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Tree ring pattern of roots exhumed by soil erosion

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(with 31 figures, and 1 table)

Mountains are subject to uplift and erosion. Human interference with the landscape by intensive agriculture, construction works, and tourism contributes to the removal of soil. We measured erosion rate by root exposure dating. Results of a pilot study of Shen Men Mt. at Tianshui and Kong Tong Mt. at Pingliang, Gansu province of China are reported here. New exhumation markers are introduced, separating aboveground features from mechanical stress-induced features. Change from root texture to stem texture, as defined by ring width and latewood width changes, reaction wood, distorted symmetry, simple and repeated wounds, open and closed wounds, abraded wound, onlap and offlap pattern of wound-affected growth increments, and simple and multiple discolouration by phenolic staining are illustrated and described here.

Introduction

Soil erosion is a primary driver of land degradation worldwide (VERHEIJEN et al., 2009). New, pristine areas are brought into cultivation to replace degraded lands, especially in developing countries. However, clearing natural vegetation cover makes land increasingly prone to erosion. Removal of the uppermost layer of land not only affects fertility, but, among others, increases downstream sedimentation, blocks irrigation channels and reduces the design life of reservoirs (ROMERO-DÍAZ et al., 2012). Construction of transport lines and urban development changes relief. Even increasing tourism takes its toll, by over-using existing paths. Extreme weather events, especially heavy rainfall, remove an increasing amount of soil from unprotected surfaces.

There is a multitude of studies describing and measuring the pattern and rate of soil erosion, ranging from the simple pin method up to high-resolution terrestrial laser scanning (e.g. GODFREY et al., 2008; LUCÍA et al., 2011). However, time series longer than a couple of years are rare, and decadal-scale measurements – mostly represented by radionuclide dating – lack annual temporal resolution (MABIT et al., 2008).

Tree roots are suitable for dendrochronological dating, i.e. can be cross-dated with each other and with tree trunks (KRAUSE & ECKSTEIN, 1994). This make them suitable for dating purposes. Dendrogeomorphological analysis of exposed tree roots is a method capable of dating soil erosion on a decadal to centennial temporal scale at annual (occasionally even at seasonal) resolution (for a recent review see STOFFEL et al., 2013). Both sheet erosion of slopes and linear erosion of gullies can be quantified.

Most soil erosion studies are related to arable soils (e.g. ZHENG, 2006), while forested regions are neglected in this respect (ZHOU et al., 2013).

Most studies have been done in the USA, the Mediterranean area and in the Alps (see STOFFEL et al., 2013, for an exhaustive list). Additionally, a gully erosion story was pubished by KÓRÓDY et al. (2009) in Hungary. There were only two studies in China, one on hillslopes in the temperate north (ZHOU et al., 2013) and another on karst in the subtropical south (LUO et al., 2011).

SCHULMAN'S (1945) seminal paper started the 'career' of root-based soil erosion studies. First the age of exposed roots (e.g. HUECK, 1951), then dating the starting asymmetry of buttress roots (LAMARCHE, 1961), and dating cambium damage were the methods used. When cambium is damaged, it dies back, and growth is discontinued along various sectors of the root circumference. However, segments diametrically opposed, usually in lower parts, continue growing. It was a 'revolutionary' new method in assessing erosion rates over millennia (LAMARCHE, 1963). A further step on methodological development was recognizing that growth rings, which are mostly concentric in underground settings, tend to change to elliptical cross-section of various eccentricity (MCCORD, 1987). Dating the initiation of reaction wood in exposed roots, in combination with scar-induced cambium dieback became a further indicator of initial root exposure (CARRARA and CARROLL, 1979). In the present paper we provide detailed description of select root cross sections from Gansu Province, People's Republic of China, applying these features to describe and quantify root exhumation caused by erosion and lowering of soil surface.

Root growth

Where do roots grow?

LAMARCHE'S method (1961) of root exhumation dating is based on the assumption that roots start to grow at the soil surface. This opinion is maintained in the reviews of GÄRTNER (2007) and STOFFEL et al. (2013) without further comment. We challenge this assumption.

The depth distribution of tree roots is controlled by a multitude of factors, e.g. species and age, climate (esp. temperature), soil properties, nutrient availability, etc. (ZIEMER, 1981; ZIEMER et al., 1991; SCHMIDT et al., 2001; ROERING et al., 2003; SCHWARZ et al., 2010). The major factor influencing rooting depth is water supply or lack of it (desiccation) (EAPEN et al., 2005). Negative factors affecting root distribution close to the surface are frost (REPO et al., 2014) and desiccation, both affecting mainly young roots (TRON et al., 2014).

Considering these factors we suggest that roots in temperate climate start growing not on the soil-air surface, but beneath at least a few cm of soil cover (Figs 1-2). Roots growing near the surface will suffer dieback soon. Unfortunately, root depth below soil has not been studied systematically in natural settings; assessment of this factor will be considered elsewhere.

While in temperate environments at least 10 cm of soil and/or abundant leaf litter provides protection from most of the above factors (ROERING et al., 2010), in subtropical and tropical environments young roots can grow without the protective layer of soil or leaf litter (Figs 5-8). Roots – under a certain soil cover and precipitation/temperature conditions – grow at a more or less constant depth. This depth is shallow, if compared to the tens of metres high trees these roots support. Majority of roots grow in the 15-25 cm depth interval on steep slopes of the Oregon Coast Range, US (ROERING et al., 2010).

We suppose the root andt its axis (the pith) is not displaced while in the soil. This is true only if free growth is allowed on all sides. If there is anything hard the root cannot push aside by its growth, either the root cross-section will be distorted or the root axis will be removed or both. Other roots and stones are the most frequent agents in displacing root axis . One should be careful to avoid sampling these roots.

Roots can be found above ground even in lack of any erosion. Increase of root diameter by growth causes the top of the root appear above the soil. This is not considered erosion, but even this root is suitable for erosion measurement. To avoid this pitfall we measure the location of the root's axis (the pith) and calculate any change of ground level relative to it.

Material and methods

The sites

Shi Men Mountain near Tianshu in eastern Gansu province (34° 26' 27" N, 106° 02' 29", 2085 m above sea level) is a sacred mountain with several Taoist shrines. Rock is coarse granite bearing thin soil. The mountain has steep ridges, where many roots are conveniently exposed. Still, there is a thin, brown forest soil cover on granite. Forest trees are Chinese pine (*Pinus* *tabulaeformis*). Thirty root disk samples were taken (SMM101–SMM130). Six of them are related to a living tree, which was also sampled (Table 1) (FANG et al., in prep.).

Kong Tong Mountain (Fragrance Hill) is west of Pingliang town in eastern Gansu. There is a monastery on terraces and on the hilltop between 1900-2000 m elevation above sea level. Kongtong Mountain is a national geopark (ZHANG, 2008). Annual precipitation is 500-600 mm, annual mean temperature is 8.9 °C. Soil is mountain brown earth, occasionally skeletal soil. A young, broadleaved forest is growing on 30-40° steep slopes. The soil is covered by 10-15 cm thick, halfway degraded, loose leaf litter, penetrated by young rootlets. There are no roots visible on the surface. Larger trees are 50-150 years old. There is no forest management. The sampled trees are Chinese pine (*Pinus tabulaeformis*). Five root disk samples were taken (KTM101–KTM105) (Table 1).

Sampling and measurements

For quantification of the erosion rate two parameters are needed: the number of rings grown since exposure and the thickness of the eroded soil layer since exposure. We suppose – in absence of contrary data – that the root axis was stable during growth.

Results and discussion

Microscopic versus *macroscopic analysis*

Recently there has been a shift in studies of root-based erosion measurement from ring width variations and textural changes towards microscopic analysis and dating of exposure (GÄRTNER et al., 2001; STOFFEL et al., 2013). While the latter method is certainly more sensitive to oncoming exhumation, and can sense the approach of soil surface even a few years before it reaches the root (CORONA et al., 2011), it needs special wood anatomical equipment and is time-consuming. Therefore we stick to the 'old-fashioned' identification of tree-ring pattern features to promote further studies in this field by those who has no access to specialized laboratory. Large number of data, gathered from a rich variety of sites is necessary to provide meaningful information for geomorphological and geological studies.

Exhumation markers in conifers

Exhumation is the process when roots growing underground appear at the soil surface due to natural or man-made causes. Exhumation can be rapid or slow, yielding sudden or gradual change of root texture, respectively. We discuss those markers below which can be recognized without any special equipment (no microtome and anatomical thin sections are needed). Features visible on the sanded and polished surface of a root disk by a simple microscope, even by a hand lens, or on magnified digital photographs, are described below.

PATEL (1965) recognized long time ago that roots – having their own texture while underground – produce tissue similar to stem wood in the year or season of exhumation. FAYLE (1968) described wider tree rings, occurrence of compression wood, and smaller cell diameter (associated with thicker cell walls) in those portions of root which grew above ground.

1) *Change from root texture to stem texture* around the circumference (Figs 13-31). Cell lumina in earlywood of stems reflect temperature and moisture at the start of the growing season (ANTONOVA & STASOVA, 1993). The same applies to roots (CORONA et al., 2011). Soil cover protects roots from oscillating extremes (esp. of frost and drought) to a considerable degree. The reduced environmental signal mostly yields uniformly sized cell lumina and thin walls in the earlywood of conifer roots. Latewood is often a single row of cells only. Exposure to aboveground conditions usually yields smaller cell lumina and thicker cell walls, both in the earlywood and in the latewood. In macroscopic view this change is displayed as lighter below-ground and darker above-ground rings. Latewood is particularly affected by aboveground conditions: it is significantly thicker than the underground latewood. In short: roots produce xylem similar to that of stems after exposure to aboveground conditions (Patel, 1965). Appearance of stem texture in roots usually occurs all around the circumference. This is an easy way to distinguish it from reaction wood, which is mostly reduced to a sector of the disk only.
2) *Reaction wood* is formed in the wood under mechanical stress (Figs 14-16, 20-26).

Conifers' reaction wood has wider rings than normal and latewood is accentuated, thicker, and much darker than usual, containing an extra amount of lignin. The difference in color results from much thicker and rounded cell walls of earlywood and latewood tracheids. It is always below an inclined stem, branch or root, supporting it against gravity. Reaction wood starts to grow in stems upon tilting for any reason. In roots its growth starts probably when the root loses the support of soil during exhumation, and mechanical stress – extension – is generated below the axis. The first ring with reaction wood dates the exhumation of the root (compression wood is always missing in the underground portion of roots: WESTING, 1965). Reaction wood extends to partial circumference of the root only; mostly to the lower part but not exclusively (Figs 28-31), depending on the direction of stress. Multiple tilting events in the same stem may be recognized by changes in – among others – orientation of compression wood (STOFFEL & CORONA, 2014). Similar features in roots are unexplained yet. Reaction wood can be overprinted by factors affecting the growth of the whole plant. Formation of reaction wood has not been studied experimentally in roots and we are not aware of many details of growth. The most obvious feature of the appearance of reaction wood is the distortion of the circular symmetry of the cross section into an elliptical one; however, asymmetry can appear without any reaction wood present. Dark, lignin-rich, thick latewood might appear simultaneously in the first reaction wood ring, or later, or not at all.

