

Tectonic and lithological controls on fluvial landscape development in central-eastern Portugal: Insights from long profile tributary stream analyses



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ABSTRACT

This study examines the long profiles of tributaries of the Tagus and Zêzere rivers in Portugal (West Iberia) in order to provide new insights into patterns, timing, and controls on drainage development during the Quaternary incision stage. The studied streams are incised into a relict culminant fluvial surface, abandoned at the beginning of the incision stage. The streams flow through a landscape with bedrock variations in lithology (mainly granites and metasediments) and faulted blocks with distinct uplift rates. The long profiles of the analyzed streams record an older transitory knickpoint/knickzone separating (1) an upstream relict graded profile, with lower steepness and higher concavity, that reflects a long period of quasi-equilibrium conditions reached after the beginning of the incision stage, and (2) a downstream rejuvenated long profile, with steeper gradient and lower concavity, particularly for the final reach, which is often convex. The rejuvenated reaches testify to the upstream propagation of several incision waves, interpreted as the response of each stream to increasing crustal uplift and prolonged periods of base-level lowering by the trunk drainages, coeval with low sea level conditions. The morphological configurations of the long profiles enabled spatial and relative temporal patterns of incisions to be quantified. The incision values of streams flowing on the Portuguese Central Range (PCR; ca. 380–150 m) are variable but generally higher than the incision values of streams flowing on the adjacent South Portugal Planation Surface (SPPS; ca. 220–110 m), corroborating differential uplift of the PCR relative to the SPPS. Owing to the fact that the relict graded profiles can be correlated with the Tagus River T1 terrace (1.1–0.9 My) present in the study area, incision rates can be estimated (1) for the streams located in the PCR, 0.38–0.15 m/ky and (2) for the streams flowing on the SPPS, 0.22–0.12 m/ky. The differential uplift inferred in the study area supports the neotectonic activity of the bordering faults, as proposed in previous studies based upon other geological evidence.

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1. Introduction

The Portuguese territory, positioned along the western Atlantic border of Iberia, presents a complex geodynamic setting characterized by interplay between (i) passive margin Atlantic ridge push effects and (ii) interplate interactions related to NW-SE convergence of Eurasia

and Africa (Nubia; at 4–5 mm/y; Calais et al., 2003; Nocquet and Calais, 2004; Cloetingh et al., 2005; Fernandes et al., 2007). The resulting stress field produces long wavelength vertical movements (uplift/subsidence) as well as fault movements, which together accommodate the tectonically induced finite strain. This neotectonic activity impacts on the regional landscape, acting upon an inherited morphology that has evolved through the Cenozoic (Cabral and Ribeiro, 1993; Ribeiro et al., 1996; Cloetingh et al., 2002, 2005; De Vicente et al., 2007, 2008, 2011; Cabral, 2012).

The landscape of mainland Portugal is characterized by a high average elevation, dominated by the northern Meseta (a plateau at an altitude ranging from ca. 650 to 700 m). It also presents a succession of

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~NE-SW trending mountain ranges, with altitudes of up to ca. 2000 m, and intervening topographic lows corresponding to sedimentary basins at altitudes of ca. 600 to 100 m. These regional scale topographic variations trend normal to the present-day intraplate compressional stress trajectories, having been interpreted as the result of lithospheric buckling coupled with reverse faulting (Cloetingh et al., 2002, 2005; Vegas, 2005; De Vicente et al., 2008). The morphology is largely dominated by erosional plateaus elevated to different heights. These are cut onto metasedimentary rocks and granites of the Neoproterozoic and Palaeozoic Hesperian Massif, as well as onto Mesozoic and Cenozoic sedimentary basin fill successions. Relief distribution and hypsometry (43% of the landscape area is below 200 m, 30% above 400 m, and only 0.5% above 1200 m altitude) reflects the amplitude of the vertical movements. Some 95% of the landscape areas above 400 m are located in the northern and central parts of the country. In the central region, uplift was the greatest, raising the Portuguese Central Range (PCR) to a maximum altitude of 1993 m.

A broad regional scale characterization of the Quaternary vertical movements in mainland Portugal has been tentatively performed through the use of geological and geomorphological markers. Sea level markers in modern coastal regions include a regional Pliocene wave-cut platform dated as ca. 3.70–3.61 My (Diniz et al., 2016) overlain by a sedimentary unit that has the top surface (the Culminant Fluvial Surface) with a probable age of 1.8 My (Cunha et al., 2016) and some dated Pleistocene marine terraces (e.g., Ramos et al., 2012; Carvalhido et al., 2014). Inland, terrestrial land surface markers include also the Culminant Fluvial Surface (CFS) as well as fluvial terraces along major river valleys. When using the CFS as a geomorphic marker for the last ca. 1.8 My, the estimated long-term uplift rate varies from 0.05 to 0.2 mm/y, but is generally higher inland relative to coastal areas. The highest estimated uplift rates, of ca. 0.2 mm/y, relate to the NE part of Portugal and the PCR (Cunha et al., 2005, 2008, 2012, 2016; Martins et al., 2009; Cabral, 2012).

River terraces provide useful insights into the dominant forcing mechanisms for fluvial systems: tectonics, climate, and sea level. However, terrace records are often spatially and temporally fragmented and where preserved are more likely to be associated with higher order trunk river systems. Lower order tributary streams commonly lack terrace records because sediment storage space is limited and the steeper gradients result in higher stream power, which tends to promote sediment erosion and transport. Thus, the valley floors of tributary streams are often dominated by bedrock reaches or, at the very least, by a thin transitory cover of alluvial material. In such settings, the long profile of the tributary stream is often the only geomorphological information that can be used to provide insights into the long-term fluvial landscape history.

In this study we use fluvial drainage analysis, namely river long profiles and slope–drainage area analyses to characterize the Quaternary uplift evolution in a study area located in the PCR and its adjacent South Portugal Planation Surface (SPPS), where relatively high uplift rates and significant differential vertical movements between fault-bounded crustal blocks have been documented.

For this we used a section of the Tagus River that flows across the SPPS adjacent to the SE piedmont of the PCR, and the related drainage network, including one major tributary (the Zêzere River) that flows through the PCR (Figs. 1 and 2). The Tagus River was chosen because of its size (longest river in Iberia, with a length of 1040 km and the third largest drainage area, of 81,000 km²), thus assuring a relatively fast response to external forcing mechanisms and providing a relatively stable regional base level, and because of its location in the regional morphotectonic framework. The targeted tributaries are located in the main relief of the PCR. Their long profiles and knickpoints are used to identify differential uplift between uplifted blocks and local fault interactions as components of the regional long-term uplift rate.

Three main objectives are considered: (i) to estimate the magnitude of fluvial incision post-dating a generalized steady phase on landscape

evolution and consequently formation of a graded longitudinal profile on drainage; (ii) to use the fluvial incision as a proxy for uplift; (iii) to analyze the stream profiles and drainage basins to calculate the normalized steepness index k_{sn} (Wobus et al., 2006), which is considered a sensitive parameter to tectonics, in order to detect differential uplift between crustal blocks and to infer neotectonic activity of bordering faults.

2. Geological and morphotectonic setting

The drainage network of the study region flows mostly on the Iberian Hesperian Massif, consisting predominantly of slates and metagreywackes of Neoproterozoic to Cambrian age intensely folded by the Variscan Orogeny. Ordovician to Devonian quartzites and slates occur at the core of synclines exposed along narrow bands trending NW-SE, following the regional Variscan fabric. Also outcropping are some pre- and late to post-orogenic granite intrusions (Fig. 2). From the end of the Variscan Orogeny in the late Carboniferous and continuing to the early Cenozoic, the basement was eroded to a broad planation surface (the Iberian Meseta), above which the Ordovician quartzites and slates form elongated ‘Appalachian’ style resistant reliefs, but also occurring scattered inselbergs in granite areas (Cunha, 1992; Cunha and Pena dos Reis, 1995; Dinis et al., 2008).

During the Cenozoic, this broad planation surface was deformed into topographic highs (pop-ups) and lows (pop-downs); these constituting sedimentary basins) as a result of the Alpine interplate compression (Ribeiro, 1984; Ribeiro et al., 1990; De Vicente et al., 2007, 2011; Pais et al., 2012). The Alpine compression generated the NE-SW trending PCR, corresponding to a complex pop-up structure bounded by major NE-SW reverse faults, though slightly asymmetric, with one major fault (Seia-Lousã fault, SLf) on the NW side and deformation distributed across several faults on the SE side (including the Sobreira Formosa fault, SFF; e.g., Ribeiro et al., 1990; Sequeira et al., 1997; Figs. 2 and 3).

Tectonically controlled piedmont depressions occur on the SE side of the PCR, namely the Sarzedas and the Ródão-Idanha a Nova-Moraleja (Fig. 2), displacing the SPPS (Ribeiro, 1942; Cunha, 1987, 1992; Dias and Cabral, 1989; Vegas, 2006). These are bounded to the NW by the Sobreira Formosa and Rapoula faults (Sff and Rapf) and by the Ponsul fault (Pf), respectively (Fig. 2), corresponding to subbasins of the wider Lower Tagus Cenozoic basin. The sedimentary infill of this basin consists predominantly of alluvial fan gravelly sandstones (probably Eocene) and fluvial sands and silts (Miocene), overlain by coarser lithoclastic (slates and metagreywackes clasts) alluvial fan deposits attributed to the latest Miocene and Zanclean. These coarser deposits have been correlated to the main phases of mountain building (Cunha, 1992, 1996), thus indicating that major uplifting of the PCR occurred in the upper Neogene. The uppermost sedimentary unit, represented by the siliciclastic Falagueira Formation, has been considered of Piacenzian to Gelasian in age (3.65 to 1.8 My) and interpreted to record the capture of an Iberian endorheic drainage (Madrid Cenozoic basin) by a westward-draining Atlantic fluvial drainage (Lower Tagus basin) (Cunha, 1992, 1996; Cunha et al., 1993, 2005, 2008, 2012; Pérez-González, 1994; Pais et al., 2012).

The study area partially covers the southwestern part of the PCR and the adjacent SPPS, across which the Tagus River flows in an entrenched valley. In this area, the Falagueira Formation is generally 10–20 m thick, always at the top of interfluvial, associated with the coeval relict Culminant Fluvial Surface (expressed as a very large paleovalley) preserved in remote areas away from the modern Tagus channel, and in minor sheltered areas of the PCR (Fig. 3). The geomorphic and sedimentary characteristics indicate that the ancestral Tagus River flowed on a laterally extensive low gradient alluvial plain. This period of the drainage history marks the final stage of sedimentary infilling in the Lower Tagus basin prior to the onset of the fluvial incision stage, which probably began just after the Gelasian (1.8 My; Cunha et al., 2012, 2016; Rosina et al., 2014).

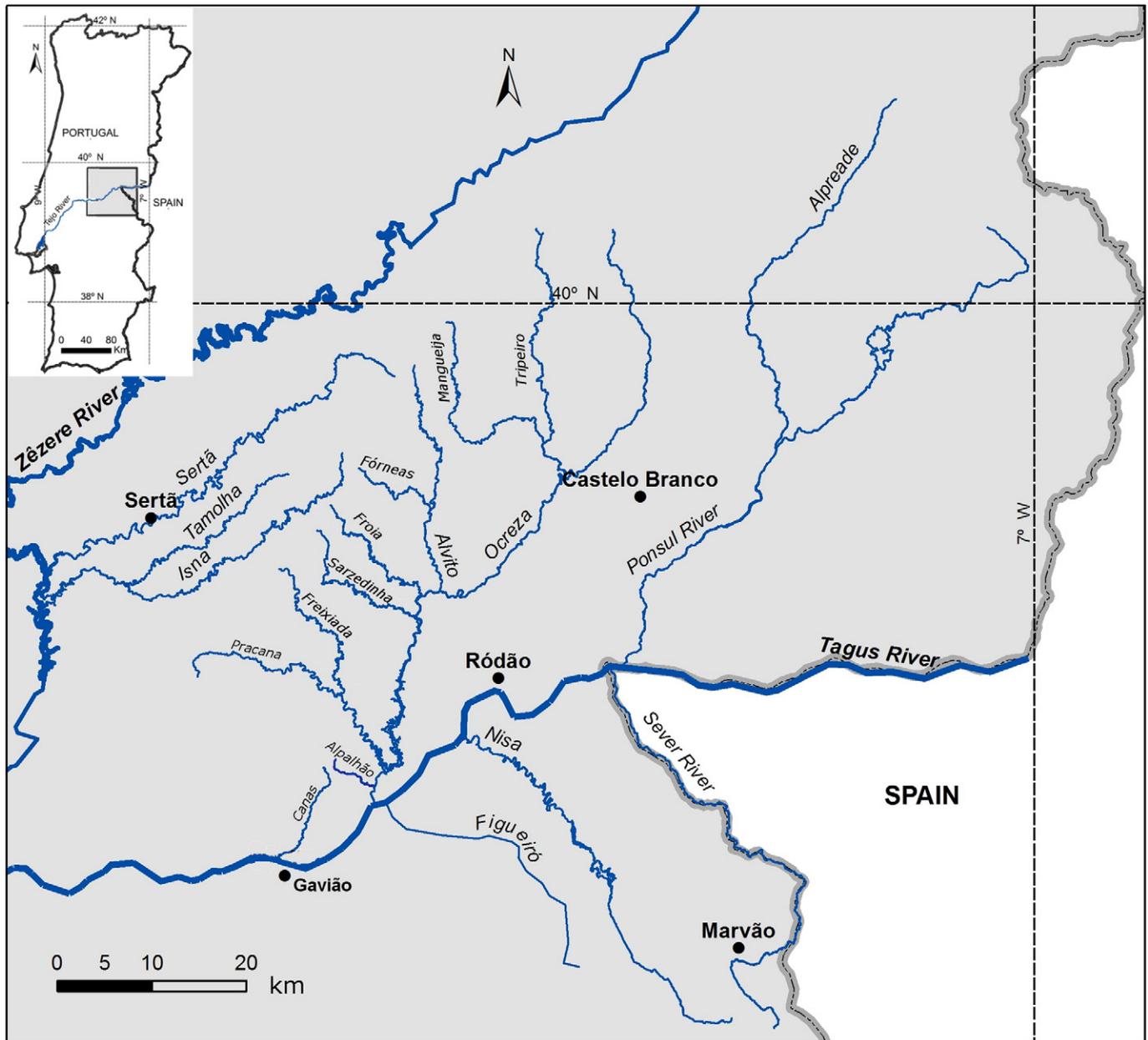


Fig. 1. Geographical setting of the study area (inset) and identification of the rivers and streams analyzed in this paper.

