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Ancient juniper trees growing on cliffs: toward a long Mediterranean tree-ring chronology

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ABSTRACT

Juniperus phoenicea is a tree that can grow on vertical cliff faces in dry and warm Mediterranean climate conditions. These trees are adapted to extreme growing conditions where the main constraints are verticality, compact hard limestone, and low water supply. They respond to these constraints via various specific features and high longevity. The objective of this study is to confirm whether or not their tree-rings are annual in order to specify growth strategies and accurately date these trees. Trunk morphology, anatomical wood anomalies and radial growth were analyzed on 53 trees in the Ardèche canyon. Crossdating of the ring widths using traditional dendrochronological techniques was unsuccessful, so radiocarbon dating of tree pith was used to assess tree age, and wiggle-match dating was used to test for differences between number of rings counted and radiocarbon dates. Radiocarbon dates span the period 2520–685 BP. Minimal difference between radiocarbon dates and ring counts was apparently small—missing rings occur, but not in large numbers. Tree-ring formation is annual and radial growth is low, which creates stunted old trees. Such old living trees are uncommon in the Mediterranean basin, especially at low elevation. They can provide long tree-ring chronologies back to 792–524 cal BC. Results from the radiocarbon dating indicate that accurate annual dating of these rings may be possible by crossdating. *J. phoenicea* growing on cliffs offer a valuable model to better understand cliff population ecology and the functional responses of trees that can live in harsh environmental conditions.

1. Introduction

Most forest ecosystems have been impacted by human civilizations on both spatial and temporal scales (Blondel and Aronson, 1999), but work by Larson et al. (1999, 2000) shows that cliffs support ancient, primary or virgin woodland, as cliff face habitats are too inaccessible to support anthropogenic disturbances. Trees that are able to grow on cliff faces have to support high abiotic constraints such as a limited root space, a low water storage capacity, and recurrent rockfalls (Larson et al., 1993; Matthes and Larson, 2006), but in turn they benefit from the absence of logging, fires, grazing, and competition from more aggressive level-ground vegetation. A study of 65 different temperate climate-zone cliffs reported exceptional longevity in some treelike cliff species such as *Thuja occidentalis*, (Northern USA), *Juniperus virginiana* (USA), *Taxus baccata* (United Kingdom), *Juniperus phoenicea* (Verdon canyon, France), which can reach ages of over 1000 years (Larson et al., 2000). Other studies confirm this site-specific longevity: a 1890-year *Thuya occidentalis* was discovered in the Niagara Escarpment (Southern Ontario, Canada; Larson, 2001) and a 1500-growth-layer *J. phoenicea* was found in Ardèche canyon (South of France, Mandin, 2005).

J. phoenicea L. (family *Cupressaceae*) is a treelike shrub or small evergreen tree growing up to twelve meters tall (Farjon, 2005). Its geographic range extends from the Canary Islands and the Atlas mountains in Africa in the West, to Jordan and Saudi Arabia in the East (Dzialuk et al., 2011), where it thrives under Mediterranean climate. It is a heliophilous, xerophilous and thermophilous species (Rameau et al., 2008) of saxicline plant that is found on rocky soils or orthent in the Mediterranean region (Garraud, 2003). Two sub-

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species are identified, *J. phoenicea* subsp. *turbinata* in populations of the coastal maritime areas and *J. phoenicea* subsp. *phoenicea* in all the other populations growing in hinterland landscapes up to 2500 m asl, such as on the slopes of the Atlas Mountains. It is a drought-tolerant, light-demanding tree characterized by pioneer properties (Quézel and Pesson, 1980; Quézel and Médail, 2003). The Ardèche marks the northern limit of its distribution on the right bank of the Rhône.

In the French Mediterranean region, populations of *J. phoenicea* tree can also grow on vertical and exposed limestone cliffs. These trees are adapted to extreme growing conditions where the main constraints are verticality and compact hard limestone that place strong mechanical stress on roots, which effectively limits both their growth and nutrients and water supply in dry and warm Mediterranean climate conditions. *J. phoenicea* tree colonizing these very harsh sites respond to these constraints via various specific features, one of which is a deformed gross architecture with slow and often asymmetric growth and a high proportion of strip-bark where trunk dieback is caused by partial cambium mortality. Stem or trunk stripping is known to occur in angiosperms and gymnosperms but is most common in the *Cupressaceae* family (Matthes et al., 2002). It is possible that this significant partial cambial mortality is triggered by hydraulic pathway sectoriality. Sectoriality means that there is no radial sap flow, i.e., each root only supplies the radial part of the crown to which it is connected (Mandin, 2006).