3) *Distorted symmetry* (Fig. 31). The change from circular to elliptical to variable-axis elliptical rings (of twisted symmetry) (LAMARCHE, 1961, 1963; MCCORD, 1987) is also a marker of root exhumation. The growth of rings with eccentric symmetry and of reaction wood goes hand-in-hand (CARRARA & CARROLL, 1979). For a detailed study lately see BODOQUE et al. (2011, with references).

4) Wounds (Figs 18-19, 21, 24-31) are caused by injury to the root by mechanical means, mostly above ground, rarely below ground. If the cambium is damaged and suffers dieback, growth is stopped at that place, bark falls off, and an open wound is formed. Wounds do not date exhumation precisely to the year: injury can be later than the year of exhumation (**i** – reaction wood precedes wound by one year). There are various geometries of wound cross-sections, discussed below.

- *Onlap* (Fig. 15). Onlap is the geological phenomenon of successively younger rock strata extending progressively further across an erosion surface cut in older rocks (CHRISTIE-BLICK, 1991). In turn, we use this notion for successively younger rings overgrowing an erosion surface or a wound in tree stems and roots. Undamaged cambium around the wound allows growth to continue in adjacent areas, and the wound is slowly covered by new tissue, called callus (KRAUSE & ECKSTEIN, 1994; SCHWEINGRUBER, 1996). As the newly formed rings prograde over the dead surface of the wound, the geometry produced is called onlap, a term borrowed from geology (CHRISTIE-BLICK, 1991).
- *Offlap* (Fig. 31). If under adverse conditions the wound cannot be overgrown, and the cambium dieback continues, an offlap geometry of rings is produced. (The term is borrowed from geology: CHRISTIE-BLICK, 1991). In extreme cases it leads to unidirectional growth, usually on the underside of the root. Often it indicates repeated wounding, e.g. on animal or tourist path. This feature is analogous to strip bark formation on stems . Growth of offlapping rings leaves wounds open, exposed to abrasion. Offlap is not to be confused with eroded ring terminations. Offlapping rings grow under a bark cover, under reduced cambium activity.
- *Open* versus *closed wound*. A closed – completely overgrown – wound (Fig. 18) indicates mechanical injury at least several years ago. It is important to discover these closed wounds, as they indicate an exhumation event previous to those ones identified from seeing the surface of the root.
- *Repeated injury* (Fig. 17) indicates that the wound is still open to mechanical effects. The first one marks the first exhumation, while others indicate sustained influence of harmful effects. It can include repeated closure of the wound.
- *Abraded wound* (Figs 26, 29, 31). Abrasion of the wounded surface can lead to loss of information). Even in this case a detailed story of erosion is preserved along the flanks of the eroded wound. Erosion can be pre-exhumation (if done by undeground rodents, for example), but mostly it is a post-exhumation process.

Roots bearing abraded wounds still maintain growth on the underside (LAMARCHE, 1963).

5) *Phenolic staining* (by dark, reddish brown compounds) adjacent to the wound (Figs 17-18, 23). These precipitates isolate the open wound from infection by bacteria and fungi. Spreading beyond the actual margin of wounded tissue phenolic stains indicate the presence of a wound even if the transverse section we study does not display the injured portion itself. Identifying phenolic staining is crucial to find hidden, overgrown wounds. External surface of the stain is parallel with a ring – this is the year when the injury occurred.

Features of roots were first discussed extensively by KRAUSE & ECKSTEIN (1994). All the trees they studies were windthrown trees, therefore no exhumation markers have been found.

Relative dating of exhumation features

Wound – in the year of exhumation or later (almost never in a preceding year) in case of rapid exhumation.

Stem texture – up to 3 years before exhumation in case of slow process (CORONA et al., 2011); same year as exhumation in case of rapid process.

Reaction wood – wider rings plus enhanced latewood: can be earlier or later than exposure or missing completely. Practically simultaneous with rapid exhumation in most cases.

Phenolic substances – extends externally as far as the wound, internally as far as the pith. Develops in unspecified time, in months to years.

Conclusions

Roots, when exhumed above ground, display various features in their altered tissue. Features are grouped as (1) change from root texture to stem texture (gradual or sudden), (2) formation of reaction wood of increased ring width and lignin content, (3) injuries causing wounds and their overgrowth ring patterns, and (4) phenolic staining. Recognition of these features allows us to date the exhumation and decide whether it was slow or fast.

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References

ANTONOVA, G.F., STASOVA, V.V., 1993. Effects of environmental factors on wood formation in Scots pine stems. – Trees 7, 214–219.

BODOQUE, J.M., LUCÍA, A., BALLESTEROS, J.A., MARTÍN-DUQUE, J.F., RUBIALES, J.M., GENOVA, M., 2011. Measuring medium-term sheet erosion in gullies from trees: a case study using dendrogeomorphological analysis of exposed pine roots in central Iberia. – Geomorphology 134, 417–425.

CHRISTIE-BLICK, N., 1991. Onlap, offlap, and the origin of unconformity-bounded depositional sequences. – Marine Geology

EAPEN, D., BARROSO, M.L., PONCE, G., CAMPOS, M.E., CASSAB, G.I., 2005. Hydrotropism: root growth responses to water. – Trends in Plant Science 10 (1), 44–50.

CARRARA, P.E., CARROLL, T.R., 1979. The determination of erosion rates from exposed tree roots in the Piceance Basin, Colorado. – Earth Surface Processes 4, 307–317.

CORONA, C., LOPEZ-SAEZ, J., ROVERA, G., STOFFEL, M., ASTRADE, L., BERGER, F., 2011. High resolution, quantitative reconstruction of erosion rates based on anatomical changes in exposed roots at Draix, Alpes de Haute-Provence—critical review of existing approaches and independent quality control of results. – Geomorphology 125:433–444

FAYLE, D.C.F., 1968. Radial growth in tree roots. Technical Report.Faculty of Forestry, University of Toronto, Canada

GÄRTNER, H.W., 2007. Tree roots — methodological review and new development in dating and quantifying erosive processes. – Geomorphology 86, 243–251.

GÄRTNER, H.W., SCHWEINGRUBER, F.H., DIKAU, R., 2001. Determination of erosion rates by analyzing structural changes in the growth pattern of exposed roots. – Dendrochronologia 19, 81–91.

GODFREY, A., EVERITT, B.L., MARTÍN-DUQUE, J.F., 2008. Episodic sediment delivery and landscape connectivity in the Mancos Shale badlands and Femont River system, Utah, USA. – Geomorphology 102, 242–251.

HUECK, K., 1951. Eine biologische Methode zum Messen der erodierenden Tätigkeit des Windes und des Wassers. – Berichte der Deutschen Botanischen Gesellschaft 64, 53–56.

KÓRÓDY, G., KÁZMÉR, M., SZÉKELY, B., 2009. Dating gully erosion by root exposure (Bátaapáti, Mórágy-Geresd Hills, Hungary). In: KÁZMÉR M. (ed.): Környezettörténet. Az elmúlt 500 év környezeti eseményei történeti és természettudományi források tükrében. [Environmental History. Environmental events during the last 500 years reflected by historical and science sources.] Hantken Kiadó, Budapest, pp. 367–380. (In Hungarian)

KRAUSE, C., ECKSTEIN, D. 1994. Dendrochronology of roots. – Dendrochronologia 11, 9-23.

LAMARCHE, V.C., 1961. Rate of slope erosion in theWhite Mountains, California. – Geological Society of America Bulletin 72, 1579–1580.

LAMARCHE, V.C., 1963. Origin and geologic significance of buttress roots of bristlecone pines, White Mountains, California. – U.S. Geological Survey Professional Paper, 475–C, pp. C149–C150.

LUCÍA, A., LARONNE, J.B., MARTÍN-DUQUE, J.F., 2011. Geodynamic processes on sandy slope gullies in central Spain — field observations, methods and measurements in a singular system. – Geodinamica Acta 24, 61–79.

LUO, M., ZHOU, Y., WANG, K.K., 2011. Response of anatomical features of broadleaf tree root in karst area to soil erosion. In: Second SREE Conference on Chemical Engineering. – Procedia Engineering 18, 232-239.

MABIT, L., BENMANSOUR, M., WALLING, D.E., 2008. Comparative advantages and limitations of fallout radionuclides (^{137}Cs, ^{210}Pb and ^{7}Be) to assess soil erosion and sedimentation. – Journal of Environmental Radioactivity 99, 1799–1807.

MCCORD, V.A.S., 1987. Late Holocene sediment yield and transport in a northern Arizona drainage basin reconstructed by tree-ring analysis. U.S. Department of Energy, Publication CONF-8608144, pp. 213–223.

Patel, R.N., 1965. A comparison of the anatomy of the secondary xylem in roots and stems. Holzforschung 19, 72–79

REPO, T., SIRKIÄ, S., HEINONEN, J., LAVIGNÉ, A., ROITTO, M., KOLJONEN, E., SUTINEN, S., FINÉR, L., 2014. Effects of frozen soil on growth and longevity of fine roots of Norway spruce. – Forest Ecology and Management 323, 112-122.

ROERING, J.J., SCHMIDT, K.M., STOCK, J.D., DIETRICH, W.E., MONTGOMERY, D.R., 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. – Canadian Geotechnical Journal 40, 237–253.

ROMERO-DÍAZ, A., MARÍN-SANLEANDRO, P., ORTIZ-SILLA, R., 2012. Loss of soil fertility estimated from sediment trapped in check dams. South-eastern Spain. – Catena 99, 42–53.

SCHMIDT, K.M., ROERING, J.J., STOCK, J.D., DIETRICH, W.E., MONTGOMERY, D.R., SCHAUB,T., 2001. The variability of root cohesion as an influence on shallow land-slide susceptibility in the Oregon Coast Range. Can. Geotech. J. 38, 995–1024.

SCHULMAN, E., 1945. Root growth-rings and chronology. – Tree-Ring Bulletin 12, 2–5.

SCHWARZ, M., PRETI, F., GIADROSSICH, F., LEHMANN, P., OR, D., 2010. Quantifying the roleof vegetation in slope stability: a case study in Tuscany (Italy). – Ecological Engineering 36 (3), 285–291.

SCHWEINGRUBER, F.H., 1996. Tree Rings and Environment. Dendroecology. Paul Haupt, Bern.

STOFFEL, M., CORONA, Ch. 2014. Dendroecological dating of geomorphic disturbance in trees. – Tree-Ring Research 70(1), 3-20.

STOFFEL, M., CORONA, CH., BALLESTEROS-CÁNOVAS, J.A., BODOQUE, J.M., 2013. Dating and quantification of erosion processes based on exposed roots. – Earth-Science Reviews 123, 18-4.

TRON, S., DANI, A., LAIO, F., PRETI, F., RIDOLFI, L., 2014. Mean root depth estimation at landslide slopes. – Ecological Engineering 69, 118-125.

VERHEIJEN, F.G.A., JONES, R.J.A., RICKSON, R.J., SMITH, C.J., 2009. Tolerable versus actual soil erosion rates in Europe. – Earth-Science Reviews 94, 23-38.

WESTING, A.H., 1965. Formation and function of compression wood in gymnosperms. – Botanical Reviews 31, 381–480.