The SE boundary fault of the PCR (Sobreira Formosa fault, SFF) is crossed by tributary streams of the Tagus River flowing southward from the mountain to the adjacent lower SPPS (Fig. 2). Within the study area, however, other major tributaries (the Zêzere and Sertã rivers) flow along low-lying intra-montane corridors trending longitudinally to the mountain range, which are interpreted as tectonic depressions located between uplifted blocks (Daveau et al., 1985–1986), in a sequence of reverse fault bounded pop-up/pop-down structures similar to those proposed by De Vicente et al. (2007) for the Gredos sector of the SCS.

Besides the ENE-WSW longitudinal faults, there are a limited number of WNW-ESE transverse faults that cross the mountainous system, such as the Sertã fault (SF) in the southwestern part (Fig. 2). The kinematic of the SF is poorly constrained, but geomorphic evidence suggests a dominant right lateral strike-slip movement with a subsidiary vertical movement component corresponding to some uplifting of the southern block relative to the northern block. The Sertã, Isna, and Tamolha

streams flow across the uplifted southern block possibly by an antecedent process (Daveau, 1985; Fig. 3).

Slip rates are estimated for two main regional ENE-WSW reverse faults based upon estimated offsets and the probable age of the Cullinant Fluvial Surface, namely a slip-rate of 0.14 to 0.19 mm/y for the Seia-Lousã fault (northern boundary fault of the PCR) and of 0.04 to 0.07 mm/y for the Ponsul fault (southern boundary fault of the PCR) in the last 1.8 My. These slip rates fall in the range of 0.005 to 0.3–0.5 mm/y that has been inferred for the active faults in Portugal mainland corresponding mostly to low activity rates and thus evidencing the dominance of slow fault movement (Cabral, 1995, 2012).

In the study area, the upstream section of Tagus River tributaries, including the Zêzere River, display long profiles with a smooth concave-up shape. This shape represents a steady state, or dynamic equilibrium profile, graded to an older and more elevated base level than the present. As stated, in these upper reaches the drainage is slightly inset into

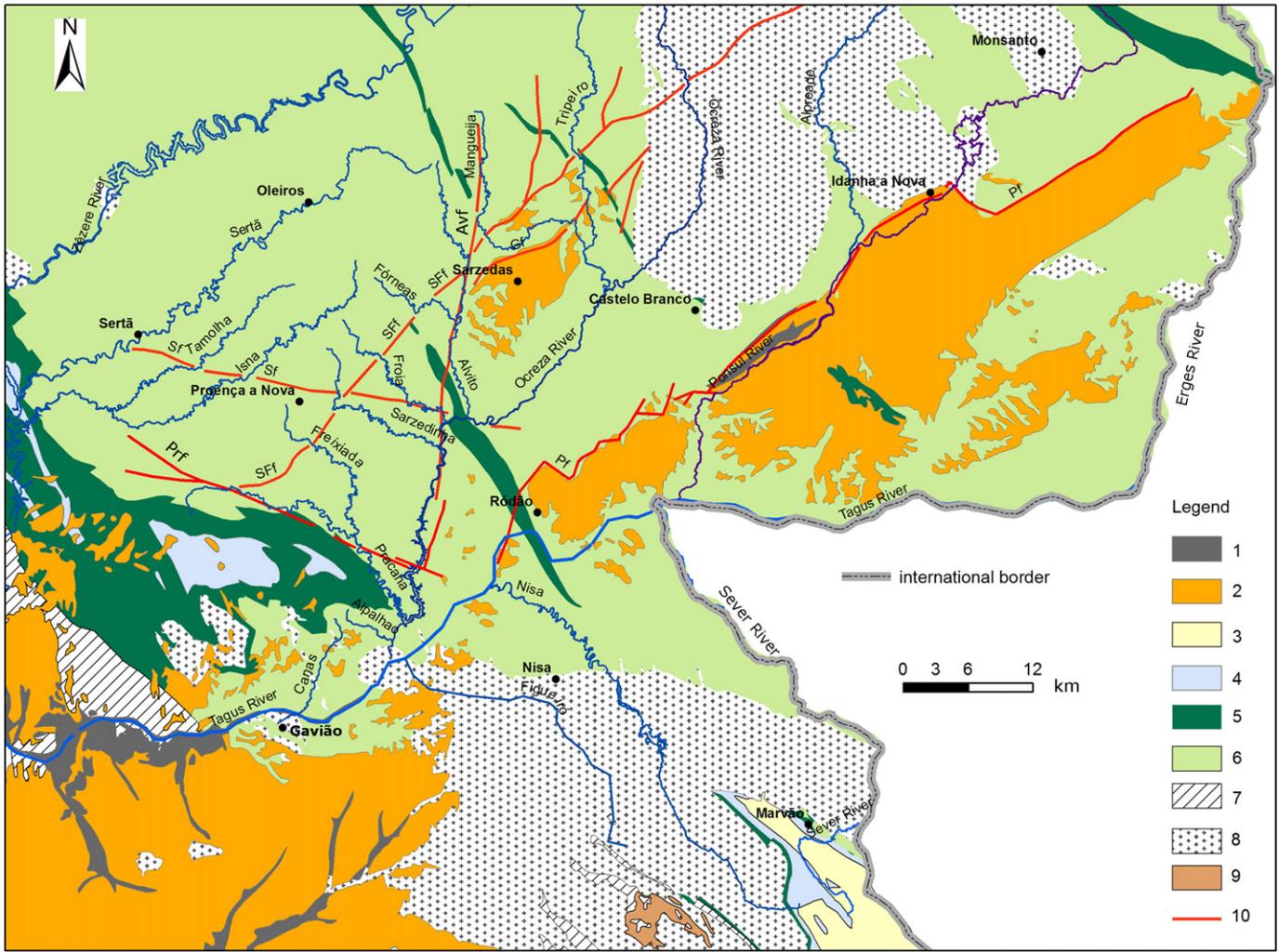


Fig. 2. Geological map of the study area (adapted from ‘Mapa Geológico de Portugal na escala 1/500000, S.G.P., 1992’). 1 - Fluvial terraces (Pleistocene); 2 - sedimentary cover (Paleogene and Neogene); 3 - slates and metasandstones (Devonian); 4 - slates and quartzites (Silurian); 5 - quartzites (Ordovician); 6 - slates and metagreywackes (Neoproterozoic to Cambrian); 7 - slates, metagreywackes, and limestones (Neoproterozoic); 8 - granites and orthogneisses; 9 - diorites and gabbros; 10 - fault. SFF - Sobreira Formosa fault; Sf - Sertã fault; Pf - Ponsul fault; Gf - Grade fault. The SFF constitutes the border between the PCR (at NW) and the SPPS (at SE).

a culminant rolling topography, interpreted as a fluvial landscape with a probable age of Piacenzian to Gelazian age (ca. 3.65 to 1.8 My).

The graded upstream relict profiles link to rejuvenated downstream reaches via oversteepened segments that mark the upstream limit of an incision wave. The transition to the oversteepened segments corresponds to transitory knickpoints or knickzones developed owing to a rate change in forcing (increase in river energy). In each channel, the knickpoint/zone has migrated upstream and incised the valley floor of the relict profile, leaving only short reaches in the headwaters not yet affected by the incision wave. In the main tributaries, the incision has left behind a perched bedrock bench feature, akin to a strath terrace, which can be used to pinpoint the location of knickpoints/zones by tracing the benches upstream until they merge with the relict bedrock channel.

3. Methodology

In an area that is being subjected to continuous uplift (i.e. the study region), the amount of long-term river incision (comprising several eustatic and climatic short-term cycles) can be considered a proxy for uplift. At the stream mouth/confluence, the magnitude of incision is at a maximum and it encompasses all of the successive incision phases since rejuvenation of the drainage network has occurred (Kirby and Whipple, 2012). In order to quantify the magnitude of fluvial incision

in the lower reaches of the studied drainage, the upstream graded relict profiles of tributaries can be reconstructed downstream until the trunk river using the mathematic formula of an idealized equilibrium long profile (Bishop and Goldrick, 2000; Goldrick and Bishop, 2007). The magnitude of incision is then calculated by subtracting the elevation of the modern long profile from that of the projected relict profile at the junction (e.g., Antón et al., 2012; Kirby and Whipple, 2012).

To describe and quantify the river long profile shape, the profiles were extracted from 10 m resolution digital elevation models (DEM) generated from digital topographic maps (1/25,000 scale). For each stream, elevation, distance, and drainage area data were compiled utilizing a group of built-in ArcGIS functions. Longitudinal profiles (distance versus elevation) were then plotted. The recognition of an equilibrium relict profile in the upstream reach of the studied streams was then performed visually and analytically corroborated by constructing distance-slope (DS) plots for each stream and verifying the goodness of fit to a linear trend for that upper reach. The DS plots are derived from the power law relationship between slope and downstream distance (D , or L ; Bishop and Goldrick, 2000; Goldrick and Bishop, 2007; Eq. (1)),

$$S = kL^{-\lambda} \quad \text{or} \quad \ln S = \gamma - \lambda \ln L \quad (1)$$

where S is the slope at a point along the stream profile, L is the

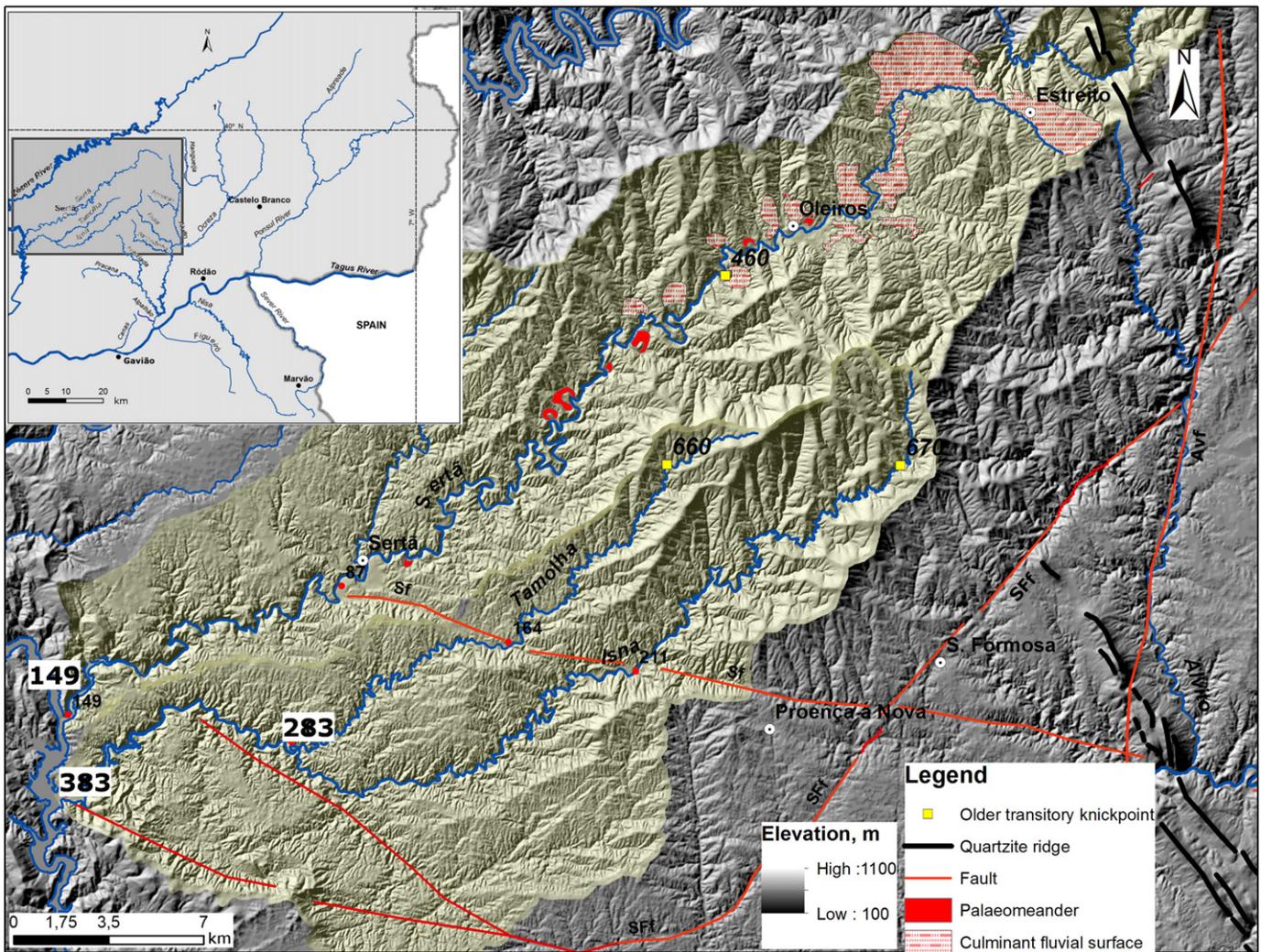


Fig. 3. Hillshade (digital elevation model - DEM) showing the morphology of the SW sector of the PCR, evidencing the longitudinal depressed corridor where the Sertã stream flows. In the study area, the Culminant Fluvial Surface (CFS), recording an exorheic Atlantic drainage during the Piacenzian to Gelasian (ca. 3.65 to 1.8 My), is preserved in the headwaters of the Sertã stream as an erosion surface but also as a sedimentary aggrading surface along the Tagus valley (e.g., Ródão). The first incised relict graded profile – in some places showing paleomeanders, a strath terrace level (N1), or a sedimentary terrace level (T1) – document the first long period of dynamic equilibrium prior to the dominant downcutting of the incision stage. Filled squares correspond to the older transitory knickpoint (older tKP), with the altitude indicated (m); incision values (m) at the stream mouth and near the Sertã fault are also indicated. Sf – Sertã fault; SFF – Sobreira Formosa fault; AVF – Alvito fault.

downstream distance from the drainage divide to that point, k and λ are constants, and γ is equal to the natural logarithm of k ($\ln k$). The exponent λ relates to the long profile concavity, while the parameter k reflects the influence of lithology and other factors, including equilibrium incision rate and stream hydraulic geometry.

