These data agrees with the major alluvial fan progradation and with the increase in the terrigenous sediment supply pointed out by Ferrús (1998) in the lower part of the macrosequence III.

The fourth stage in the evolution of the drainage areas corresponds to deposition of macrosequences IV and V (Fig. 7E). The western coal-bearing sequence shows a higher proportion of opaque heavy minerals than the eastern succession (see Tables II and III), whereas the translucent heavy minerals show the same general features. Thus, the western section contains a high contribution of zircon, tourmaline and titanium oxides (mainly anatase) as well as variable proportions of amphiboles, whereas the eastern succession has significant proportions of a wide range of metamorphic minerals (Table III). However, there are also some peculiarities. Some samples of borehole 6006 indicate that apart from amphiboles, the western part of the basin was locally supplied by variable proportions of pyroxene and biotite grains (Table II and Fig. 5). In the lower units of this western section, biotite was a negligible constituent, whereas pyroxene was absent. The presence of biotite grains in the upper part of the succession is not related to other metamorphic mineral contributions, but to pyroxenes and amphiboles. This suggests that during this stage the catchment area which fed the western alluvial fans eroded headward up to the basic rocks of the Cabo Ortegal complex, the only rocks which could supply a biotite, pyroxene and amphibole assemblage into the As Pontes basin (Fig. 7E). However, this down cutting of the drainage network in the Cabo Ortegal rocks would be incipient and areally restricted since it did not result in a generalized supply, to the basin, of other characteristic heavy minerals which could be provided by this source area (i.e. garnet, olivine).

The samples collected from the upper part of the eastern succession (drillhole 601), which are characterised by their general high content of metamorphic heavy minerals, do not show any vertical variation. Thus, despite its wide spectrum of metamorphic mineral composition (Table III), the biotite content clearly decays with respect to the earlier stages, whereas the decreasing garnet disappears in the uppermost part. This minor content in biotite and garnet is counteracted by an increase in kyanite, staurolite and andalusite contents. This suggests the areal spread of the eastern catchment area towards the inner part of the Mondoñedo domain, over the aforementioned metamorphic zones. This eastward erosion on the Mondoñedo nappe constituted the greatest eastwards extension of the drainage network that supplied the eastern As Pontes basin (Fig. 7E). The present-day drainage network supplies the currently open-drainage and inactive As Pontes basin (Fig. 7F).

Concluding remarks

The evolution of the source areas and the drainage network which fed the As pontes basin from Oligocene to Early Miocene times is made evident by means of the analysis of the heavy mineral assemblages recorded in two borehole successions and used them as provenance indicators.

The heavy mineral associations differ significantly in both sections, which were located in distinct basin zones. These major differences concern both the opaque-translucent heavy mineral ratio and the relative percentages between translucent heavy mineral species. These differences were mainly controlled by the varying lithology of the source areas and, to a lesser degree, by mineral neoformation processes related to the anoxic early burial diagenetic conditions that developed in marsh-swamp peat-forming environments. Taking into account that climate and transport influence on the 6006 and 601 heavy mineral assemblages were similar, we propose that these factors do not account for the different heavy mineral assemblages recorded in both boreholes.

The sedimentary succession of the western subbasin is characterised by a high proportion of opaque heavy minerals -mainly sulfides and siderite- related to the widespread development of peat-forming marsh-swamp environments, where intense sulphate reduction took place. The detrital translucent heavy minerals are dominated by resedimented rounded ultrastable minerals (zircons, tourmaline) coexisting with widespread non-stable amphiboles. All these detrital components came from a close source area mainly developed on the Ollo de Sapo domain rocks. There is no clear evidence that the source area that fed the western subbasin included the mafic rocks of the Cabo Ortegal complex (to the north) or the major igneous plutons (to the west).

By contrast, the heavy mineral associations that characterised the eastern subbasin show a minor occurrence of opaque heavy minerals (related to the minor development of peat-forming lacustrine environments) and a major relative content in translucent heavy minerals. Ultrastable minerals (zircon, tourmaline and rutile) are scarce in this eastern succession, whose heavy mineral content is dominated by a metamorphic assemblage, with variable proportions of biotite, garnet, kyanite, staurolite, andalusite and sillimanite. This mineral association defines a source area that developed on the Cambrian metamorphic rocks of the Mondoñedo nappe domain located 10km to the east of the basin. There is no evidence of contributions from the Precambrian rocks or the main plutons in this domain, although minor contributions from the Ollo de Sapo domain are recorded.

These differences between the heavy mineral associations in both subbasins originated early in the evolution of the basin. Only the basal and lowermost samples in the macrosequence I are similar in both subbasins. This would record the earliest settling in of the alluvial systems and the initial drainage network entrenchment in the neighbouring rocks, i.e. the

Ordovician quartzites of the Ollo de Sapo domain. Subsequently the heavy mineral associations in the overlying successions (upper macrosequence I and macrosequence II) rapidly acquired their own characteristics in each subbasin, recording the drainage headward erosion in each source area. These differences were maintained even during the sedimentation of the macrosequence III, when both subbasins joined and gave rise to a single basin. Both the eastern and western successions related to the small sized alluvial fans do not show any homogenization trend of their heavy mineral compositions. This indicates the low efficiency of the small sized northern alluvial fans developed in the As Pontes basin in dispersing even the finest sediment.

The style of erosion and the development of the drainage networks which fed the As Pontes basin underwent changes since the early evolutionary stages of the basin. Their development on the northern source areas was probably controlled by the uplift of the hangingwall of the Pedroso-As Pontes-Moiñonovo major fault zone. The drainage networks show a northward restricted development and they only affected the Precambrian and Ordovician rocks of the Ollo de Sapo domain. No significant contributions from the neighbouring Silurian rocks of this domain, the mafic rocks of the Cabo Ortegal complex -located slightly to the north-, or from the plutons to the west are recorded. This indicates the restricted northward and westward spreads of the drainage networks. By contrast, the eastward spread of the catchment was fairly significant and occurred quite soon, as shown by the early detrital contributions from the Mondoñedo nappe domain.

The final distribution of the Oligocene-Early Miocene drainage network that surrounds the As Pontes basin bears a considerable resemblance to that of the present-day drainage, differing mainly in the open drainage conditions resulting from the capture of the former drainage by the Eume river network.

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