ZHANG, Rong, 2008. Geological relics of Kongtong Mountain National Geopark in Pingliang city and its geoscientific value. – Gansu Geology 17 (2), 94-95 (in Chinese)

ZHENG, F.-l.. 2006. Effect of vegetation changes on soil erosion on the Loess Plateau. – Pedosphere 16(4), 420-427.

ZHOU, F., GOU, X., ZHANG, J., ZHAO, Z., CHEN, Q., CAO, Z. 2013. Application of *Picea wilsonii* roots to determine erosion rates in eastern Qilian Mountains, northwest China. – Trees 27, 371-378.

ZIEMER, R.R., 1981. Roots and the stability of forested slopes. Erosion and SedimentTransport in Pacific Rim Steeplands. – IAHS Journal 132, 343–361.

ZIEMER, R.R., LEWIS, J., RICE, R.M., LISLE, T.E., 1991. Modeling the cumulative watershed effects of forest management strategies. – Journal of Environmental Quality 20, 36–42.

Fig. 1. Mango tree roots in road cut. Photo: Aaron Escobar. Roots extend into the soil (rather into bare rock about the diameter of the trunk. http://commons.wikimedia.org/wiki/File:Exposed_mango_tree_roots.jpg. Accessed 2 November 2014.

Fig. 2. Temperate climate with arid summer and freezing winter (Mecsek Hills, Hungary). Beech roots grow along the interface between a 10-15 cm thick humic level and a felspar-rich sand derived from strongly weathered Carboniferous granite (Bátaapáti, Mecsek Hill, Hungary). Soil cover protects young roots from winter frost and from summer desiccation.

Fig. 3. Tropical climate of year-round humid air and no frost. Root system of teak (*Tectona grandis*), on sale in a woodworking specialty shop in Yogyakarta, Indonesia. Major roots do not extend deeper than 40-60 cm into the soil, while extending extensively laterally. Photo #6317.

Fig. 4. Thick roots arranged parallel with the slope. Exhumation was due to construction of the path. Warm temperate climate at medium high elevation; frost occurs in winter. Kong Tong Mt., Gansu, China. Photo #3070.

Fig. 5. Subtropical climate with year-round humid air and rare winter frost. Roots of cliffside trees grow downwards on the cliff surface, seeking water. Subtropical climate - no frost, closed canopy – no desiccation. On this vertical wall certainly there was no leaf littter cover ever protect the young roots. Guibei Hill National Scenic Area, Guizhou province, China. Photo #5849.

Fig. 6. Tree with broken branch. A seedling is growing in the wound: stem upward, roots downward, hanging in the air. There is neither winter frost nor summer drought in this subtropical region: roots can grow practically anywhere without soil or litter cover. Southern Guizhou, China Photo #5878

Fig. 7. Roots of streetside tree overgrow pavement blocks. Subtropical climate with year-round humid air and rare winter frost. Luodian, southern Guizhou, China. Photo #2040

Fig. 8. Roots of streetside tree overgrowing iron grill in Hong Kong (subtropical climate of year-round humidity and no winter frost.). Photo A. Boc.

Fig. 9. Moderately exposed and wounded roots before sampling; leaf litter carefully removed. Xingren, Guizhou, China. Photo #6121.

Fig. 10. Exhumed root, marked with a cross at the highest point above ground. Kong Tong Mountains, Gansu, China. Photo #3023

Fig. 11. The thick root, marked with black cross, parallel with the slope is an excellent erosion marker. The thin root across the thick one is unsuitable for erosion studies: although grown under soil cover, its axis has been uplifted above the thick root. Uplift is caused both by thickening of the thin root and by thickening of the underlying, thick root. Shi Men Mountain, Tianshu, Gansu, China. Photo #2710.

Fig. 12. A small hole dug around the root, ready for sampling.. It is important to clear the underside of the root from soil and stones, so the saw won’t hit anything. Shi Men Mountain, Tianshu, Gansu, China. Photo #2699.

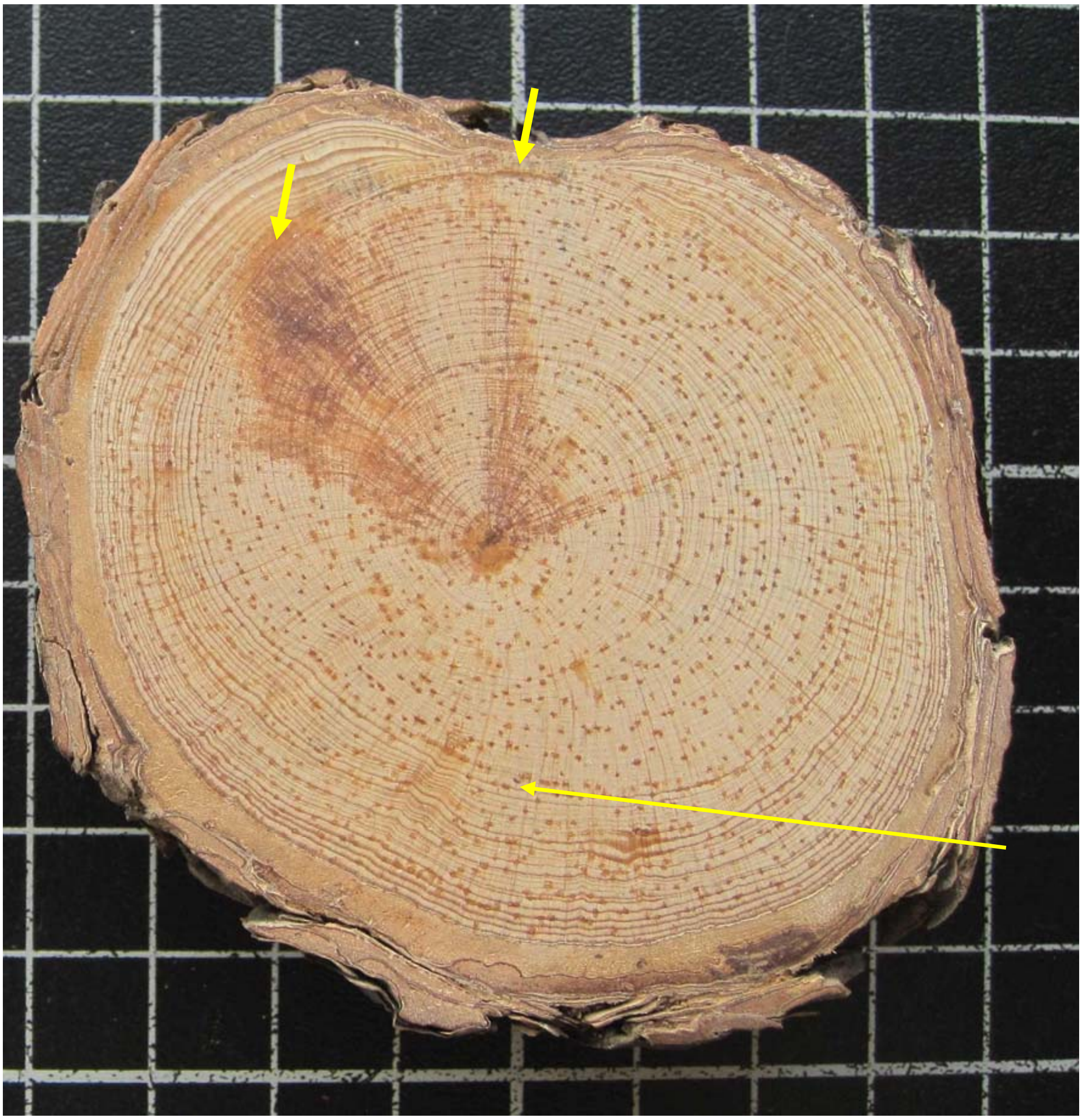

Fig. 13. Gradual change from root texture to stem texture. Centre: root texture, margins: stem texture. Root texture consists of wide, light-coloured earlywood and very narrow, barely visible, dark-coloured latewood. Latewood of central rings gradually changes into slightly wider, better visible latewood (thin arrow); it is the period when the root was gradually exhumed. Wounds (wide arrows) on top and in the upper left sector were formed at least three years apart. The top wound caused narrower rings to grow with slightly thicker latewood on top. The same rings are less distinguished at the bottom sector, indicating that the root was partially exposed to the elements, partially buried below the soil. Both wounds are marked by brownish phenolic compounds deposited towards the pith. The top wound was fully overgrown by onlapping rings and covered by bark. Resin ducts visible throughout. Exhumation 22 and 80 mm on both sides, respectively. Photo #2251. Tianshui, Gansu, China. Sample SMM129. Scale: 10 × 10 mm grid pattern in background.

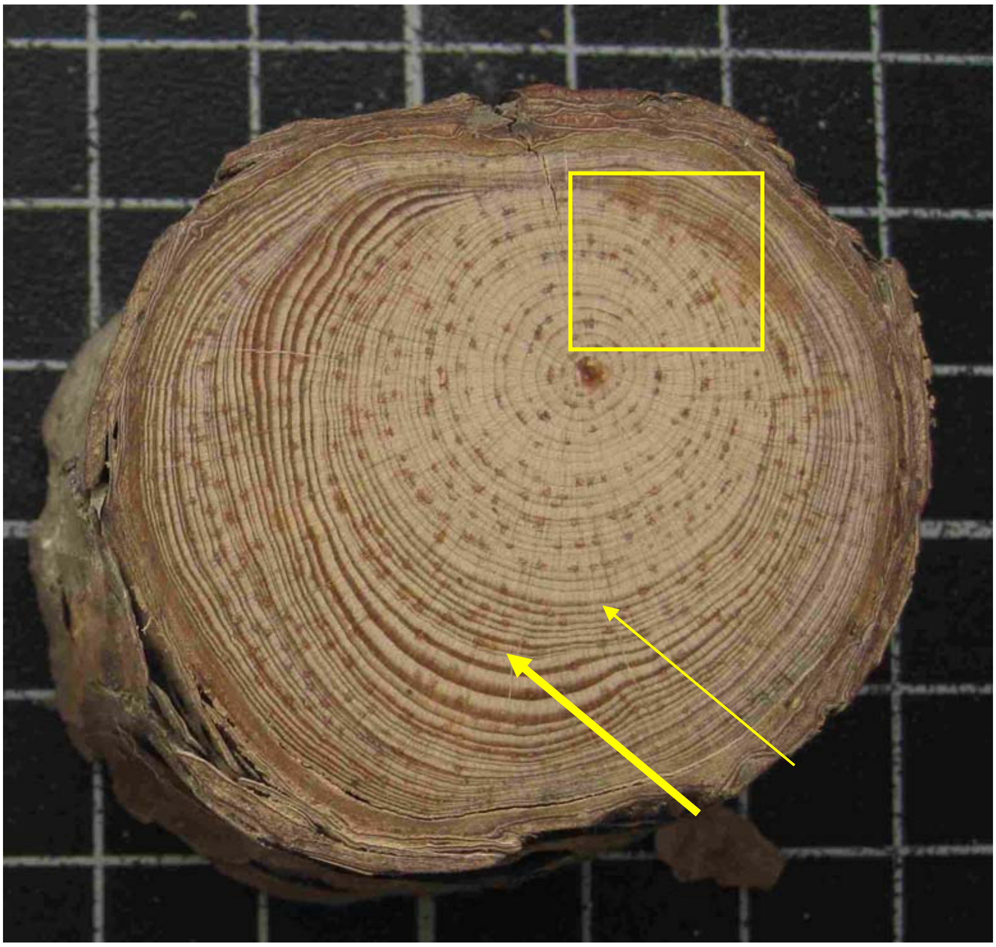

Fig. 14. Stepwise change from root texture to stem texture. Root texture consists of wide, light-coloured earlywood and narrow, dark-coloured latewood. Where narrow latewood of central rings suddenly changes to highly visible (dark and wide) latewood (thin arrow), it is the year when the root was rapidly exhumed. This exhumation preceded the appearance of reaction wood (thicker rings with thick latewood) (thick arrow), a marker of mechanical stress. Barely visible latewood portion displays circular symmetry. Visible latewood portion lost well-defined circular symmetry: rings are extremely narrow on top. Reaction wood portion with wide rings and wide latewood lost all symmetry and displays growth in variable directions. Resin ducts visble throughout. Rectangle: see Fig. 15. Exhumation 22 and 80 mm on both sides, respectively. Photo #2255. Tianshui, Gansu, China. Sample SMM118. Scale: 10 × 10 mm grid pattern in background.