The slope model described by Eq. (1) can be expressed in terms of a derivative of elevation with respect to distance, such that $S = dH/dL$. From this equation, the graded long profile can be obtained by integration:

$$H = \int S dL \quad (2)$$

Replacing S by the value given by Eq. (1) and integrating produces the equilibrium long profile formula:

$$H = H_0 - k \frac{L^{1-\lambda}}{1-\lambda} \quad (3)$$

where H_0 is an integration constant, and $\lambda \neq 1$. The H_0 (the value of H for $L = 0$) stands as an estimate of the theoretical elevation of the drainage divide if hydraulic processes were active right up to this point (Montgomery and Dietrich, 1988; Goldrick and Bishop, 2007).

The theoretical shape of the equilibrium relict profile thus identified in each stream was then derived by a regression analysis of the plotted longitudinal profile to a power function expressed by Eq. (1). The k and λ parameters adequate for each relict profile were then obtained and the shape of the profile was derived from Eq. (3). For each stream, H_0 was adjusted by imposing a vertical shift onto the modeled profile so that it fitted with the DEM extracted profile. The best adjustment was sought by minimizing the average of the differences in elevation between the points obtained from the DEM and the elevation of the theoretical profile points.

As stated, the streams of the study area flow through fault-bounded crustal blocks affected by different uplift rates (Cabral and Ribeiro, 1993; Cabral, 1995, 2012). Some flow along the PCR, others flow from the PCR to the southern piedmont area, while others flow on the SPPS (where the Cenozoic sedimentary cover is mostly eroded). Considering this diverse setting relative to the regional neotectonic structures, we also explored the stream profiles to extract tectonic activity using the steepness index factor (Wobus et al., 2006), which is a parameter sensitive to tectonics, particularly to changes in strain rates.

The steepness index can be extracted from the power law relationship between slope and the contributing drainage area (Hack, 1973;

Flint, 1974; Howard and Kerby, 1983), as in Eq. (4):

$$S_e = k_s A^{-\theta} \quad (4)$$

where S_e is the equilibrium channel gradient, k_s and θ are parameters that describe the relative steepness and the concavity of the curve in the plot of the slope versus drainage area, respectively. The concavity index (θ) expresses the rate of stream gradient change with the drainage area and corresponds to the slope of the linear expression of that function in a log slope-log area plot, while the steepness index (k_s) corresponds to the y-intercept in this plot. Eq. (4) holds only above a critical drainage area, usually interpreted as the transition from debris-flows to fluvial processes within a drainage basin (Wobus et al., 2006).

Both the concavity index (θ) and the steepness index (k_s) are easily obtained by linear regression of the log of stream gradient ($\log S$) versus the log of upstream drainage area ($\log A$). However, because small variations and uncertainties of the concavity index can significantly influence the value of k_s derived from linear regression, the regressions are usually done with an imposed reference concavity (θ_{ref}), and a normalized steepness index (k_{sn}) is thus obtained. The reference concavity is usually taken as the regional mean of the observed θ values, which in undisturbed segments typically fall in a range of 0.30 to 0.60 (Whipple and Tucker, 1999; Snyder et al., 2000; Kirby and Whipple, 2001; Kirby et al., 2003; Wobus et al., 2006).

Many streams show a single slope-area scaling for their entire length; but for tectonic information to be extracted from the landscape it is preferable to analyze individual segments, as each segment may exhibit a different value of k_{sn} (Wobus et al., 2006). In fact, the simplest approach is to use a single regression from headwaters to the stream mouth, but the normalized steepness index thus obtained determines a value representative of the centroid of the data bound by the upstream and downstream limits of the regression. Recognizing the segmented nature of river profiles and choosing these limits is thus an important methodological step.

In this study, the normalized steepness indices were calculated using the method of Wobus et al. (2006), described above. After examining the slope-area data of each stream, we divided the long profile into individual segments, and for each one the appropriate regression limits were chosen. The channel steepness index (k_s) and concavity index (θ) were calculated using the power law regression of river slope against drainage area (Eq. 4). A second regression calculation was then undertaken whereby individual segments of slope-area data were fitted using a reference concavity (θ_{ref}) to determine the normalized steepness index (k_{sn}) of each segment. A value of 0.45 was used as the reference concavity, taking into account the obtained regional values of concavity indices.

The different segments of the studied rivers are separated by knickpoints or knickzones marked by a distinctive change in channel gradient. These correspond mostly to slope-break knickpoints (Whipple et al., 2013), consisting of a longitudinally extensive change in channel gradient from an upper graded relict profile to a steeper, rejuvenated lower reach. These knickpoints/zones separate channel reaches with different channel steepness (k_s) values and are readily recognized on long profiles and on slope-area plots (e.g., Wobus et al., 2006). Localized, vertical step knickpoints are also easily recognizable on the long profiles and as spikes in DS and in slope-area plots, while a broad zone of disequilibrium steepening is clearly expressed as an area of dispersed and incoherent distribution of points in DS plots (Goldrick and Bishop, 2007).

The recognition of knickpoints or knickzones in the studied streams was first performed by visual inspection of the stream profiles and then analytically corroborated in DS and logS-logA plots, according to the above referred criteria. Several knickpoints and knickzones were thus identified and classified as either transitory (mobile) or permanent (stationary). Transitory knickpoints or knickzones develop in response to disturbances in the steady state conditions of the long profile and

pinpoint the present location of an upstream propagating incision wave or of a channel steepness adjustment (Howard et al., 1994; Crosby and Whipple, 2006). Permanent knickpoints/zones are typically associated with resistant bedrock lithologies (rKP).

4. Stream profile analysis results

4.1. Streams flowing along the Portuguese Central Range

This group comprises the Sertã, Tamolha, and Isna streams, whose valleys are located within the PCR and trend longitudinally to the mountain system, flowing NE-SW (Figs. 2 and 3). The 78 km-long Sertã stream is located within a corridor, at ca. 450–500 m of altitude, while the Tamolha and Isna streams probably flow along a tectonically more elevated block (ca. 1100 m of maximum altitude).

The long profiles of these streams (Fig. 4A, B, and C) reveal an upstream relict graded profile and a downstream rejuvenated reach, separated by a knickpoint (tKP) situated at altitudes of 460 m (Sertã), 670 m (Isna), and 660 m (Tamolha; Older transitory knickpoint on Fig. 3). The amount of migration of the older tKP from the stream mouth to its current position(s) is a function of the drainage area (Fig. 5). Effectively, the older tKP has traveled farther along the Sertã stream (60 km). However, in the Sertã stream, the relict profile still represents around 20% of the total length, while for the other streams it only represents <10%.

The distance-slope (DS) plots for the three rivers (Fig. 4A, B, C inset plots) indicate that the relict profiles (lozenges) are close to graded, while the more disordered points of the rejuvenated profiles (crosses) indicate ungraded profiles. Other transitory knickpoints, located between the older tKP and the Sertã fault, were recognized on the rejuvenated profiles.

The incision value, calculated from the difference in elevation between the downstream projection of the relict graded profile and the modern river bed at the stream mouth (Tables 1, 2, and 3), is significantly less in the Sertã stream (ca. 150 m) compared with the Tamolha (ca. 280 m) and Isna (ca. 380 m) streams.

To evaluate the influence of the Sertã fault on the stream profiles, we used the normalized steepness index (k_{sn}) extracted from slope/area data (Table 4). The k_{sn} of the relict profile (reach upstream of the older tKP) and of the rejuvenated reaches were calculated separately. In the rejuvenated profile, the segments located upstream and downstream of the fault were also considered separately to compare the k_{sn} values for uplifted and subsided tectonic blocks.

The k_{sn} values of the relict profiles and of the rejuvenated profiles upstream the Sertã fault increase from the Sertã stream (flowing in a less uplifted block) to the Isna and the Tamolha streams, which flow in a relatively more uplifted block (Fig. 3). However, the k_{sn} values of the rejuvenated profiles downstream of the Sertã fault do not show a uniform variability tendency between the three streams: for the Tamolha and Isna streams, the k_{sn} values diminish in the downstream side of the Sertã fault, while for the Sertã stream it is the opposite. This stream probably does not cross the Sertã fault, which ends near the town of Sertã, SE of the stream. So, for the Sertã stream, the increase in k_{sn} value of the reach downstream of Sertã should be related to an incision wave rejuvenation triggered from the Zêzere River. For the Isna and Tamolha streams, routed by an antecedence process through the southeastern uplifted block of the Sertã fault, the incision wave has been counterbalanced by the uplift forming a reduced channel gradient ($k_{sn} = 31$). This reduction seems consistent with some vertical component in this right lateral slip fault, whose strike-slip component is well expressed by a significant (ca. 2 km) dextral stream channel offset.

4.2. Streams flowing from the Portuguese Central Range to the South Portugal Planation Surface

The streams of this group (Tripeiro, Mangueija, Alvito, Fórneas, Froia, Sarzedinhas, and Freixiada) are tributaries of the Ocreza River that cross

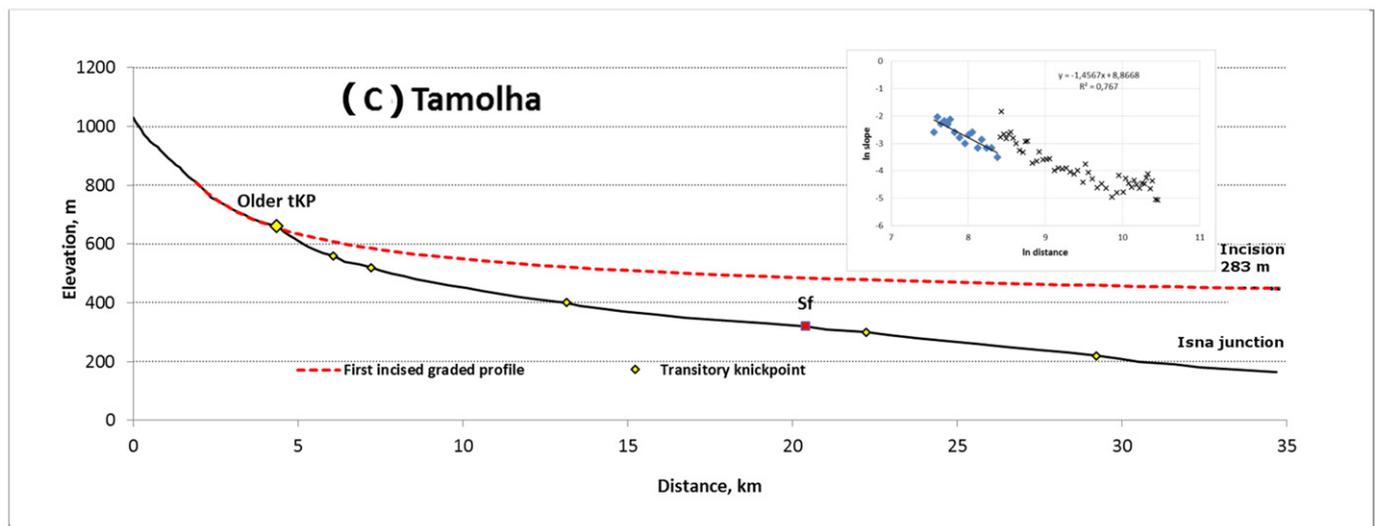
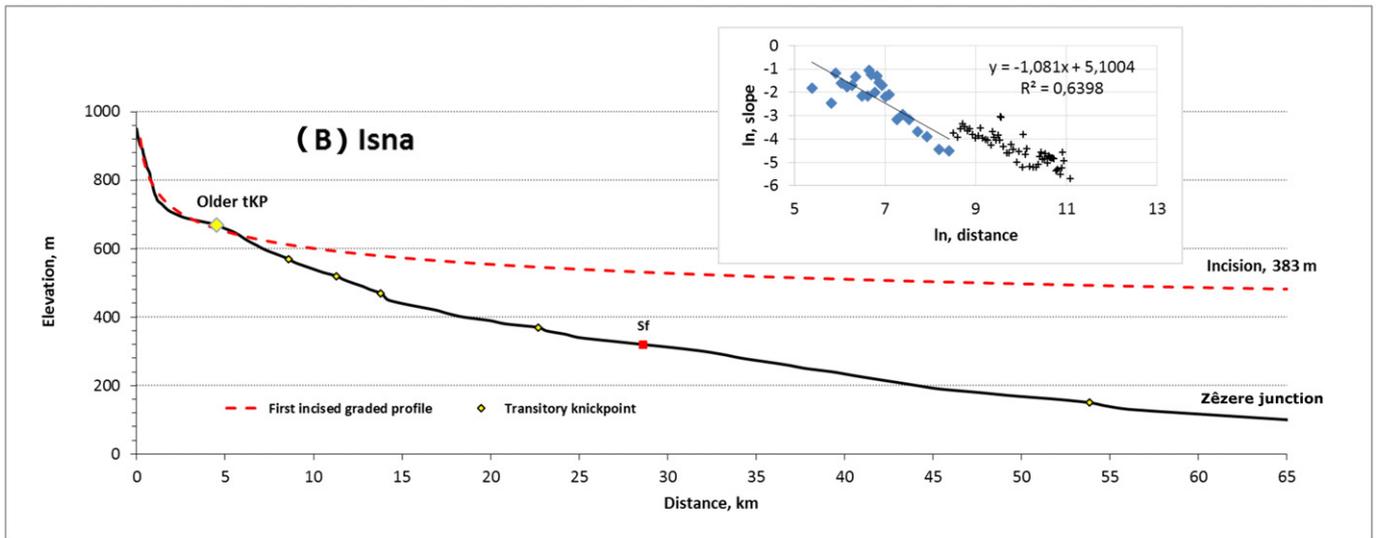
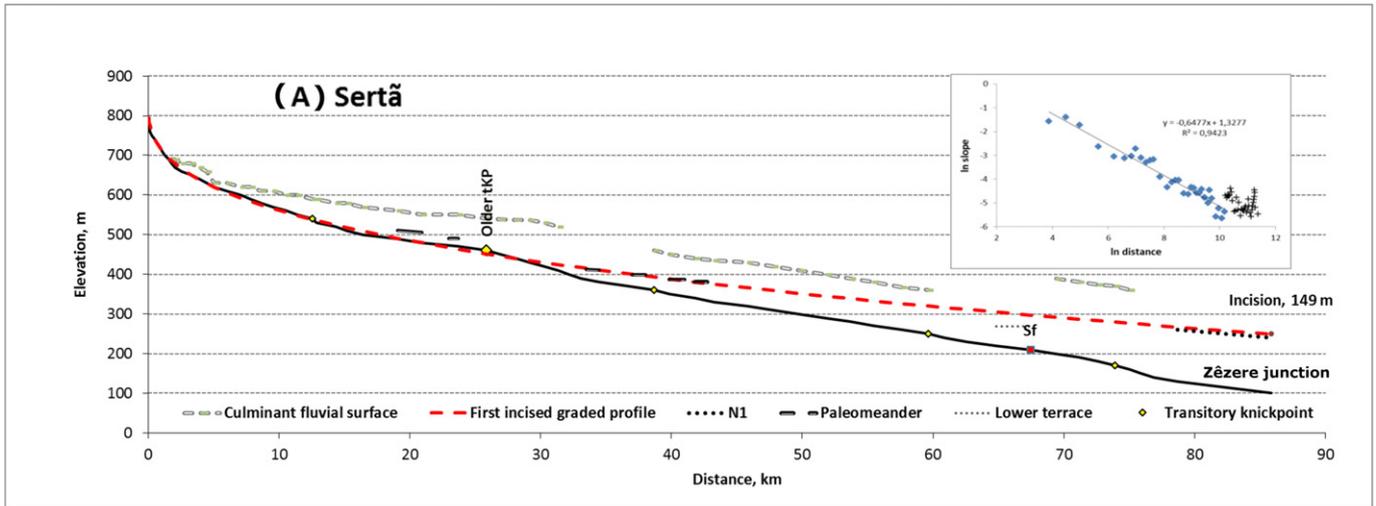