Trees can reach exceptional lifespans (Mandin, 2005). In the Mediterranean region, a major problem in achieving long tree-ring chronologies is the scarcity of long-lived trees which often results of anthropogenic impact (Luterbacher et al., 2012). A further problem is that a majority of the few long-lived trees in the Mediterranean Basin are evergreens that produce anatomical anomalies such as double rings (Cherubini et al., 2003), features that make cross-dating very difficult. However, some authors have proposed that tree rings of long-lived Mediterranean evergreens, such as *Juniperus* sp. and *Quercus ilex* L. can nevertheless be dated and used for dendrochronological studies (Cherubini et al., 2003; Campelo et al., 2007).

J. phoenicea demonstrates especially remarkable longevity and are abundant in the cliffs of the Ardèche valley. The longevity of these trees in such habitats potentially offers very long tree-ring series, but as with many other *Cupressaceae* species, there is persistent uncertainty over the annual status of a ring (Lemoine, 1966; Abdoun et al., 2005; Couralet et al., 2005). However, in another evergreen cliff species in Canada, a 1397-year tree-ring chronology has been built, and radial increment was negatively correlated with the previous year's maximum summer temperature (Kelly et al., 1994).

The objectives of this study were to accurately date *J. phoenicea* growing on cliffs and determine the representativeness of a ring. For this purpose, three techniques are used: cross-dating, radiocarbon dating on the tree pith to determine the age, and wiggle-match dating to test for differences between number of rings counted and radiocarbon dates.

2. Materials and methods

2.1. Field study

This study was performed on vertical cliffs (altitude range 50–300 m) in the protected nature reserve of Ardèche canyon in Southeast France (Fig. 1) and its surroundings. Ardèche canyon (1575 ha) was classified as a nature reserve in 1980. This reserve encompasses eight towns, with Vallon-Pont d'Arc (118 m asl) upstream. Downstream of Vallon-Pont-d'Arc, the river Ardèche turns eastwards through the reserve to cross a vast plateau of Cretaceous Urgonian limestone, forming a meandering 300 m-deep 29 km-long canyon (Mocochain et al., 2009). All the cliffs along the river Ardèche form this deep limestone canyon. The plateau is covered by coppices and garrigue dominated by holm oak (*Q. ilex* L.) and box tree (*Buxus sempervirens* L.).

The study area is submitted to a Mediterranean climate with a pronounced summer drought and autumn rainfall peak. At Orgnac (230 m asl, south of Ardèche canyon), average annual precipitation and mean annual temperatures are respectively 925 mm and 13.3 °C (1970–1998).

2.2. Tree sampling

The fieldwork was carried out in two steps. First, the trees were surveyed using binoculars to locate potentially very old trees. The most important criterion to find ancient *J. phoenicea* is inaccessibility to humans, which has preserved these rocky cliffs against disturbances such as deforestation for centuries. The second criterion is the presence of very compact rock enabling trees to remain in place. The third criterion in a Mediterranean climate is the absence of slope at the foot of the cliff, which could expose tree to pow-

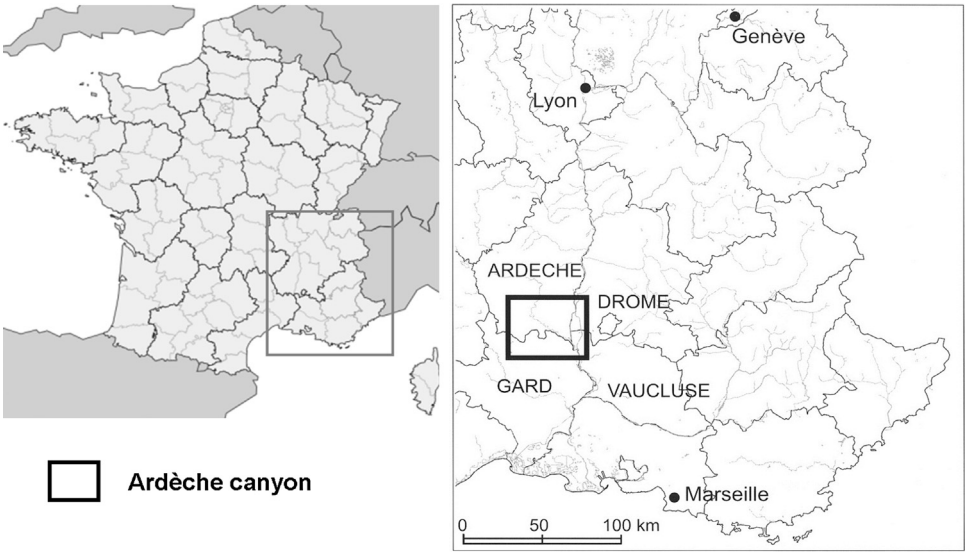

Fig. 1. Location of the Ardèche canyon (France). Courtesy of Christophe Gauchon.