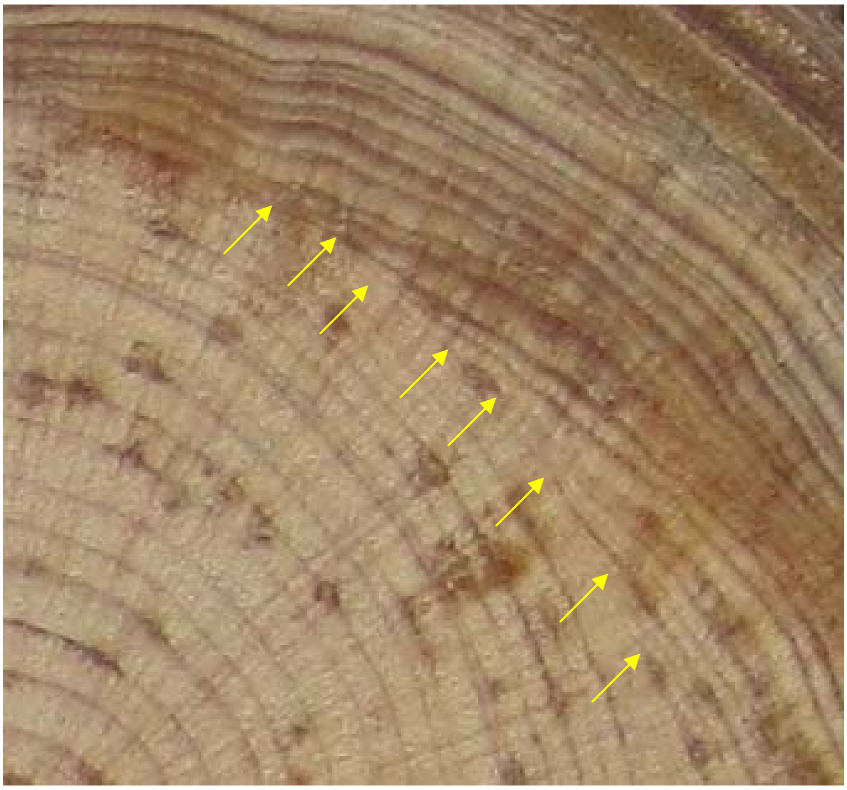

Fig. 15. Enlarged portion of Fig. 14. Onlapping rings formed during the healing of a wound. Arrow marks the terminations of the wedged rings on the surface of the last undamaged ring, i.e. the year of injury. Photo #2255. Tianshui, Gansu, China. Sample SMM118. Scale: see rectangle and 10 × 10 mm grid pattern in background on Fig. 14.

Fig. 16. Central root texture of narrow rings and inconspicuous latewood suddenly changes to 3 white rings of uncertain affiliation (probably initial reaction wood). Sudden appearance of reaction wood (wide rings and wide, dark latewood simultaneously) marks rapid exhumation of the root (__arrow__). There was no particular symmetry either before or after exhumation. Tianshui, Gansu, China. Sample SMM110. Photo #3078. Scale: 5 × 5 mm grid pattern in background.

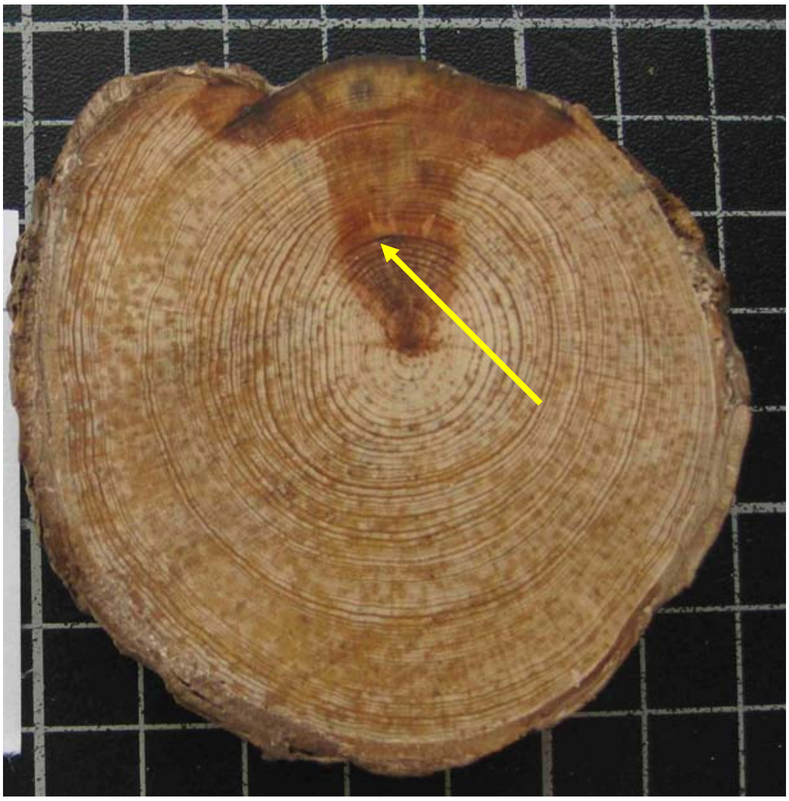

Fig. 17. Gradual change from root texture to stem texture (mostly stem texture). Root section displaying almost circular symmetry. (The oval shape is caused by the plane of section across a division of the young root.) Initial, narrow rings with barely visible latewood grew underground. These are surrounded by wider rings with well-defined latewood grown above ground. Change is gradual, indicating progressive exhumation of the root (see details on Fig. 18.). Four years after expressed latewood growth started, an injury external to this section (arrow) caused increased ring width in part of the circumference. There was no cambium dieback in this section. Brown spots caused by repetitive deposition of phenolic substances due to repated injuries (dark colouration) protect the damaged portion from infections. A second, major damage on top caused cambium dieback and loss of phloem and bark. Onlapping rings left of the wound started to overgrow the wound. Eight years later another event damaged the rings overgrowing the big wound. During the next five years this wound has been overgrown by another set of onlapping rings. This root does not display reaction wood despite repeated injury above ground.All latewod is of even thickness around the circumference. Kong Tong Mts., Gansu, China. Sample KTM105.. Photo #2252. Scale: 10 × 10 mm grid pattern in background.

Fig. 18. Magnified image of the central portion of Fig. 17. Change is gradual from central root texture towards stem texture indicating progressive exhumation of the root. An injury external to this section (arrow) caused increased ring width in part of the circumference. There was no cambium dieback in this section. Brown spots were caused by deposition of phenolic substances due to the injury (dark colouration) to protect the damaged portion from infections. Kong Tong Mts., Gansu, China. Sample KTM105.. Photo #2252. Scale: 10 × 10 mm grid pattern in background.

Fig. 19. Initial wide rings were gradually replaced by narrower rings, following the usual age-related decrease of groth of stems. Initial rings bear reasonable amount of latewood, while later, narrow rings have only very thin latewood. Exhumation date can be approached by the first injury only: a black wound, a dark deposit of phenolic substances below, and a single ring of the same year with accentuated latewood gives evidence. There are further two minor injuries, accentuated by phenolic compounds. The root is surrounded by thick bark, i.e. it is now fully above ground in the whole cross-section. Despite this, there is no obvious reaction wood. Tianshui, Gansu, China. Sample SMM119. Photo #3068. Scale: 5 × 5 mm grid pattern in background.

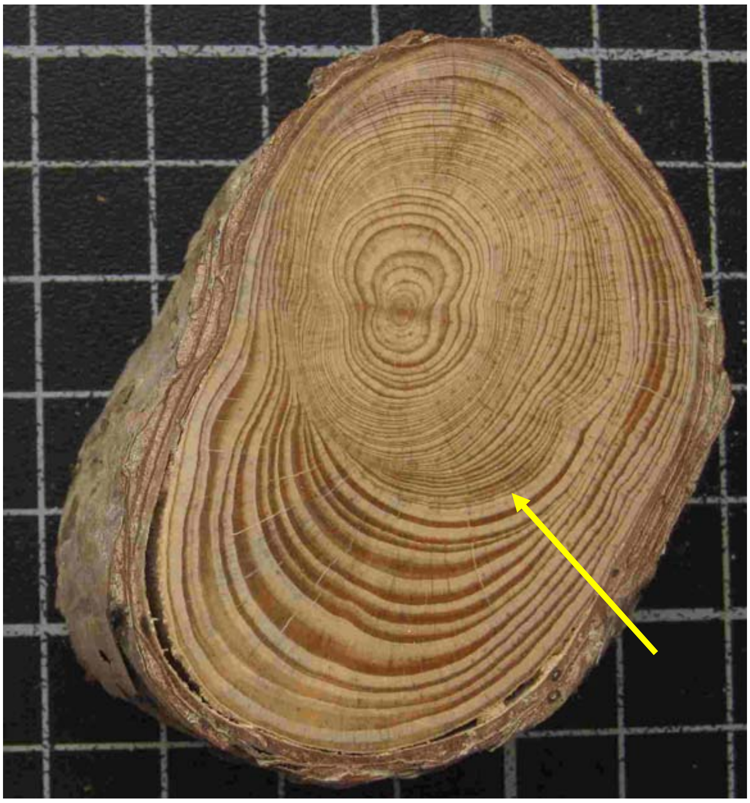

Fig. 20. Root section displays narrow rings with thin latewood grown underground. Rapid exhumation yielded reaction wood of wide rings and thick latewood (arrow). Symmetry deteriorated from an inner oval shape to an outer, highly asymmetric one. Direction of fastest growth changed repeatedly, showing a twisted pattern. Tianshui, Gansu, China. Sample SMM109. Photo #2254. Scale: 10 × 10 mm grid pattern in background.