Fig. 4. Long profiles of the Sertã (A), Isna (B), and Tamolha (C) streams. In the inset distance–slope plots, fill lozenges correspond to the relict graded profile, while crosses correspond to the rejuvenated profile located downstream of the older transitory knickpoint (tKP). The red squares indicate the position of the Sertã fault.

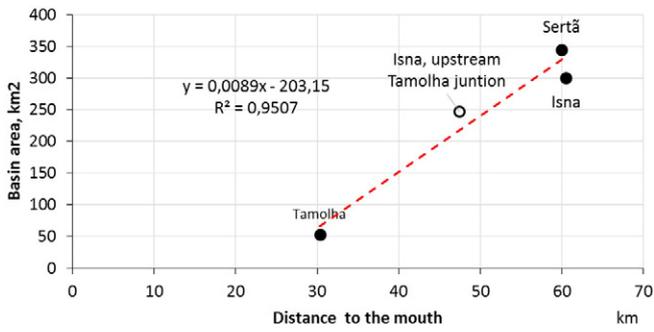


Fig. 5. Distance traveled by older transitory knickpoint from the mouth versus the drainage area for the Sertã, Isna, and Tamolha streams.

the Sobreira Formosa fault (Sff) along the SE side of the PCR (Figs. 2 and 6). In this sector the tributary drainage flows on Neoproterozoic to Cambrian phyllites, slates, and metagreywackes, except for the Ocreza River which crosses an area of granite in its upstream part and metasedimentary rocks in the downstream rejuvenated reach. The Ocreza River will be included in the fluvial system that runs on the SPPS because it flows mostly on the planation surface.

For the streams of this group, the reach upstream of the Sff is characterized by a smooth concave-up shape located headward of an older tKP, while downstream occur several scattered transitory vertical step-knickpoints (Figs. 7 and 8). This upper section is generally very short, <10% of the total channel length and, although poorly preserved, it has been considered as a remnant of an upper graded reach. Thus, after subtracting the hillslope/colluvial reach in the upstream limit of the streams, the contributing area upstream of the older tKP approaches the critical area (A_{crit}) below which the knickpoint cannot propagate farther upstream. The critical area falls in a range of 0.1–5 km² (Montgomery and Foufoula-Georgiou, 1993; Wobus et al., 2006; Kirby and Whipple, 2012).

The area upstream of the older tKP is 8.8 km² for the Alvito stream and is even smaller for several of the other streams. The migrating incision waves are therefore close to the upper limit of their upstream propagation, and the relict profile is almost nonexistent. Owing to the short length of the relict profile, its reconstruction down to the stream mouth is problematic, and the amount of the incision is undetermined in several cases or uncertain in the others (Figs. 7 and 8; Table 2).

For these streams, the k_{sn} value of the remnant relict graded reach compared to the k_{sn} values of the downstream rejuvenated reaches are similar for the Alvito stream, slightly lower for the Sarzedinha and Fórneas streams, and higher for the other streams of this group (Fróia and Mangueja). The Fróia (Fig. 7B) and the Tripeiro (Fig. 9B) streams flow in a less resistant metamorphic basement, but the Ocreza River flows largely in the hard granite basement (Figs. 2 and 6).

For all of the streams of this group, the k_{sn} value systematically increases in reaches upstream of the Sff, compared to those on the downstream side of the fault, which flow on the mountain piedmont. This spatial variability of k_{sn} values may indicate some continued uplift of the PCR, explaining the set of transitory knickpoints in the reaches located between the Sff and the older tKP. In fact, the long profile

Table 1
Topographic characteristics of streams flowing in the Portuguese Central Range.

Stream	H_0	H_i	H_f	k	λ	Incision
Sertã	836	780	460	3.77	0.64	149 ± 5
Isna	–132	900	670	166.9	1.10	383 ± 12
Tamolha	317	810	660	7093	1.45	283 ± 2

H_0 is an estimate of the theoretical elevation of the divide, if hydraulic processes were active right to the drainage head, corresponding to the necessary adjustment (up or down) in order to obtain the best fit of the idealized curve to the real profile; H_i and H_f are the altitudes in the edge of the analyzed stream reach, k and λ are constants reflecting the steepness and curve concavity; incision values are in meters (see Goldrick and Bishop, 2007).

Table 2

Topographic characteristics of streams flowing from the Portuguese Central Range to the South Portugal Planation Surface.

Stream	H_0	H_i	H_f	k	λ	Incision at junction
Alvito	1016	700	420	19.30	0.771	undetermined
Fórneas	235	700	440	3463	1.448	175 ± 11
Fróia	2143	850	540	77.59	0.886	undetermined
Sarzedinha	1268	720	400	31.56	0.799	96 ± 5
Mangueja	450	710	550	17,161	1.778	261 ± 16
Tripeiro	20	640	260	1837	1.314	34 ± 28

H_0 is an estimate of the theoretical elevation of the divide if hydraulic processes were active right to the drainage head; H_i and H_f are the altitudes in the edge of the analyzed stream reach, k and λ are constants reflecting the steepness and curve concavity; incision values are in meters.

morphology of the reaches located upstream of the Sff suggests an upstream propagating adjustment with a permanent increase of channel steepness, inherent to an increasing rock uplift rate of the PCR relatively to the piedmont area and adjacent SPPS. The extensive changes in channel gradient of segments between the older tKP and the Sff suggest a slope-break knickpoint morphology (Kirby and Whipple, 2012; Whipple et al., 2013), separating channel reaches with different channel steepness related to differential uplift between the PCR and the piedmont area/adjacent SPPS. In the study area this is most probably accommodated by tectonic activity of the Sff.

4.3. South Portugal Planation Surface streams

The streams of this group flow on basement rocks of the SPPS at an altitude of 300–400 m (Fig. 2). Three main tributaries of the Tagus River (the Ponsul, Ocreza, and Sever rivers) were analyzed, together with other lower order tributaries. The Ponsul River crosses the Ponsul fault (Pf), flowing in its upstream reach on granites and metasediments of the northern uplifted block of the fault (at 400–450 m) and on the Cenozoic deposits at Ródão - Idanha a Nova (at ca. 200 m) in its lower reach downstream of the fault. The Ocreza River flows mostly on the Precambrian to Palaeozoic basement of the crustal block located between the Sff, at the north, and the Pf, at the south, crossing granites in the upstream part and metasediments in the lower reach (Figs. 2 and 6). The Sever River flows mostly on Precambrian to Palaeozoic metasediments but also on granite and quartzites in the upstream part (Fig. 2).

As for the previously described streams, those that flow on the SPPS display an upstream relict graded profile and a rejuvenated lower reach, separated by a pronounced slope-break knickpoint (older tKP). For the Ocreza River (Figs. 6 and 9A), the relict profile corresponds to the reach between the point situated at an altitude of 650 m (ca. 4 km from the divide), above which the DS plot lacks linearity, and the point situated at 380 m, ca. 16 km from the divide. Downstream, in the rejuvenated profile, the river crosses a resistant quartzite ridge at Portas do Almourão, where it forms a deeply incised gorge (Figs. 2 and 6).

Table 3

Topographic characteristics of streams flowing in the South Portugal Planation Surface (the parameters on the first row are the same as those of the Tables 1 and 2).

Stream	H_0	H_i	H_f	k	λ	Incision
Ocreza	240	630	300	3,612,822	2.057	214 ± 23
Sever	699	600	490	1.512	0.563	199 ± 2
Alpreade/Ponsul	5240	600	330	60.91	0.985	153 ± 12
Nisa	89	600	390	693	1.244	209 ± 8
Figueiró	378	340	310	1.376	0.685	221 ± 3
Freixiada	761	560	410	15.47	0.855	137 ± 11
Pracana	806	430	210	21.52	0.918	116 ± 3
Canas	844	300	220	24.55	0.933	110 ± 3
Alpalhão	362	330	290	1.44	0.580	159 ± 3

Table 4
Normalized steepness index (k_{sn}) of the studied streams.

Stream	$A_{min.}$ (m ²)	$A_{max.}$ (m ²)	θ	k_{sn} ($\theta = 0.45$)	Reach
Sertã	1.91E+04	1.03E+08	0.46	26	First graded incised profile
	1.03E+08	2.91E+08	0.82	33	Rejuvenated profile upstream fault, at 450–210 m a.s.l.
	2.91E+08	3.45E+08	–0.87 convex reach	46	Rejuvenated profile downstream fault, at 210–100 m a.s.l.
Isna	1.82E+04	9.86E+06	0.48	31	First graded incised profile
	9.86E+06	7.58E+07	0.54	40	Rejuvenated profile upstream fault
	7.58E+07	3.05E+08	0.27	31	Rejuvenated profile downstream fault
Tamolha	9.64E+05	3.87E+06	0.77	50	First graded incised profile
	3.87E+06	3.45E+07	1.02	55	Rejuvenated profile upstream fault
	3.45E+07	5.25E+07	0.46	31	Rejuvenated profile downstream fault
Alvito	5.66E+05	8.86E+06	0.60	42	First graded incised profile
	8.86E+06	6.21E+07	0.61	43	Rejuvenated profile upstream fault
	6.21E+07	1.87E+08	0.04 convex reach	24	Rejuvenated profile downstream fault
Fórneas	5.55E+02	6.38E+06	0.43	50	First graded incised profile
	6.38E+06	2.61E+07	0.19	59	Rejuvenated profile upstream fault
	2.61E+07	8.06E+07	0.60	24	Rejuvenated profile downstream fault
Fróia	5.08E+04	1.12E+06	0.57	67	First graded incised profile
	1.12E+06	1.25E+07	0.65	52	Rejuvenated profile upstream fault
	1.25E+07	5.65E+07	0.60	35	Rejuvenated profile downstream fault
Sarzedinha	1.95E+04	3.26E+06	0.40	35	First graded incised profile
	3.26E+06	2.31E+07	0.82	49	Rejuvenated profile upstream fault
	2.31E+07	6.01E+07	0.32	27	Rejuvenated profile downstream fault
Mangueja	6.34E+03	2.54E+06	0.43	41	First graded incised profile
	2.54E+06	5.03E+07	0.58	37	Rejuvenated profile upstream fault
	5.03E+07	1.44E+08	0.35	21	Rejuvenated profile downstream fault
Tripeiro	3.83E+03	6.79E+07	0.56	41	First graded incised profile
	1.39E+05	6.79E+07	0.74	102	First graded incised profile downstream 730 m a.s.l.
	6.79E+07	3.49E+08	0.45	24	First graded incised profile downstream fault
Ocreza	1.88E+04	1.81E+07	0.49	44	First graded incised profile upstream fault
	4.00E+05	1.81E+07	0.64	138	First graded incised profile upstream fault, reach at 1000–390 m a.s.l.
	1.81E+07	1.75E+08	0.66	33	First graded incised profile downstream fault
	1.75E+08	1.99E+08	–4.7 convex reach	72	Rejuvenated profile on granite
	1.99E+08	1.44E+09	0.54	46	Rejuvenated profile on schist
	2.00E+08	7.90E+08	0.84	35	Rejuvenated profile on schist upstream Almourão gorge
Nisa	9.79E+08	1.44E+09	–1.8 convex reach	46	Rejuvenated profile on schist downstream Almourão gorge
	4.80E+05	4.43E+07	0.84	33	First graded incised profile
	4.43E+07	1.67E+08	0.74	33	Rejuvenated profile upstream rKP
Ponsul	1.67E+08	2.65E+08	–3.3 convex reach	81	Rejuvenated profile downstream rKP
	1.89E+04	1.05E+07	0.33	15	First graded incised profile
	1.05E+07	1.94E+08	0.57	55	Rejuvenated profile upstream fault
Alpreade	2.59E+08	1.33E+09	0.56	25	Rejuvenated profile downstream fault
	1.37E+04	9.30E+07	0.50	30	First graded incised profile
Pracana	1.04E+08	5.56E+08	0.0 straight reach	48	Rejuvenated profile
	5.16E+03	7.97E+07	0.50	20	First graded incised profile
	8.90E+07	1.99E+08	–0.55 convex reach	36	Rejuvenated profile
Sever	nc	nc	–	–	–
Figueiró	nc	nc	–	–	–
Canas	1.32E+05	3.18E+06	0.60	19	First graded incised profile
	4.43E+06	1.77E+07	0.90	21	Rejuvenated profile upstream rKP
	4.43E+06	4.36E+07	–0.15 convex reach	39	All rejuvenated profile
Alpalhão	3.47E+03	8.39E+05	0.36	8	First graded incised profile
	1.24E+06	9.36E+06	0.76	25	Rejuvenated profile upstream 160 m
	9.36E+06	9.36E+06	–4.7 convex reach	64	Rejuvenated profile downstream 160 m a.s.l.