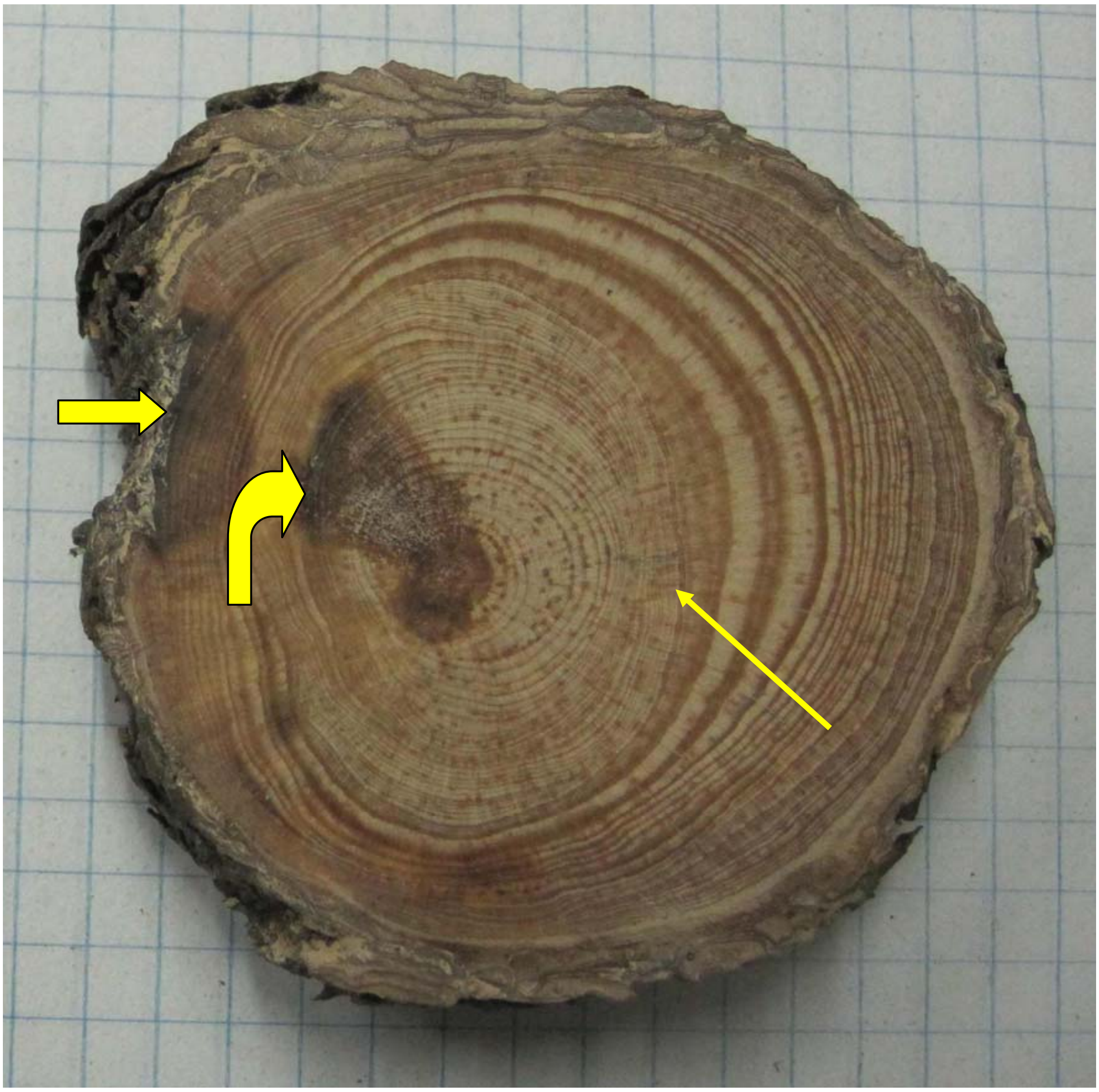

Fig. 21. The central, oval-shaped portion of the root displaying underground texturesuffered injury laterally (thick, curved arrow). Phenolic compounds protect the root here. Although yielding 1-2 thicker rings, the general appearance did not change markedly, it remained similar to the undeground pattern of narrow rings with very thin latewood. Later there was a sudden change to 4-5 very thick rings with marked latewood, i.e. reaction wood (thin arrow). Later rings are somewhat wider than the rings of the underground portion, having latewood of several cell rows. This is stem texture. The stem-textured portion has different symmetry, than the root-textured portion, indicating different stress affecting the root. A second damage on the left (thick, straight arrow) is protected by the brown spot of phenolic compounds. Attempts to overgrow and heal this wound are visible, but unsuccessful. Site of the wound was damaged repatedly, eroding about ten external rings. Tianshui, Gansu, China. Sample SMM127. Photo #3058. Scale: 5 × 5 mm grid pattern in background.

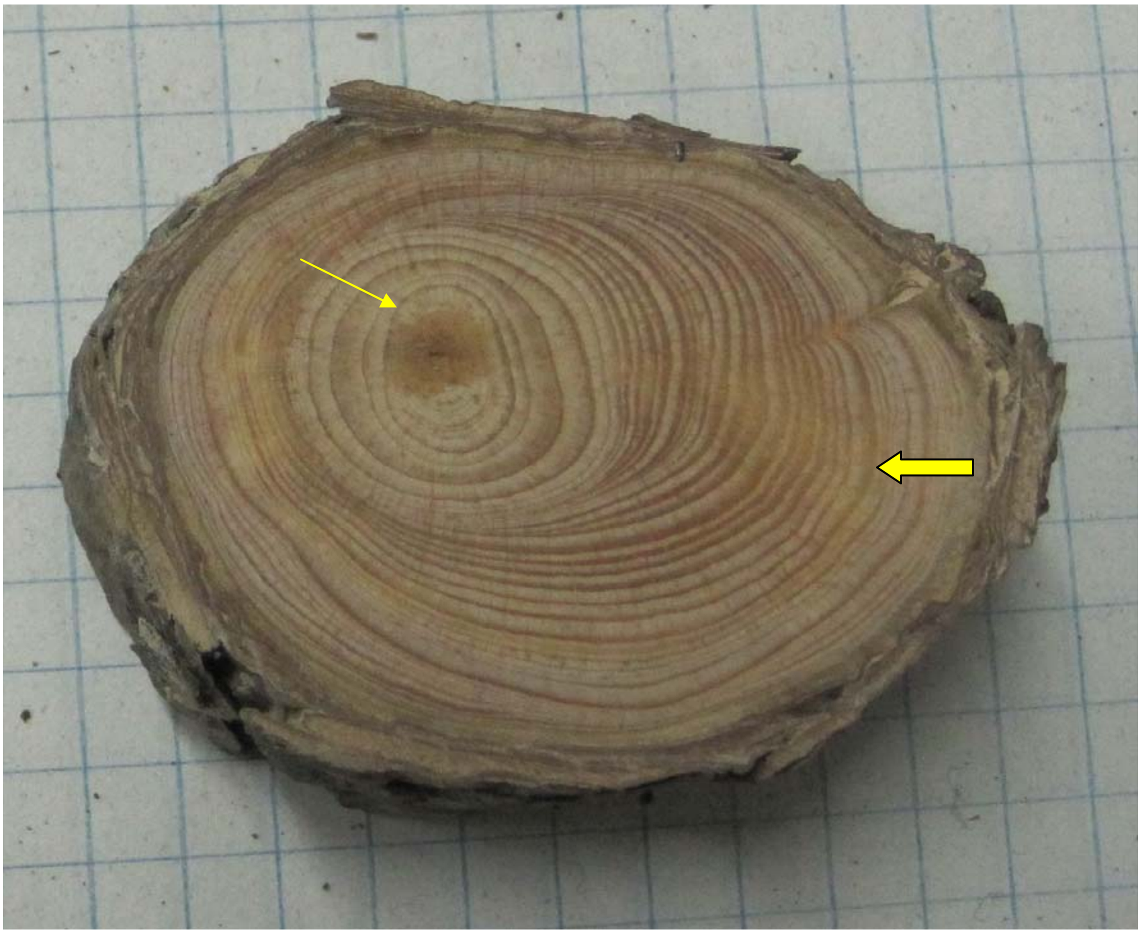

Fig. 22. A vertically elongated oval of root texture with narrow rings suddenly changes to wide rings with marked latewood (reaction wood) (thin arrow). Reaction wood indicates also a change of stress: the root started to grow laterally rather. Rings are wider on the left than on the right, and latewood is thicker here: the right side is the compression wood. Subsequently anomalous stresses cease: rings are narrow and latewood is less marked (with the exception of a single ring). Tianshui, Gansu, China. Sample SMM116. Photo #3066. Scale: 5 × 5 mm grid pattern in background.

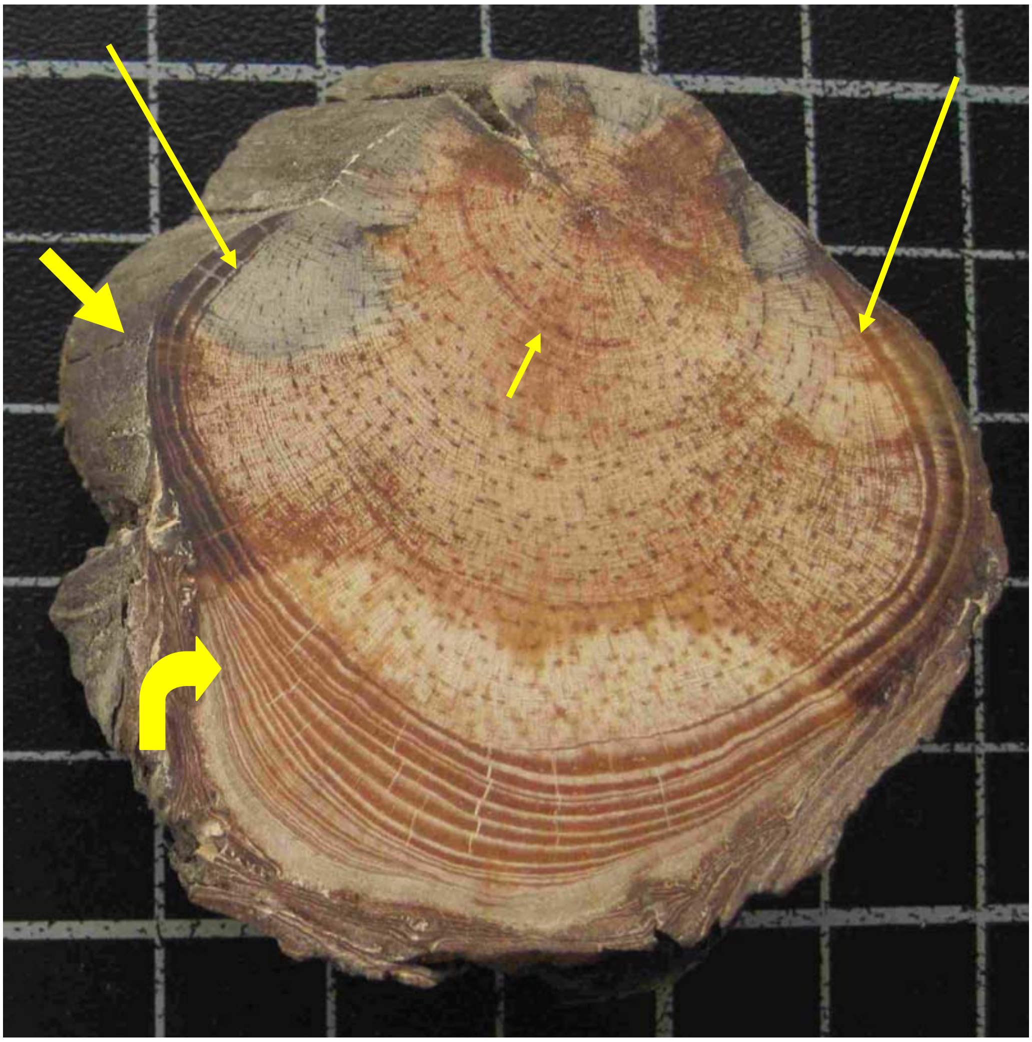

Fig. 23. This heavily asymmetric, eroded root disk describes a complex history of growth and exposure. Initial rings of almost perfect circular symmetry change to elliptical rings (short arrow), where a narrow, dark feature intertwines. Neither ring width nor latewood width changes here. Marked asymmetry is produced by growth having been concentrated at the bottom: rings of even thickness and very narrow latewood follow each other. Along the left and right flanks rings narrow upwards until they are impossible to be distinguished from each other near the top. A probable exhumation event and subsequent injury caused cambium dieback. Sudden increase in ring width and latewood width (reaction wood) marks reaction wood: onlapping rings (long arrows) progress along the wounded surface towards the top of the root. Probably a second injury caused cambium dieback, stopping growth of reaction wood rings on both sides (thick arrow). An offlapping sequence of retreating rings (curved arrow) certainly indicates something else than erosion of root: the retreating ring boundaries are uniformly covered by bark. All of the bark-free, dead surface of the disk (more than half of the circumference) is protected by phenolic substances. Note that many of the narrow rings at the top have been eroded. Tianshui, Gansu, China. Sample SM124. Photo #2257. Scale: 10 × 10 mm grid pattern in background.

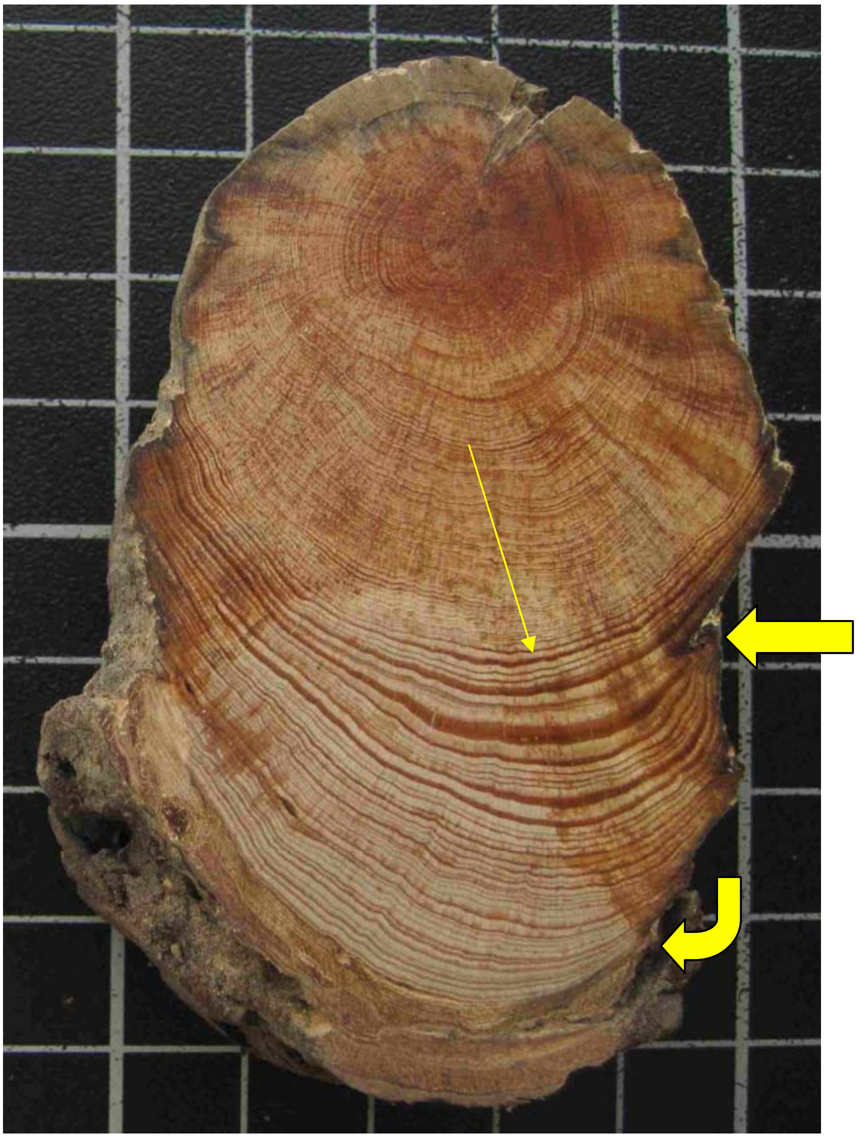

Fig. 24. Root section heavily eroded both on top and sides – the only meaningful information about exhumation history is coded in ring width and latewood width changes. Narrow rings with no remarkable latewood suddenly give place to reaction wood of wide rings and wide latewood (thin arrow). This was certainly a major erosion event caused by exhumation. Exact dimensions of the wound cannot be assessed, since all relevant parts on top and both sides have been eroded since. Asymmetry of the thin-ringed portion can be assumed only due to heavy erosion. The reaction wood portion has grown mostly downward, constrained be repeated lateral erosion. A major wound started to be covered by onlapping rings (wide arrow), while later rings display offlap (retreating growth) (curved arrow). Tianshui, Gansu, China. Sample SMM101. Photo #2258. Scale: 10 × 10 mm grid pattern in background.

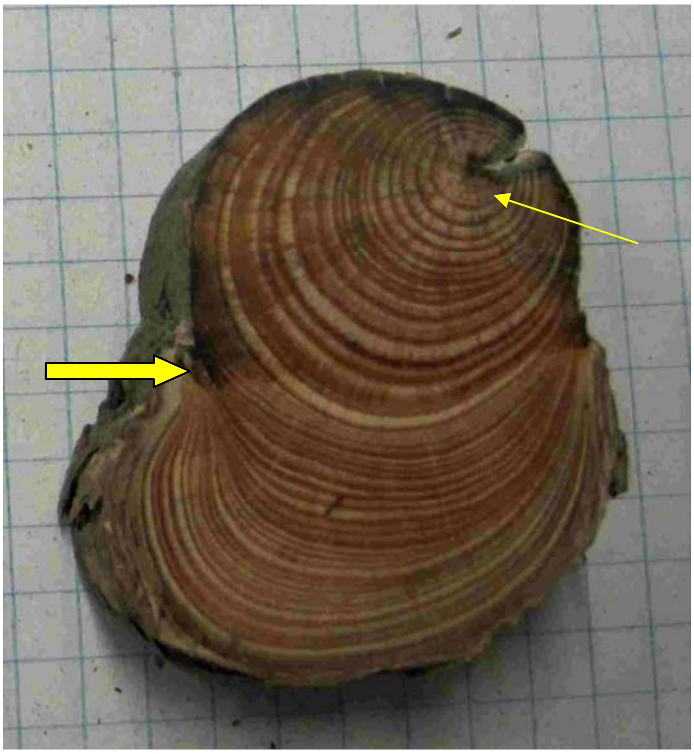

Fig. 25. This heavily eroded root (both on top and on sides) display a particular ring succession. Following the first 4-5 rings – which clearly grew underground indicated by the insignificant amount of latewood – the root has only reaction wood rings: wide rings and wide, dark latewood. Change is abrupt (thin arrow) due to rapid exhumation. Due to mechanical stress the root grew asymmetrically, first laterally, then downwards. A major injury killed the cambium along 60% of the circumference, opening the bark-less root sectors to erosion (thick arrow). The remaining sector with cambium on the lower part of the root kept growing the reaction-wood rings, slightly overlapping the wound. Post-injury latewood is thinner than pre-injury latewood! Minor discolouration by phenolic compounds above the line connecting the two wounds protects the upper part of the root from infections. Tianshui, Gansu, China. Sample SMM125. Photo #3072. Scale: 5 × 5 mm grid pattern in background.

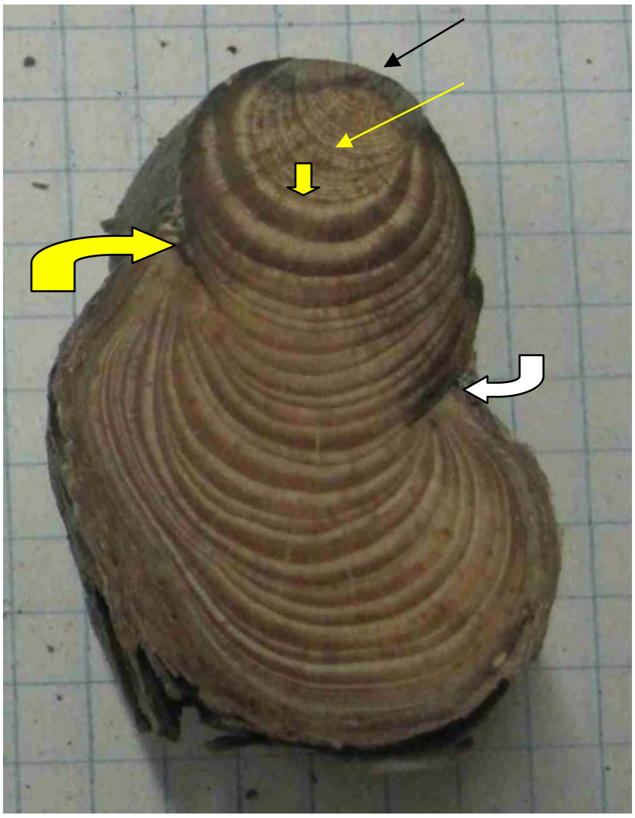

Fig. 26. Initial rings have been heavily eroded, down to the pith (pith marked by thin, black arrow). Following a decade of underground growth with narrow rings and narrow latewood, rapid exhumation and injury yielded damage to about the top half of the perimeter. The remaining lower half kept growing. Boundary between the two parts is marked by a narrow, yellow arrow. After two years a 60% cambium dieback occurred, yielding asymmetric growth. Both events allowed sustained growth of narrow rings and slightly thickened latewood, possibly undeground. A rapid, major change in mechanical stresses initiated the growth of reaction wood (wide arrow) (two extra wide rings with extra wide latewood). Sustained, asymmetric growth of reaction wood downwards formed the mass of the root. Later two wounds (curved arrows) caused cambium dieback, subsequently overgrown by onlapping rings. Each injury caused change of growth direction, ultimately producing a a twisted root. Slight discoloration in the upper right quadrant due to deposition of phenolic substances protects the root from biological damages. Tianshui, Gansu, China. Sample SMM117. Photo #3067. Scale: 5 × 5 mm grid pattern in background.