A reference concavity of 0.45 was used. $A_{min.}$ and $A_{max.}$ correspond to the areas that bound the analyzed stream segments, θ corresponds to concavity indices expressed in the power law function between slope and the contributing drainage area (Eq. (4)).

The best fit projection of the relict profile was difficult to obtain for the Ocreza River owing to the fact that it presents a sharp vertical step knickpoint associated to the Sff, ca. 9 km from the divide (Fig. 9A). This vertical step knickpoint has a convex shape with an abrupt slope break downstream (0.05 gradient between elevations of 410 and 390 m). This shape contrasts with the concave up profile of the streams flowing through metasedimentary rocks of the SE slope of the PCR, upstream of the Sff (Figs. 7 and 8). This seems to indicate that in the granites (where the former knickpoint is located) the rates of erosion are intensified at the face and base of the knickpoint (parallel slope retreat), while in schist the concave up shape suggests higher erosion rates near the knickpoint lip. A second oversteepened reach, located at ca. 28 km from the divide (Fig. 9A), corresponds to an old transitory knickpoint that marks the upstream limit of the regional incision wave

propagation. Another fixed knickpoint occurs at 63 km from the divide and is related to the crossing of the resistant quartzite ridge at Portas do Almourão gorge (permanent knickpoint). In spite of the difficulty in obtaining the best fit projection of the relict profile, incision quantification indicates 129 m at the Almourão gorge and 214 m at the confluence with the Tagus River.

The Sff segmented the relict profile of the Ocreza River in two reaches with different steepness. The k_{sn} index of the relict profile upstream of the fault ($k_{sn} = 138$, between 650 and 390 m) is significantly higher than the k_{sn} index of the relict profile downstream of the Sff ($k_{sn} = 33$). In the rejuvenated profile, the channel steepness increases in the granite basement ($k_{sn} = 72$) compared to the channel steepness of the river in slates and metagreywackes ($k_{sn} = 46$). The older tKP is on top of the rejuvenated profile, and the related downstream knickzone is

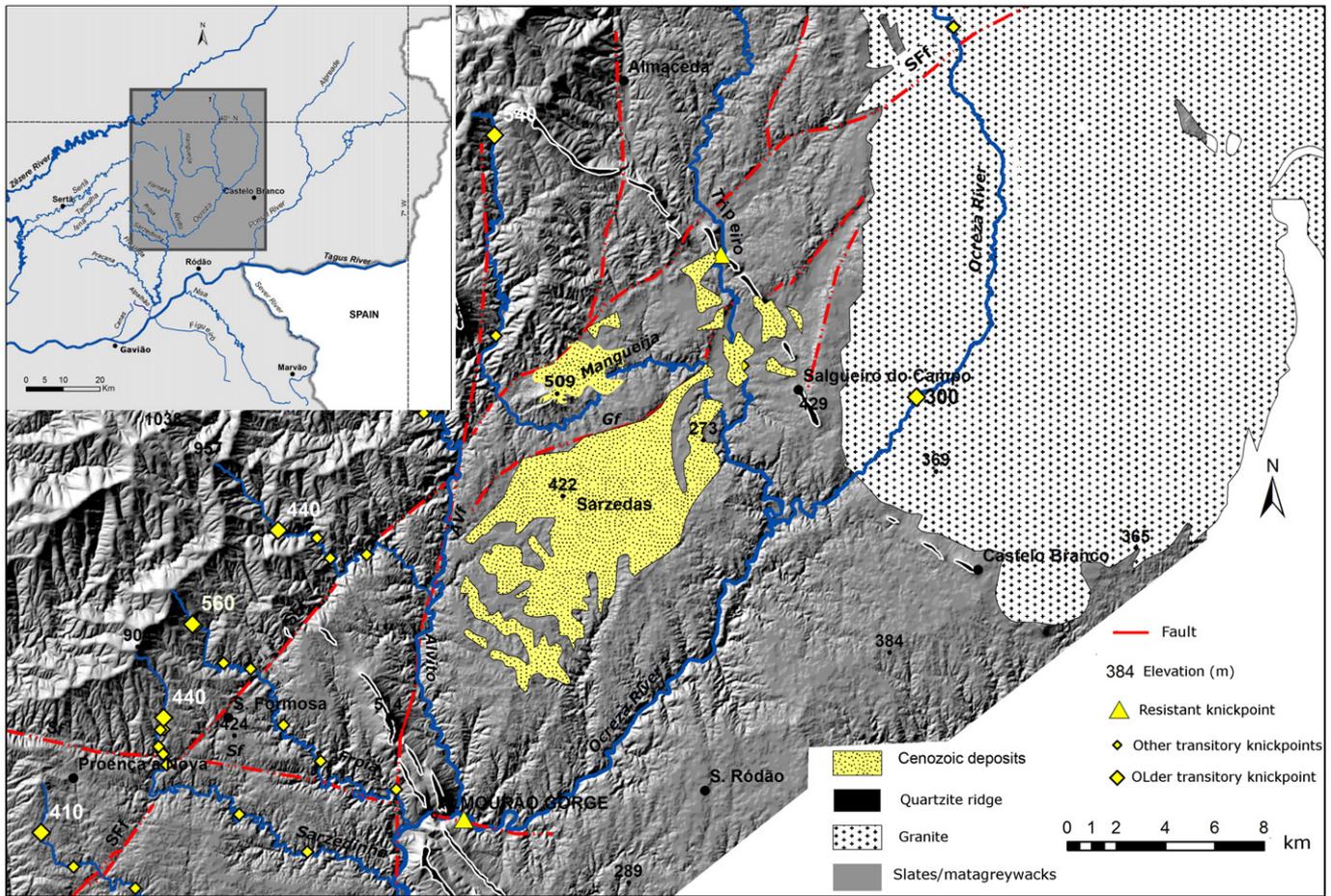


Fig. 6. Geologic map of the SE slope of the PCR and the SPPS extending southeastward from its piedmont, beyond the NE-SW Sobreira Formosa fault (SFF; for location of the streams, see Fig. 2). The areas consisting of slates and metagreywacks are represented in grey (hillshade). Remains of the Cenozoic sedimentary cover of the SPPS are only preserved in the Sarzedas tectonic depression. The numbers near the larger lozenges indicate the altitude of the older transitory knickpoints. Resistant (permanent) knickpoints are associated with the crossing of the Almourão quartzite ridge by the Ocreza River and with the crossing of the Salgueiro do Campo quartzite ridge by the Tripeiro stream. In the Ocreza River, the lozenge located immediately upstream of the SFF is interpreted as a transitory knickpoint with tectonic origin.

located near the contact between slates/metagreywacks and granite. This knickzone is, in some way, anchored to the lithological contact, considering the extension of the granite batholith. Upstream of the Almourão gorge at the quartzite ridge, the channel steepness is slightly lower ($k_{sn} = 35$) than the steepness of the reach downstream of the gorge ($k_{sn} = 46$; Table 4), suggesting that erosion waves migrating from the river mouth are pinned to the quartzite ridge, generating a fixed vertical step knickpoint.

The Ponsul River reveals several knickpoints, but the older tKP was difficult to identify because of the construction of a dam. In these circumstances, we used a tributary of the Ponsul River (the Alpreade stream; Figs. 2 and 10A) to calculate the fluvial incision. The Ponsul River crosses the Ponsul fault (Pf; Fig. 2), upstream of which occurs a knickzone with vertical step knickpoints at the contact between the slates/metagreywacks and granite. The downstream limit of the knickzone coincides with the transition from the soft Cenozoic deposits in the downthrown side of the Pf to the harder basement rocks in the upthrown side of the Pf. A vertical incision of ca. 150 m was estimated for the Alpreade/Ponsul system at the confluence with the Tagus River (Table 3).

The Figueiró, the Nisa, and the Sever streams flow toward the NW because they are located in a block tilted to the NW (the downthrown side of the Pf; Fig. 2), and this justifies the similarities in long profile shape and high incision quantification (ca. 200–220 m).

In the Nisa stream (Fig. 10B), the transitory knickpoint in the upstream limit of the rejuvenation incision wave is at 10 km from the

divide (older tKP). A fixed vertical step knickpoint (rKP) also occurs at 32 km from the divide, coinciding with a contact between slates/metagreywacks and granite. The projection of the relict profile indicates ca. 210 m of vertical incision at the confluence with the Tagus River. A similar value of incision (ca. 220 m) was obtained for the Figueiró stream, located slightly to the west (Fig. 11B).

In the Sever River (Fig. 10C), the older tKP is pinned to the resistant Ordovician quartzites, situated at 12 km from the divide. The projection of the relict graded profile gives ca. 200 m of vertical incision at the confluence with the Tagus River, a value similar to the height of the T1 terrace (ca. +190 m) above the Tagus River bed at this location (Cunha et al., 2005, 2016).

The Pracana and Canas streams are located in similar morphotectonic settings (Fig. 2). The projection of the relict older graded profile of the Pracana stream (dashed line), downstream of the old tKP, coincides with a higher level of paleomeanders; a lower paleomeander (at 150 m altitude) coincides with a more incised, graded profile reach separated from the downstream reach by a tKP (Fig. 11A). The Canas stream, in an adjacent location, also shows an older tKP and a younger tKP and a similar incision (ca. 110 m; Fig. 11C).

A set of bedrock paleomeanders occur in the Ocreza, Pracana, and Freixiada (at the Pracana junction) valleys (Fig. 12). As the long profiles of the Freixiada and Pracana streams show (Figs. 8B and 11A), the projection of these paleomeanders fit with a graded profile that is lower and therefore younger than the relict graded profile preserved upstream of the older tKP. The occurrence of distinct graded reaches in

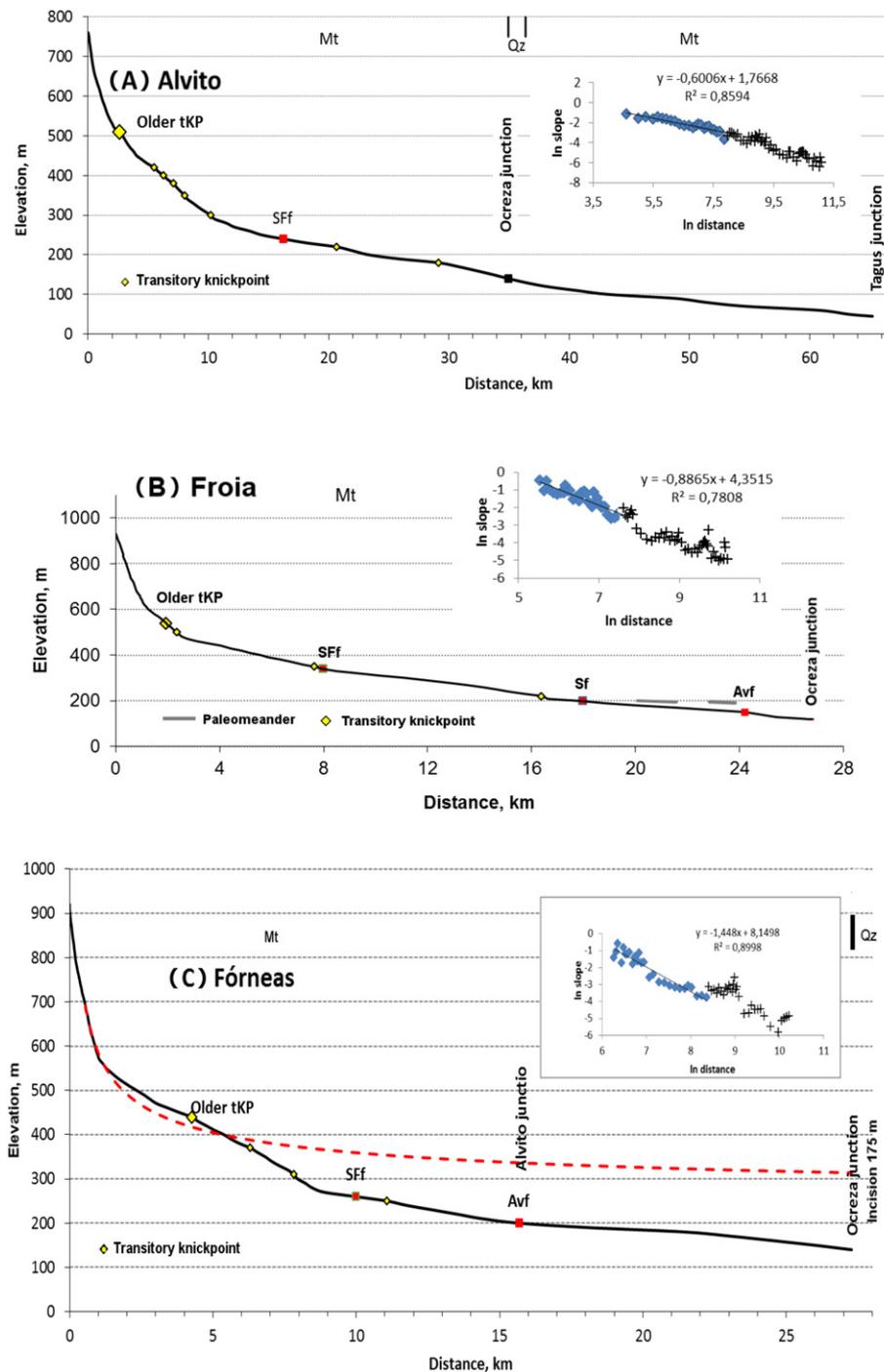


Fig. 7. Long profiles of the Alvito (A), Froia (B), and Fórneas (C) streams. In the Alvito and Froia streams the relict profile is too short to obtain a reliable fit; so the projected relict profile is not represented. In this and the following figures, the lithology of the bedrock crossed by the streams is indicated at the top of the profiles. Mt. – slates, schists, phyllites, and metagreywackes; Qz - quartzites. In the inset distance-slope plots, fill lozenges correspond to the relict graded profile, crosses correspond to the rejuvenated profile located downstream of the older transitory knickpoint (tKP).

these streams points to successive phases of dynamic equilibrium and valley enlargement during the long-term process of river incision.

With the exception of the Ocreza River, which has headwaters in mountainous regions, the other streams flowing in the SPPS have relict profiles with lower steepness ($k_{sn} < 35$) than their downstream rejuvenated profiles (Table 4). This spatial variability in channel steepness is associated with an enhancement of erosion rate in the downstream areas of the dissected landscape. It suggests a model where the drainage is responding to external forcing expressed by changes in relative base level, crustal uplift rate, and climate (Whipple et al., 2013).

5. Discussion

Despite the quite different morphostructural contexts in which the three groups of streams flow, a common pattern is discernible for the intramountainous streams and for those flowing on the SPPS. Almost all of the streams record a relict graded profile in their upstream sector and a rejuvenated reach in the downstream sector, which are separated by a spatially well-constrained break with a knickpoint on the top (older tKP). In some cases, the length of the relict profile is very short (e.g., Tamolha and Isna streams), but even in these cases it was

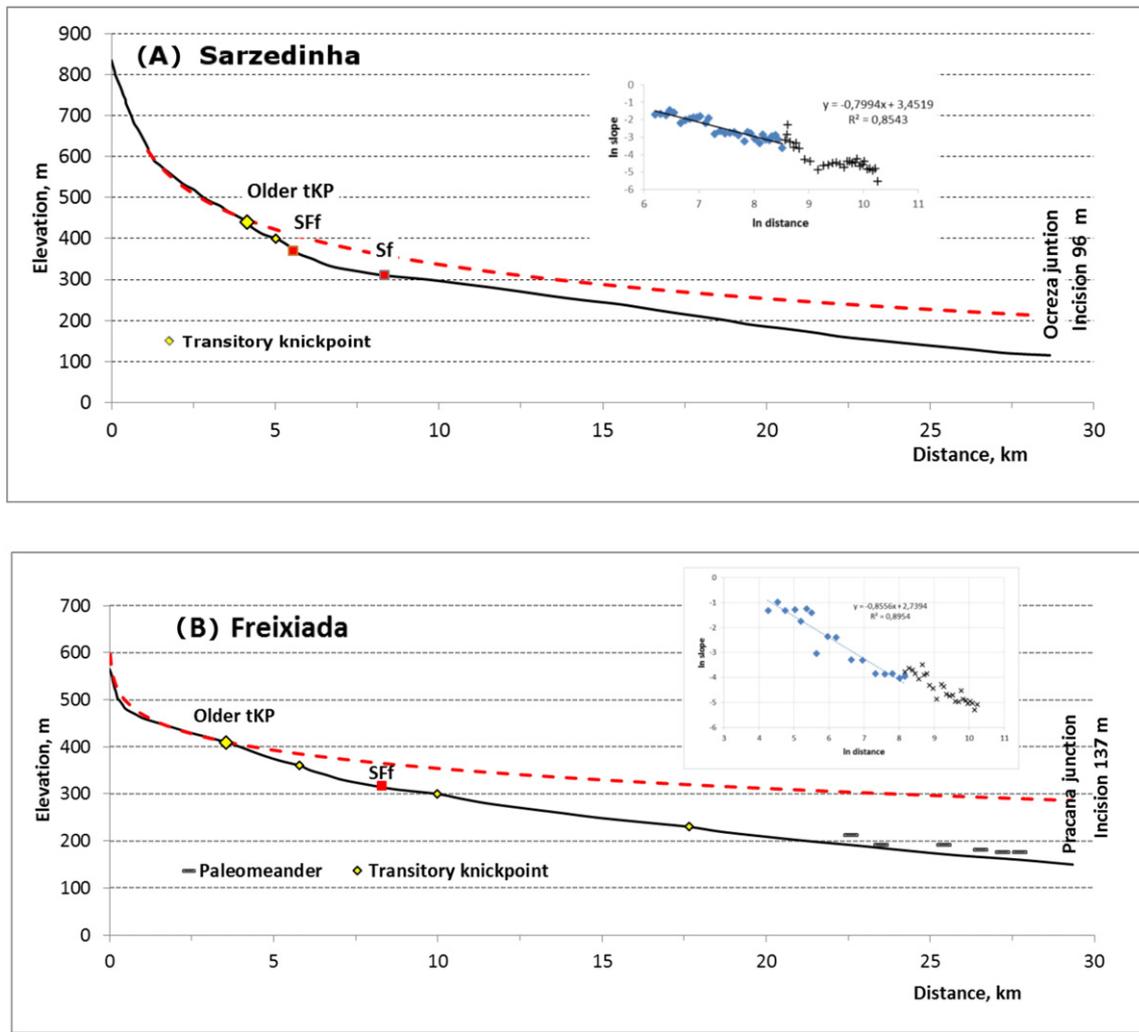


Fig. 8. Long profiles of Sarzedinha (A) and Freixiada (B) streams. The profile with paleomeanders in the Freixiada stream (dashed lines above the longitudinal modern profile), represents a relict younger graded profile (steady state) incised in the relict older graded profile preserved upstream of the older tKP. In the inset distance-slope plots, lozenges correspond to the relict graded profile, crosses correspond to the rejuvenated profile located downstream of the older transitory knickpoint (tKP).

possible to calculate a best fit curve to the equilibrium profile and to estimate the maximum incision value at the stream mouth. In turn, the streams that flow from the PCR to the adjacent SPPS reveal that the rejuvenation incision wave migrated upstream in several streams until the critical threshold drainage area, almost completely eroding the relict profile.

For the streams that still have a relict profile, this reach has a smooth concave up form corresponding to a quasi-equilibrium profile, verified by the straight line in the inset DS plots, or in the log S-log A plots. The downstream rejuvenated profiles display disordered points in the DS plots (ungraded reaches). Some segments of the rejuvenated profiles may have achieved an almost graded state upstream of knickpoints fixed in place by a resistant substrate (e.g., Ocreza River, upstream the Almourão quartzite ridge). However, while the graded reach profiles upstream of the lithologically resistant knickpoints have local significance, the relict graded profiles have a wider regional significance as they constitute a feature common to several streams in different regional contexts.

Regionally, the occurrence of the relict graded and rejuvenated profiles in the studied streams evidence a change in system conditions that had previously sustained the steady state of the relict graded profiles (Whipple et al., 2013). From that change resulted a modification in

stream erosion rate that produced a downstream long profile with steeper gradient and lower concavity, especially in the final segments that become convex in many streams. The two contrasting reaches (relict graded/rejuvenated adjusting) of a given stream are evidence of the response of the fluvial system to sustained crustal uplift superimposed onto longer term conditions of lower sea level, though also influenced by climate. While the upper reaches continued to erode at the previous steady-state erosion rate and thus maintained their original form, the rejuvenated reach is adjusting to the new base-level conditions.

The concavity index values of the relict profiles range between 0.33 and 0.84 (mean 0.53). In contrast, a considerable number of rejuvenated reaches have negative concavity indices, i.e., they are poorly described by the power law relationship between local channel gradient and the upstream drainage area. The range of concavity indices of the studied relict profiles is slightly higher than the range of the concavity indices of streams arguably in a near steady state presented in the literature, which typically range between 0.4 and 0.7 (Whipple, 2004). High concavity index values typically correspond to smooth and concave profiles, while low concavity index values are common in profiles with local concavities related to lithologic knickpoints/knickzones or in profiles subjected to adjustment owing to a persistent forcing. In the study area, high concavity index values associated with the relict profiles should

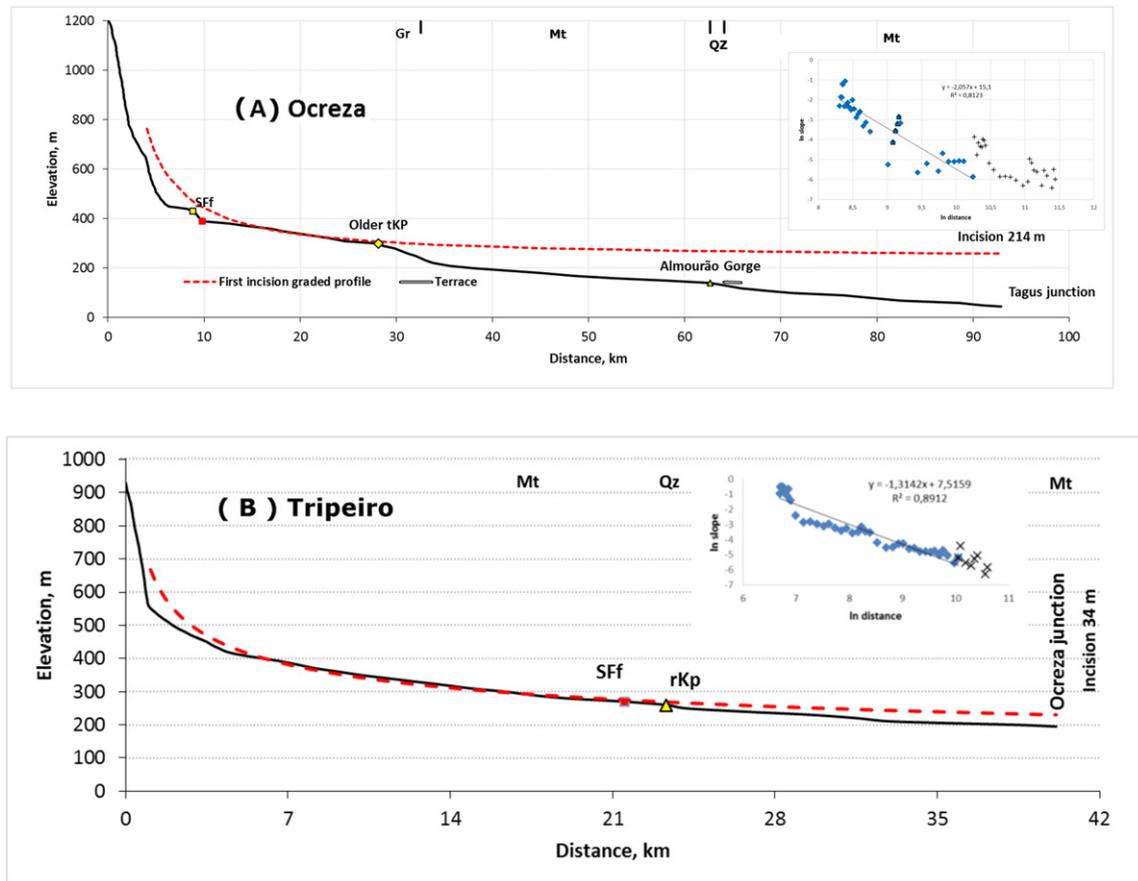


Fig. 9. Long profiles of the Ocreza (A) and Tripeiro (B) streams. The Ocreza River has three kinds of knickpoints: an upstream step related to the Sobreira Formosa fault (Sff); a transitory knickpoint in the intermediate part of the profile, and a resistant knickpoint in the Almourão Gorge. The Tripeiro stream has the confluence immediately downstream of the older tKp in the Ocreza River, and this explains the fact that its relict graded profile almost fits the present river profile.

be regarded as representative of a steady state graded profile, generally resulting from a long-lived evolutionary phase in which the rivers were adjusted to a regional base level higher than the current one.

The rejuvenated profiles display a higher k_{sn} index (Table 4; Fig. 13A, B, C), related to an abrupt change in the surrounding relief topography when compared to the landscape associated with the upstream relict graded profiles. This adjustment affects all streams and has regional significance, as it is also characteristic of other fluvial systems of mainland Portugal and the Spanish border regions (e.g., Antón et al., 2012, 2014). The period of adjustment between the initial disturbance and the final steady state is usually long, 10^4 to 10^6 years (Whipple and Tucker, 1999; Whipple, 2001; Baldwin et al., 2003).

Channel reaches with different channel steepness are readily recognized in the three maps of Fig. 13. Some reaches represent local increases in channel gradient (vertical-step knickpoints), others represent a persistent, longitudinal extensive change in channel gradient (slope-break knickpoints). From the maps (Fig. 13), the key points are: (i) the low values of k_{sn} (classes 1 and 2) are upstream of the older transitory knickpoint, associated with the first incised graded profile, especially when this is longitudinally extensive; (ii) the low values of k_{sn} are in stream reaches controlled by fault lines (i.e., reaches of Tamolha and Isna streams over the Sf, Fig. 13A; Forneas, Sarzedinha, and Alvito over the Sff and Avf, Fig. 13B); (iii) low values of k_{sn} are on stream reaches flowing in a tectonic sedimentary basin (i.e., Mangueja, Tripeiro, and Ponsul rivers, Fig. 13B); and (iv) the abrupt increases in channel gradient occur over the quartzite ridges, at the slates-metagreywakes/granite contact, or at the crossing of the Sff (Fig. 13B and C).