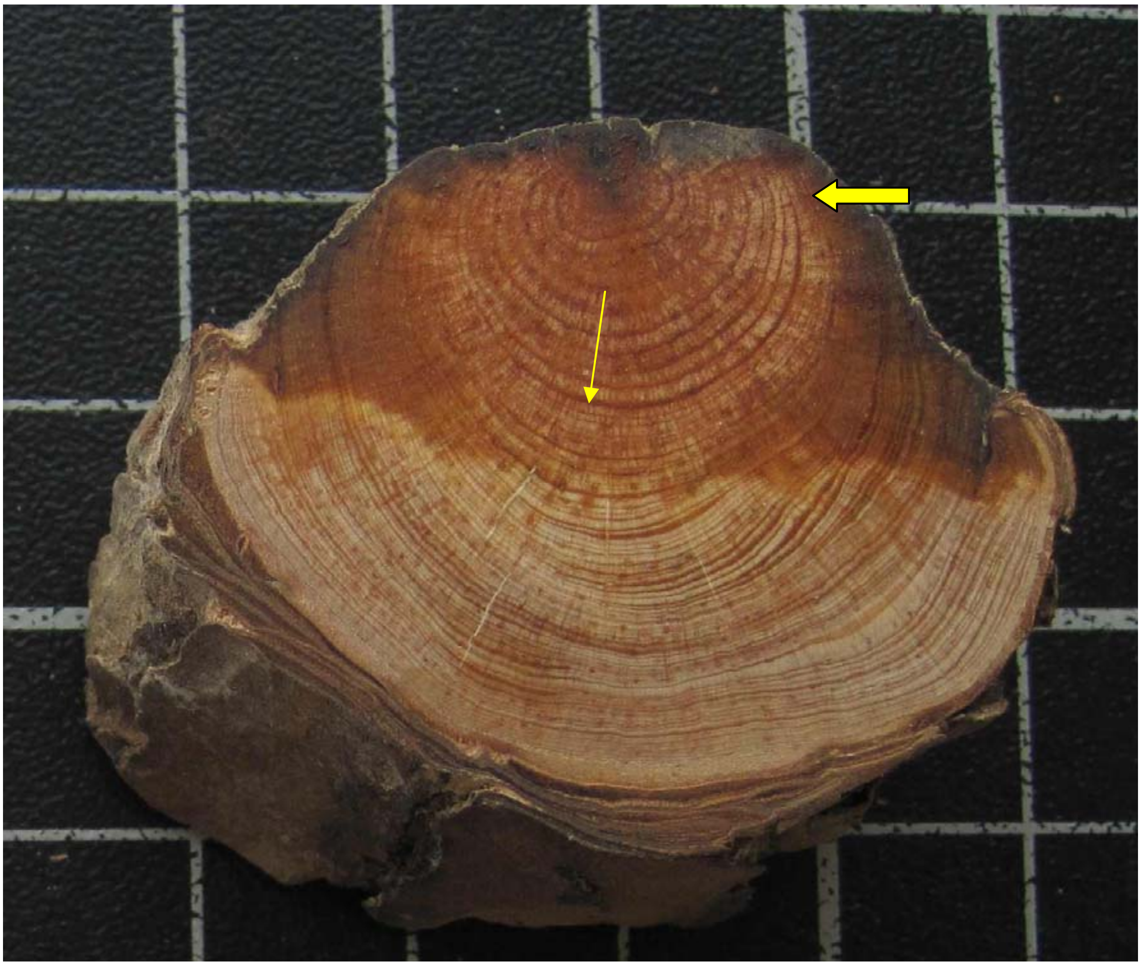

Fig. 27. This root suffered lot of erosion both on top and laterally, which removed much evidence of its exhumation history. This can be reconstructed only from changes in ring and latewood width. Wide rings with visible latewood form the centre. These suddenly give place to narrow rings with barely visible latewood (thin arrow). Termination of the latter rings (rather growth increments only) is on top of the section, indicated by significant narrowing (wide arrow). Unfortunately, this portion is camouflaged by dark brown phenolic compunds, which protect the barkless, bare root from biological degradation. Below the phenol-dyed portion, which is still protected by the bark, allowing sustained growth, bundles of rings displaying variable thickness of ring width and latewood width follow. These mark localized stress of uncertain origin. Ring width gradually decreases downward, reflecting the aging of the wood. Most of this root section is made of stem-like texture, except a few rings in the centre. Kong Tong Mts., Gansu, China. Sample KTM104. Photo #2259. Scale: 10 × 10 mm grid pattern in background.

Fig. 28. This root section is almost fully covered by intact bark, except on the top. Here, dark phenolic compounds protect the exposed wood from biological degradation. The wound exposed inner rings: about twenty, narrow rings have been eroded, possibly by repeated injuries. The central, symmetrical rings are narrow, bearing barely visible latewood: this is root texture, grown underground. However, this portion bears numerous resin ducts (scattered, small, brown spots), which indicate injury, not visible in this section. The resin duct-containing section is eclosed in a light-coloured spot of phenolic compounds. The root texture suddenly gives place to thicker rings with visible latewood (thin arrow), which are reaction wood formed due to exposure-induced stress. Tianshui, Gansu, China. Sample SMM106. Photo 3060. Scale: 5 × 5 mm grid pattern in background.

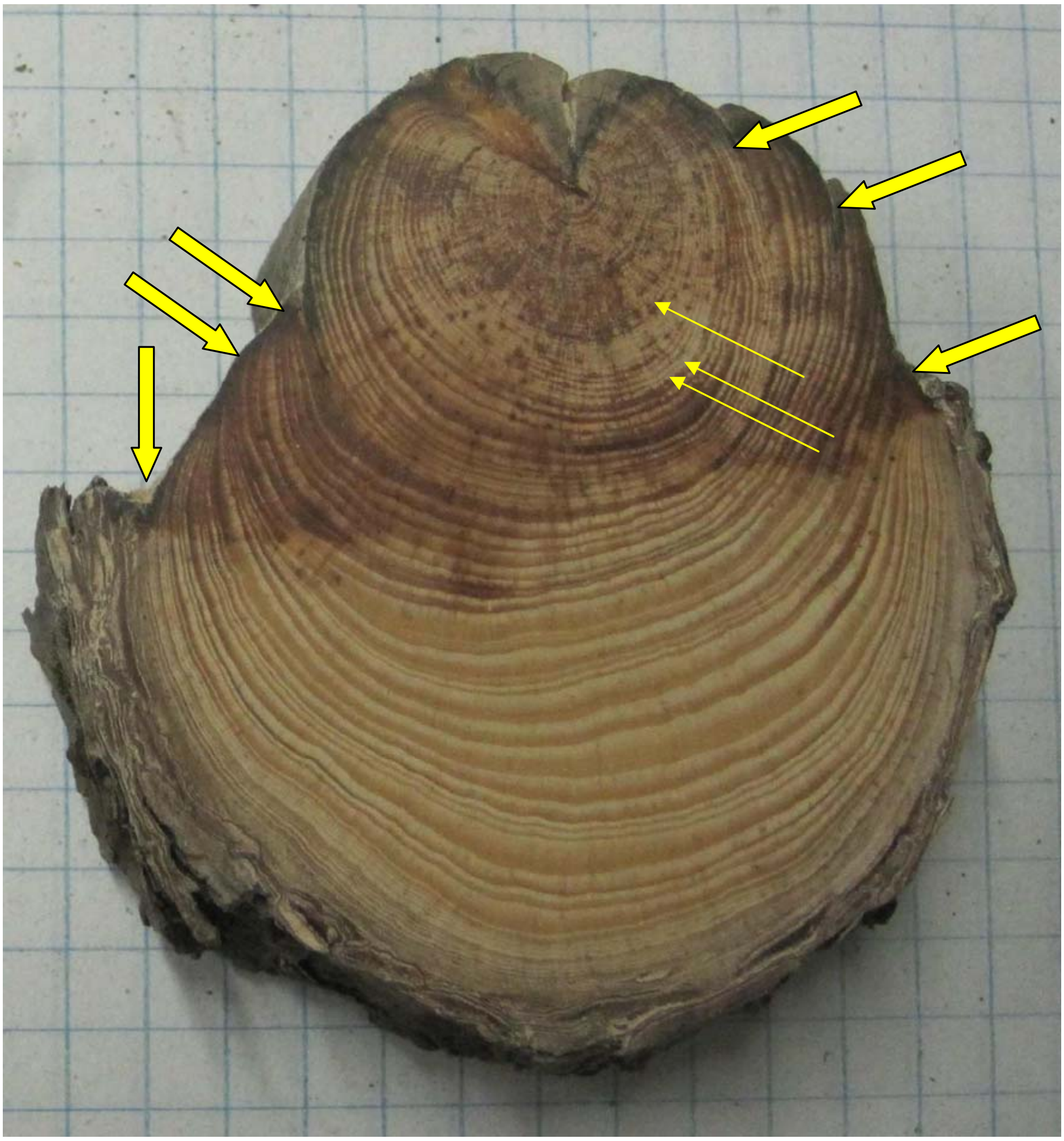

Fig. 29. Severely eroded root, which suffered multiple injuries. An almost circular innermost portion of very narrow rings and barely visible latewood is surrounded by a similar bundle of rings, with slightly thicker latewood. Their boundary is sharp, indicating rapid exhumation process (thin arrow). The root did not reach the surface while these rings grew. The next sharp boundary (double thin arrow) where reaction wood of moderately wide rings and moderately thick latewood starts, is the first result of exhumation , probably out of this section, in the vicinity. From here onwarda all rings belong to reaction wood of variable, but considerable ring width and latewood width. Repeated wounds are partially repeatedly overgrown by onlapping rings (wide arrows). Wounds extend far below the onlapping rings along the circumference, allowing exact dating of the injury. Tianshui, Gansu, China. Sample SMM126. Photo #3063. Scale: 5 × 5 mm grid pattern in background.