Tectonic forcing with increases in uplift rate produces a higher efficiency in fluvial incision (Whipple, 2001). The higher normalized

steepness index of the rejuvenated profiles associated with the dissected landscape and relief increase, compared with those of the relict profiles (Table 4), is considered to relate to a disturbance of the equilibrium relict profiles, forced by an intensification of the regional uplift during the Quaternary. A coeval adjustment of the drainage to a long-term eustatic sea level lower than that to which the relict profiles were adjusted could also be considered as an additional forcing mechanism.

In spite of the large uncertainties involved, projection of the relict profiles down to the stream mouth provides quite distinct incision values for the different streams. In this discussion we do not consider the streams located at the SE slope of the PCR because for most of these streams the maximum incision could not be calculated (Table 2) for reasons already outlined. It is important to note that the preserved remnants of the relict graded reaches, located headward of the older transitory knickpoints (older tKPs), continued to lower until the present, though at a very small rate owing to their quasi-steady state (Kirby and Whipple, 2012). The rejuvenation of incision inferred by projecting the relict profiles until the stream mouth is thus smaller than it was originally because some lowering of the relict long profiles has occurred since they were developed, hence leading to an underestimation of the regional uplift.

In the Ródão area (Fig. 2), located on the SPPS, an incision can be calculated for the Tagus River using as reference the oldest terrace (T1) at 114 to 180 m elevation above the river bed, which records the first aggradation episode in the incision stage, giving an incision rate of 0.13 to 0.20 mm/y. For the studied streams located on the SPPS, the projection of the relict profiles reveals values of incision of ca. 200 m (Ocreza, Sever, Nisa, and Figueiró). However, there are three exceptions: the Alprede/Ponsul streams (ca. 150 m), the Canas stream (ca. 110 m), and the Pracana stream (ca. 120 m). One explanation is that they flow

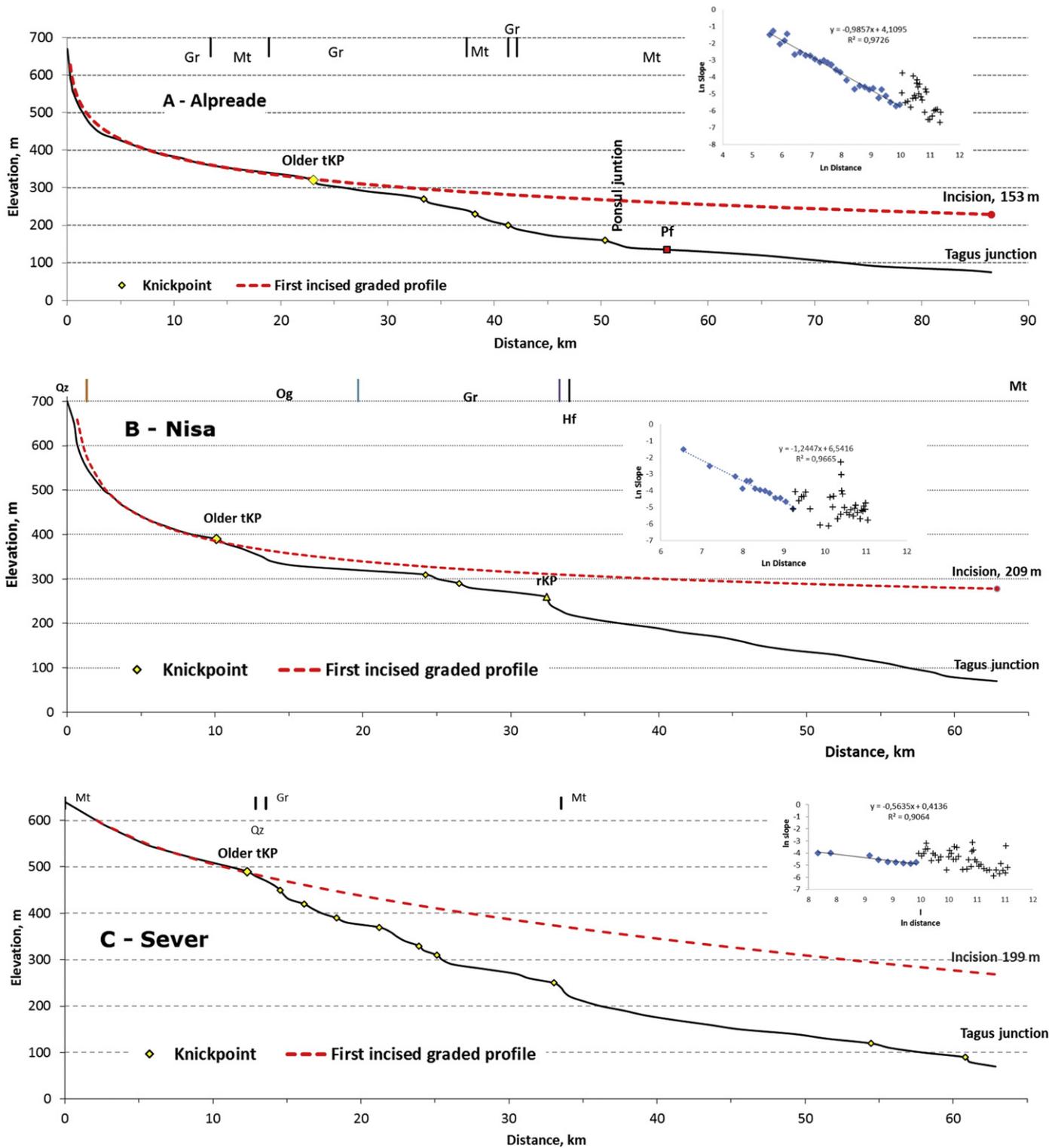


Fig. 10. Long profiles of the Alpreade/Ponsul streams (A), Nisa stream (B), and Sever River (C). Pf - Ponsul fault; rKP - resistant knickpoint; tKP - transitory KP. Mt. – Slates and metagreywackes, Gr - granite; Hf - hornfels; Og - orthogneisses. In the inset distance–slope plots, fill lozenges correspond to the relict graded profile, crosses correspond to the rejuvenated profile located downstream of the older transitory knickpoint (tKP).

in less uplifted areas (Daveau, 1985; Martins, 1999). The incision values of streams flowing in the PCR (Sertã, ca. 150 m; Tamolha, ca. 280 m; Isna, ca. 380 m) should not be directly compared with the incision of the streams located on the SPSS because the downstream projections used different trunk rivers: the Zêzere and Tagus, respectively. However, for the same group, the values of incision are higher in the streams flowing through the more uplifted areas, as would be expected.

Despite the absence of geochronological data that could directly date the relict graded profiles studied here, they can be correlated with other geomorphic references documented in the region. The culminant fluvial surface found in the headwaters of the Sertã stream (Fig. 3) and along the Tagus River is coeval with the surface of the culminant sedimentary unit of the Lower Tagus Cenozoic basin, represented by the Falagueira Formation, considered to record the drainage during the Piacenzian to

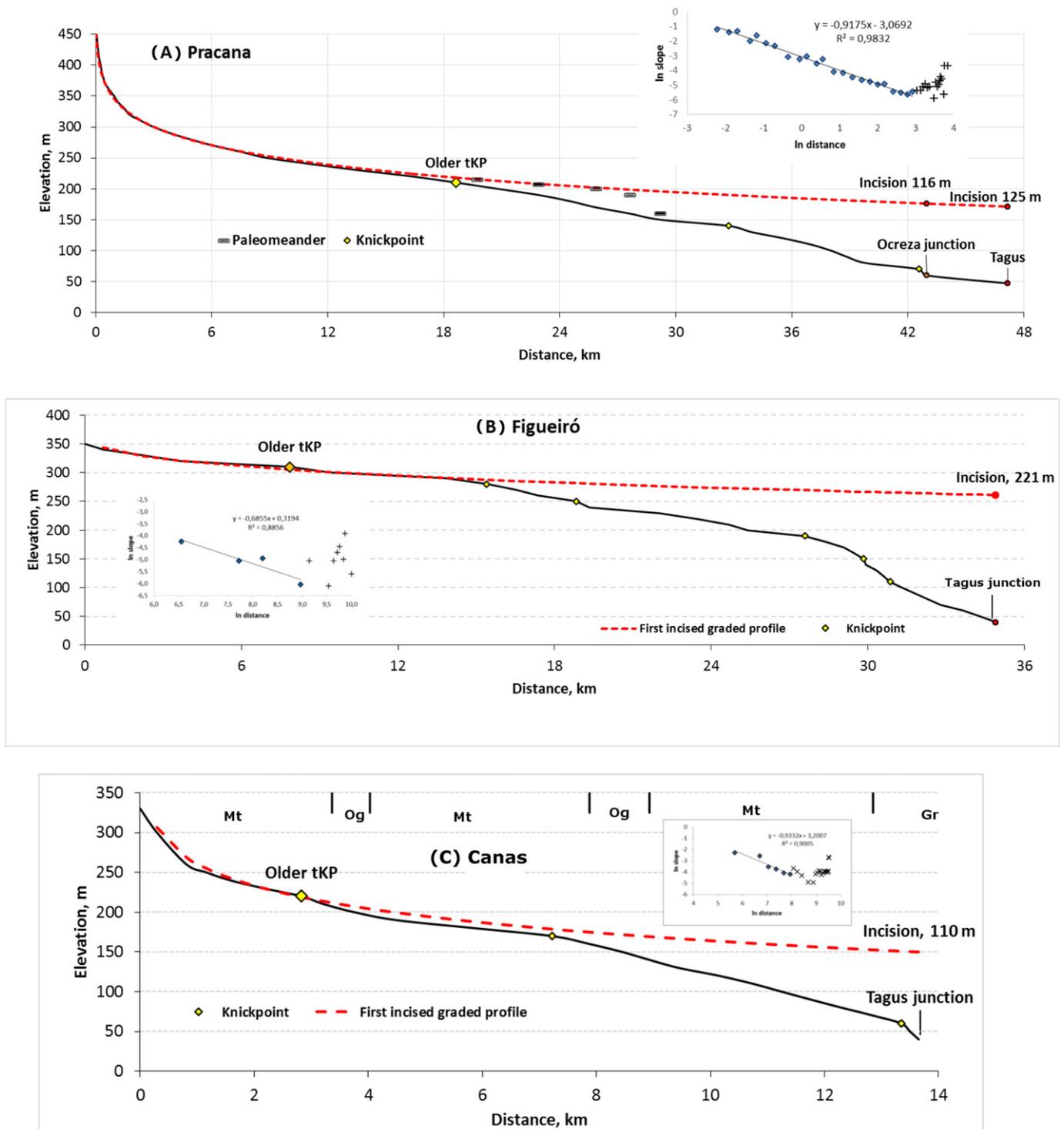


Fig. 11. Long profiles of the Pracana (A), Figueiró (B), and Canas (C) streams.

Gelasian time, ca. 3.6 to 1.8 My (Cunha, 1992, 1996; Cunha et al., 1993, 2009, 2012, 2016; Pais et al., 2012).

The first relict incised graded profile, which is incised into the previous relict culminant fluvial surface, should correlate with the oldest terrace level (T1) of the Tagus and Zêzere rivers, estimated to have an age of ca. 1.1–0.9 My by ESR and OSL dating of the terrace staircase (Cunha et al., 2012, 2016; Rosina et al., 2014; Martins et al., 2010a, 2010b, 2015). This terrace level is largely developed in the Lower Tagus valley area and headward, indicating that it corresponds to a long period of base-level

stability, thus providing the necessary conditions for the development of graded profiles along the tributary rivers. The T1 terrace is positioned at 114 to 180 m above the present Tagus River bed (a.r.b.) in the Ródão depression (Fig. 2). Near the Spanish border, the T1 terrace of the Tagus River is at ca. 190 m a.r.b., where the Sever River has a similar maximum incision value (Fig. 10C; ca. 200 m). Furthermore, the projected relict profiles of the Figueiró, Nisa, and Freixiada streams and of the Ocreza River have approximately the same elevation above the Tagus River bed, also supporting the proposed correlation.

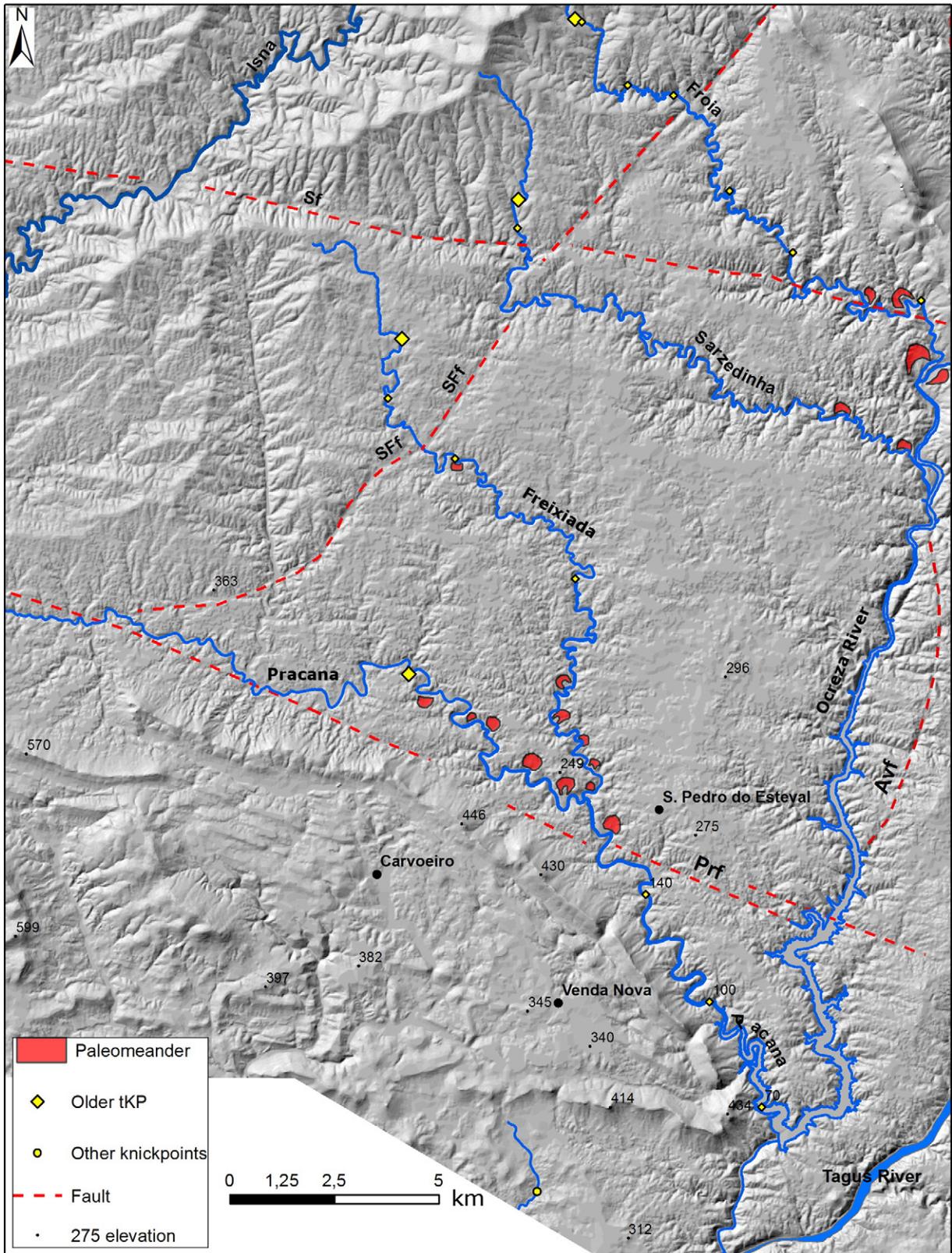


Fig. 12. Palaeomeanders in the Froia and Sarzedinha streams (at the Ocreza River confluence) and in the Pracana stream. All these paleomeanders are related to a second quasi-steady-state river profile, inset in the older first incised graded profile. The palaeomeanders developed in a depressed area located north of the quartzite ridge of Carvoeiro-Venda Nova, dominated by slates/metagreywackes, and delimited by the Sobreira Formosa fault (SFf), Pracana fault (Prf), Alvito fault (Avf), and Sertã fault (Sf).

By assuming that the relict profiles correlate with the T1 terrace of the Tagus River (ca. 1.1–0.9 My), the following average incision rates can be estimated: (i) 0.38 m/ky (380 m/1 My) to 0.15 m/ky (150 m/

1 My), for the studied streams located in sectors of the PCR; (ii) 0.22 m/ky (220 m/1 My) to 0.12 m/ky (120 m/1 My), for the streams flowing on the SPPS.

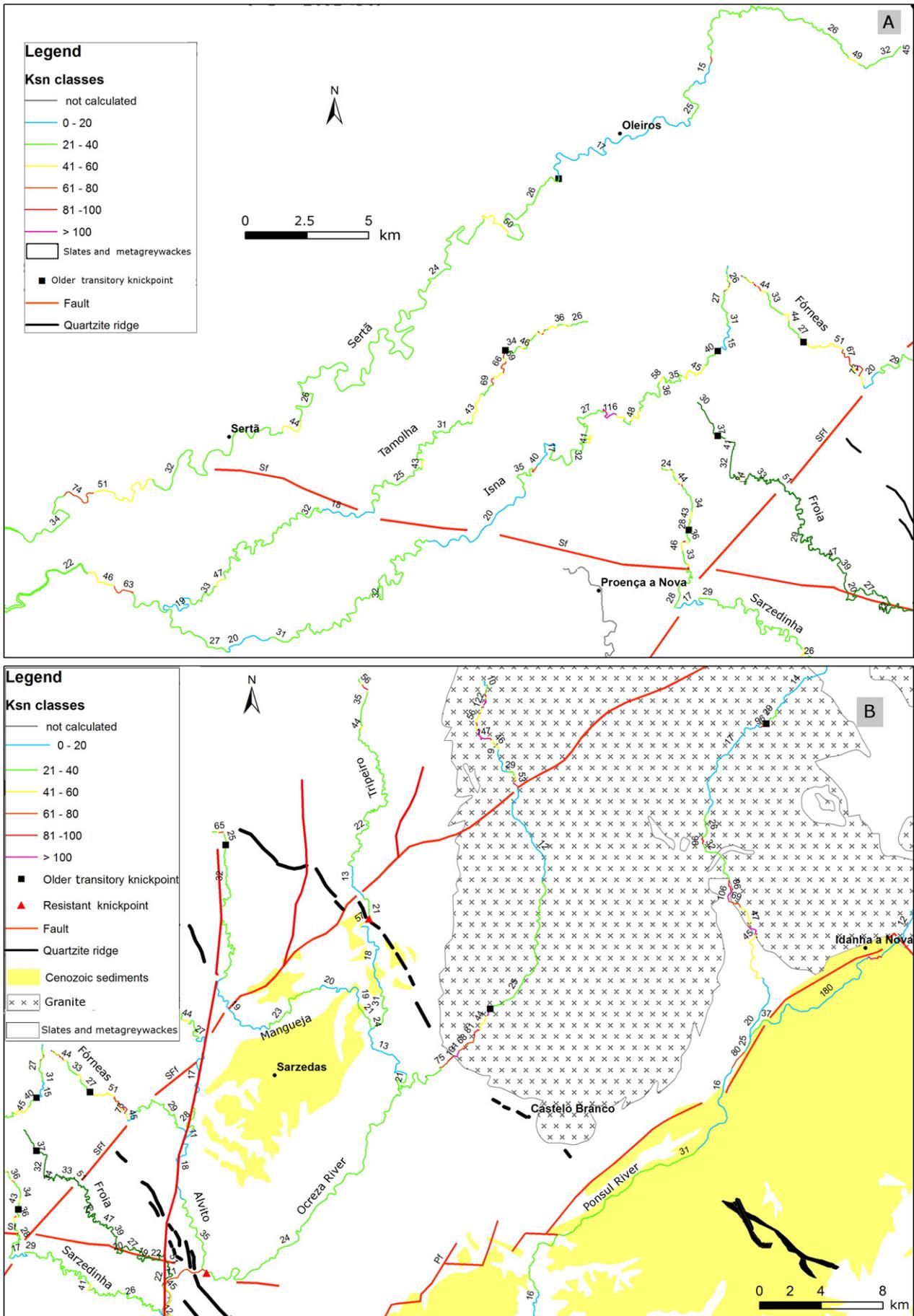


Fig. 13. k_{STI} classes for the studied streams. (A) NW sector of the study area; (B) NE sector of the study area; (C) SW sector of the study area.

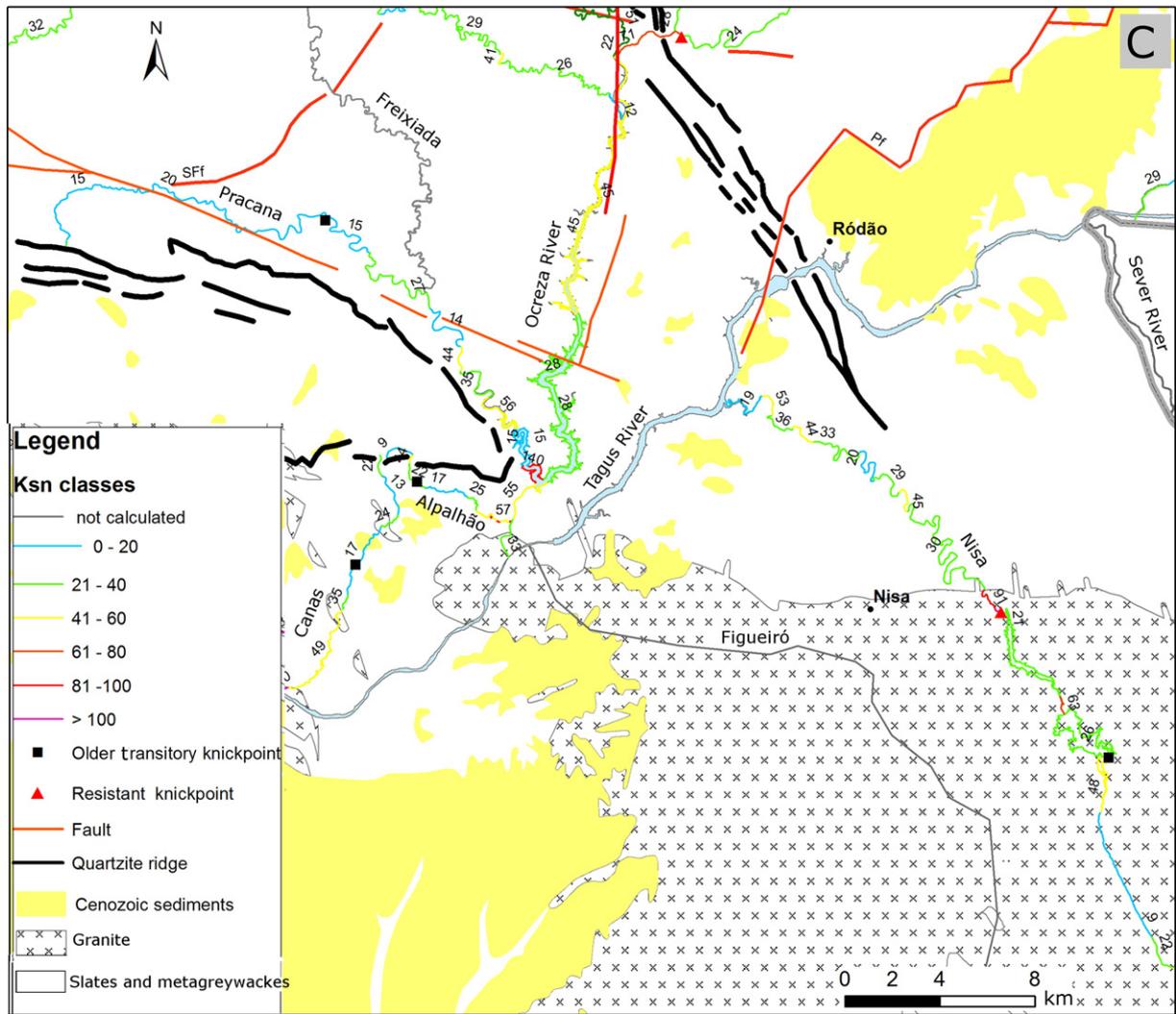


Fig. 13 (continued).

6. Conclusions

In central eastern Portugal mainland, the long profiles of tributaries of the Tagus and Zêzere rivers recorded a series of transitory and permanent knickpoints. The permanent knickpoints have direct correlation with the bedrock strength, corresponding to the outcropping of very hard quartzites or to the transition from less resistant (slates/metagreywackes) to harder (granite) basement.

Most of the analyzed streams record an older transitory knickpoint/knickzone separating an upstream relict graded reach, with lower steepness and higher concavity (concavity index values of 0.33–0.84), which reflects a long period of quasi-equilibrium conditions attained after the start of the incision stage, from a downstream reach displaying a rejuvenated long profile. This rejuvenated reach shows a steeper gradient and lower concavity, particularly the final segment which is even convex in many streams, testifying to the upstream propagation of incision waves that are the response of each fluvial system to continuous crustal uplift superposed on base-level lowering by the trunk drainages because of a coeval drop of sea level.

During long-lasting conditions of dynamic equilibrium in a stream, a graded profile develops and propagates upstream. Those conditions of dynamic equilibrium between the forcing mechanisms (tectonics, eustasy, and climate) also lead to an enlargement of the valley (by meandering) and to the genesis of a strath.

Downstream of the older transitory knickpoint/knickzone, the long profiles of several studied tributaries (e.g., Sertã, Freixiada, Figueiró, and Canas streams) show several graded reaches separated by knickpoints. This leads to the interpretation that for these streams the stage of general incision was an alternation of dominant periods of degradation (channel downcutting) and periods of quasi-equilibrium conditions (valley floor enlargement) that should correlate with terrace level development on their downstream trunk rivers.

In the present study, the normalized steepness index proved to be sensitive to active tectonics, where lower k_{sn} values were found in relict graded profiles of streams located in less uplifted blocks, namely the Sertã, Pracana, and Canas streams and the lower reach of the Tripeiro, Mangueija, and Ponsul streams ($k_{sn} < 30$), the latter three flowing through tectonic depressions. The k_{sn} parameter also reveals to be sensitive to lithology, as higher values were found associated with hard basement bedrock (quartzite and granite).

The fluvial incision values obtained from the same relict graded profile identified in each of the studied streams can be used to identify different uplifting blocks and to infer their associated active faults. The incision values of streams flowing in uplifted blocks of the PCR (ca. 380–150 m) indicate differential uplift in which they are generally higher than the incision values of streams flowing on the SPPS (ca. 220–120 m). The differential uplift indicated by the distribution of the k_{sn} values and by the fluvial incision quantification was likely

accumulated on several major faults, such as the Sobreira Formosa fault (SFF), thus corroborating the tectonic activity of these faults.

Because the relict graded profiles can be correlated with other geomorphic references documented in the study area, namely the T1 terrace of the Tagus River (with an age of ca. 1 My), the following incision rates can be estimated: (i) for the studied streams located in uplifted blocks of the PCR, 0.38 to 0.15 mm/y; and (ii) for the streams flowing on the SPPS, 0.22 to 0.12 mm/y.

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