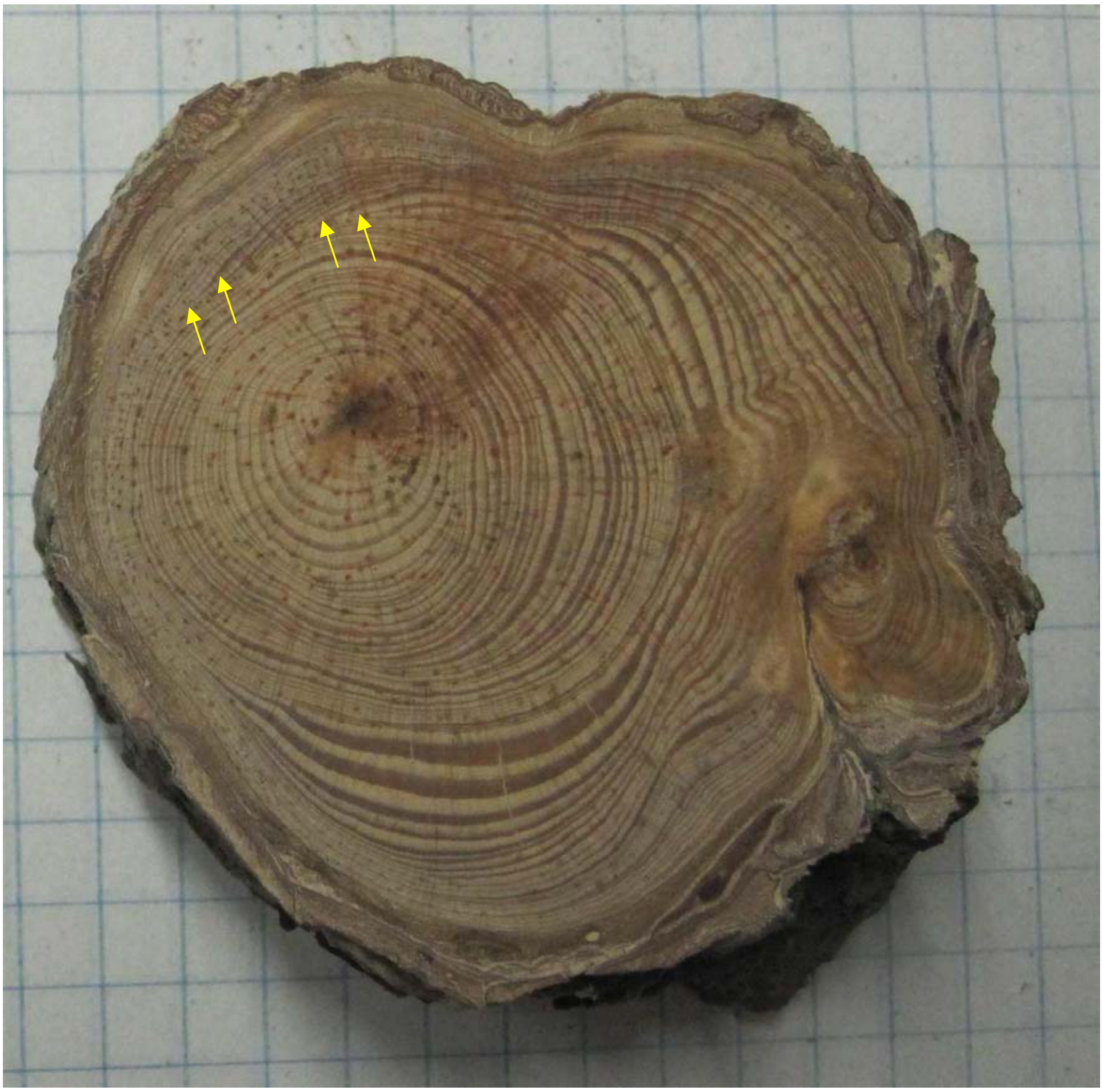

Fig. 30. Initial root texture gradually changes to stem texture, indicating gradual exhumation. More than six rings in the centre are typical root rings: narrow ones with barely visible latewood. All are almost perfectly circular. With slowly increasing latewood width the perfect circular symmetry deteriorates: thicker rings of various ellipticity follow, with a few, partial reaction wood rings (thick latewood). Onlapping rings without any trace of injury indicate cessation of cambial activity in this section without expressed physical damage to the root. A set of thin arrows indicate terminations. Strongly curved rings on the right belong to an enclosed branching root. Tianshui, Gansu, China. Sample SMM115. Photo #3064. Scale: 5 × 5 mm grid pattern in background.

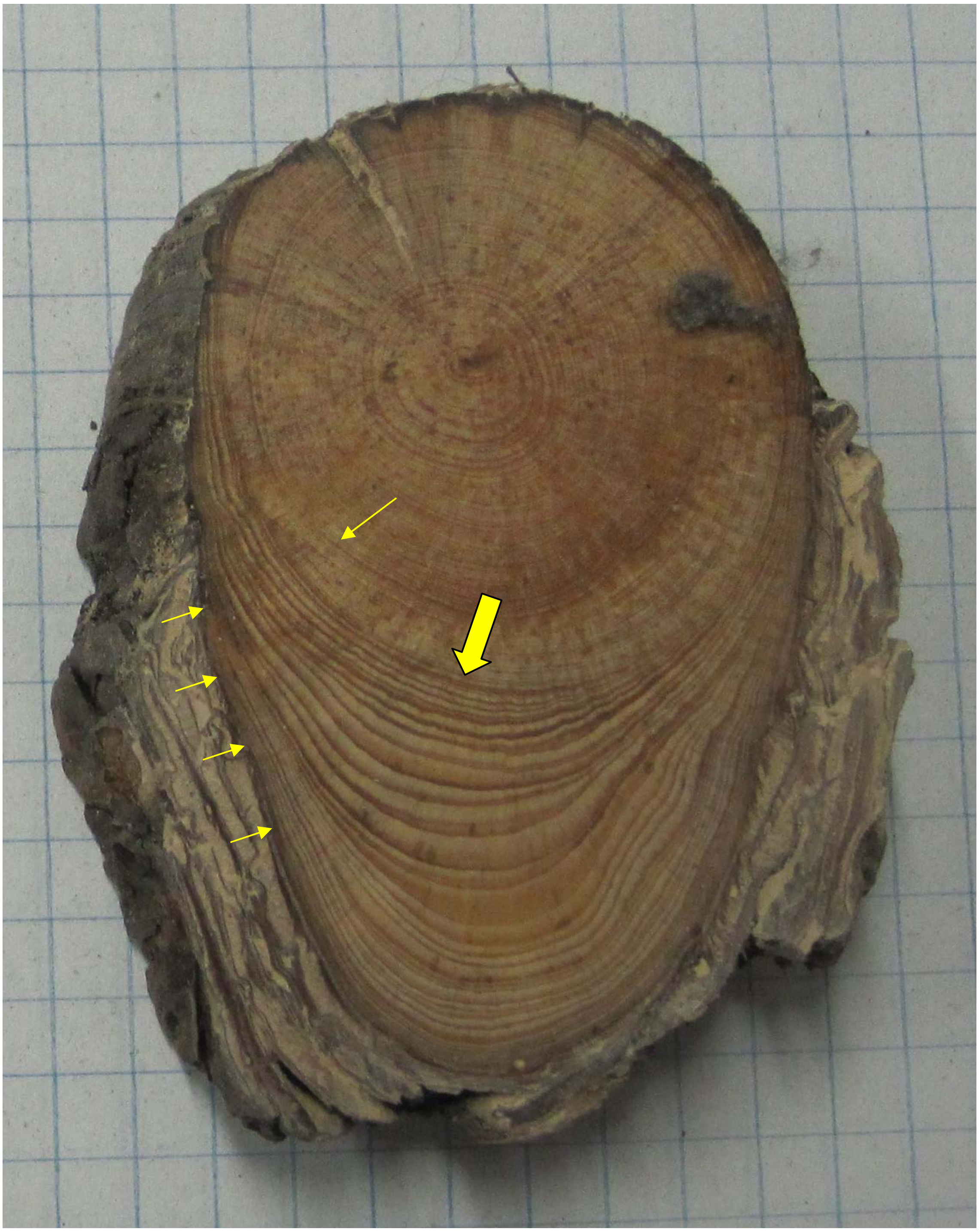

Fig. 31. Strongly eroded root with marked downward asymmetry. Perfectly circular central part of root texture: thin rings and barely visible latewood. Rings starting from thin arrow lose circular symmetry, although both rings and latewood remain thin. The cause of this change is not obvious from this section: probably increased stresses under less soil cover acting on the root are responsible for the change – start of exhumation(?) Sudden appearance of reaction wood (wide arrow) is a marker of rapid exhumation. Certainly an injury occurred at this time, although the wound has disappeared due to erosion of the upper part of the wood. Whether the injury was repeated or not, we cannot tell – all evidence were lost to abrasion. Offlapping rings terminations (set of four thin arrows) are markers of gradual cambium dieback. This retreat of cambium is responsible for the lack of onlapping rings which normally overgrow open wounds. Tianshui, Gansu, China. Sample SMM130. Photo #3076. Scale: 5 × 5 mm grid pattern in background.

Table 1. Date of anatomical changes in root texture due to exhumation.

Sample number	Root above soil		Wound								Symmetry	Reaction wood							Disk photo
															asymmetric growth				
	in part	fully	no-ne	near-by	open	partly overgrown	fully healed / overgrown	repeated wounding	abrasion / partial loss of rings	phenolic compounds	initially cricular / changed to elliptical	none	wide rings	thick latewood	downwards	laterally	changing axis	external thin rings	
Tianshui 1																			
SMM101		+											1972-	1972-					#2258
SMM102	+																		
SMM103	+																		#3083
SMM104	+					2001, 2005		+		--	1998		1998-	1998-	+	+		--	#3059
SMM105	+												1993-	1993-	1993-			2003-	#3061
SMM106	+				+					+			1990-		1990-			--	#3060
SMM107	+												1993-	1993-		1993-			#3070
SMM108	+																		#3084
SMM109	+		+							--	--		1983-, 1998-	1983-, 1998-	1998-	1983-	+	--	#2254
SMM110	+												1995	1995-	1995-	1995-			#3078
SMM111		+											1976-	1976-				1991-	#3086
SMM112	+									+			2000-	2000-					#3079
SMM113	+												1989-	1989-			2000-		#3085
SMM114	+								+				1987-1996	1987-1996				1997-pith 1983	#3081
SMM115	+	No clear buried / exposed boundary – exposure signals everywhere																	#306

Sample number	Root above soil		Wound								Symmetry	Reaction wood							Disk photo
	in part	fully	no-ne	near-by	open	partly overgrown	fully healed / overgrown	repeated wounding	abrasion / partial loss of rings	phenolic compounds	initially cricular / changed to elliptical	none	wide rings	thick latewood	asymmetric growth			external thin rings	
															downwards	laterally	changing axis		
																			4
SMM116	+																		#3066
SMM117		+							+				1983-2005	1983-2005			1973-	2006-pith 1956	#3067
SMM118	+		+								1978		1978-	1978-	1978-				#2255
SMM119	+						1973, 1986, 1988	+		+									#3068
SMM120	+	BRL																	#3077
Tianshui 2																			
SMM121	+	BRL																	#3087
SMM122	+	BRL																	#3065
SMM123	BRL	+																	#2256
SMM124		+											1987-	1987-					#2257
SMM125		+							+				1967-	1967-	1984-	1967-	1984-		#3072
SMM126		+			1972					+			1960-	1960-	1960-	--	--	1998-	#3063
SMM127		+					+	1967, 1982		+			1982-	1982-		1982-		1994	#3058
SMM128	+									+			1990-2000	1990-2000				2001-	#3082
SMM129							+	1989, 1999		+	--		--	1985-	--	--	--	--	#2251
SMM130		+							+				1982-	1982-	1982-				#307

Sample number	Root above soil		Wound								Symmetry	Reaction wood							Disk photo
	in part	fully	no-ne	near-by	open	partly overgrown	fully healed / overgrown	repeated wounding	abrasion / partial loss of rings	phenolic compounds	initially cricular / changed to elliptical	none	wide rings	thick latewood	asymmetric growth			external thin rings	
															downwards	laterally	changing axis		
																			4
Kong Tong Mts																			
KTM101	+																		
KTM102	+																		
KTM103	+																		
KTM104	+													1952-					#2259
KTM105	+					1998				+					--	--	--	--	#2252

All disks were cut between 25 and 29 May 2010. The growth year barely started. Almost all samples bear a thin earlywood of 2010.
BRL – broadleaved tree.