New estimations of ΔR for the South-eastern Pacific obtained from Marine20

Contents

Abstract

Radiocarbon (^{14}C) is a cosmogenic radionuclide produced in the upper atmosphere that is frequently used in paleoceanography to date sediments cores. However, dating marine sediment records have an important particularity, given that contemporaneous terrestrial and marine organism has different ^{14}C ages because the ocean is a source of ^{14}C , and thus marine organisms appear to be older than contemporaneous terrestrial organisms. This effect is called marine reservoir effect (MRE), it varies in space and time as a function of changes of water mass origin and circulation.

In particular case for Peru and Chile coastal, MRE could due to upwelling intensity, the origin of the upwelled waters, therefore it needs to be considered while dating marine sediment cores. Recently an internationally agreed marine radiocarbon age calibration curve (Marine20) was released and provides a global average marine record of radiocarbon from 0 to 55 cal kyr BP, thus serving as a baseline for regional oceanic variation.

Here we compare the difference of marine to terrestrial curve is called marine reservoir ages (MRA),between previous version with the new calibration curve based on 185 published data (marine-terrestrial pairs samples obtained in the Eastern Pacific Ocean between 0 to 50°S). We applied a bootstrapping method and the output data were sorted for spatial position and time period. Then, we calculated the MRA by error propagation and generalized additive model. According to our results, the MRA shows a pattern of time-space distribution at millennial time scales, with larger MRA ages north of 22°S.

These observations suggest that forming water mass, upwelling process and river discharge were a keys factor that modulated MRA during the last 12 Kyr in the Eastern Tropical South Pacific. Moreover, the estimated MRA using the new radiocarbon age calibration curve(Marine20) is up to ~400 years higher compared to the MRA obtained using the previous calibration curve(Marine13), indicating that the timing of paleoceanographic events based on marine sediment records needs to be revised and updated.

Introduction

Radiocarbon-14 (^{14}C) has produced by nuclear reaction due to cosmic rays in the upper atmosphere ~15km. Then ^{14}C is reacted with molecular oxygen to generate heavy carbon dioxide that is assimilated by primary producers via photosynthesis, reaching higher trophic levels via the food chain (Alves et al. 2018).

The contemporary distribution of ^{14}C in the ocean is closely related to the input of ^{14}C atmosphere to the ocean, the history of surface ocean $\Delta^{14}C$ ($^{14}C/^{12}C$) excess depends on the mixing process and average CO_2 invasion rate (Broecker et al. 1985). Geographic variation in the CO_2 invasion rate is dealing for temperature: CO_2 solubility, CO_2 diffusion and viscosity of seawater (Broecker et al. 1985).

The important pattern is to latitudinal and longitudinal variations of $\Delta^{14}C$ are pronounced in the Pacific ocean where the sizable west-to-east decrease in water column inventory (Broecker et al. 1985). The $\Delta^{14}C$ sign of Cold coastal water (CCW) off Peru and Chile is mixed between lighter variety South Antarctic mode water(SAMW) and an upper ocean end-member typified by the warm and salty water found in the subtropical high-salinity water or in the core of the Equatorial undercurrent (EUC) (Toggweiller et al. 1991).

In order to calculate radiocarbon age which assumes a time-independent atmospheric ^{14}C level in all past times. However, specific marine ^{14}C content could differ from the atmosphere CO_2 (Stuiver & Polach, 1977), called Marine reservoir effect (MRE).Therefore, Calibration age is required to correct by ^{14}C activity based on tree-rings in equilibrium with CO_2 atmospheric, and variability of CO_2 ensemble from Ice-core, regional winds, water depth and local upwelling which is called marine reservoir ages (MRA). It´s define the difference between Calendar age and ^{14}C age of dissolved inorganic carbon (DIC) in the mixed ocean surface layer with respect radiocarbon age of CO_2 in the Northern hemisphere (NH) atmosphere at that location (Heaton et al. 2022).

In practice, The local depletion of MRA (hereafter ΔR) is the difference between this modeled marine ^{14}C age and the measured ^{14}C age of the marine carbon sample (Russell et al. 2011). this concept could be updated how to difference between of Terrestrial´s age (it estimated by Calender date or Northern/Southern hemisphere calibration, plumb 210 calibration and Uranium to thorium calibration) and marine´s age estimated by marine curve calibration.

In Peru and Chile coast, Ortlieb mentioned that the importance of marine correction may also incorporate a ΔR, which can reach particularly high values in high-latitude coastal zones and regions affected by strong upwelling processes (Ortlieb et al, 2011). Also, another factor that could alter ^{14}C is freshwater input through rivers or runoff can bring CO_2 derived from young organic debris in south 33°S (Merino et al. 2019).

Latitudinal gradient of ΔR off Peru to Chile during early Holocene which modulated for change Humboldt system could due to upwelling enhancement alone and required that upwelled waters were more ^{14}C -depleted (Carré et al, 2016; Fontugne et al, 2004). So that, the ΔR during early to mid-Holocene were higher than Late Holocene owing to poleward contraction of the southern westerly wind (SWW) belt at ~53°S has increased contribution SAMW to the EUC (Hua et al, 2015).

At stated above the latitudinal gradient of ΔR also could explained for geographic origin of upwelled waters changed, potentially to Antarctic intermediate waters (AAIW) that are even more ^{14}C-depleted than SAMW (Carré et al, 2016). This pattern could be explained that the front between Equatorial subsurface water (ESSW) and Subantarctic Surface Water (SSW) was likely located north of its modern position (Carré et al. 2016).

Recently, Many researchers proper a new calibration curve base on MRA (Marine20) is to define the difference, at the Calendar age, between ^{14}C age of dissolved inorganic carbon (DIC) in the mixed ocean surface layer at that location and the ^{14}C age of CO_2 in the Northern or Southern Hemispheric atmosphere (Heaton, 2020). Also, this work mentioned if you were to calibrate with Marine20 you would update ΔR at your studying zone.

Marine20 is improver than Marine13 during 55 to 10.5 kyrs BP, through usage BYCYCLE model which incorporate global-scale paleoclimate and carbon cycle changes that migth influence oceanic ^{14}C depletion as currently possible (Heaton et al. 2022). Difference of Marine20 and Marine13 in magnitude is small during 14.2 Kyrs to now and recent past, you easy manner would calculate ΔR of Marine 20 if ΔR of Marine13 were add up ~150 ^{14}C yrs (Heaton et al. 2022).

Therefore, It is important to estimate ΔR for dating tools that estimate a radiocarbon age. In this work, I update values of ΔR according to the calibrated curve (Marine20 & Shcal20). Also, I focus on the ΔR relationship with space-time variables (latitude, longitude, calibrated age, and uncertainty age), and whether the hypotheses that explain previous works, still would validate with Marine20.

Materials and methods

This work estimates the ΔR off Peru & Chile (0 to 50 °S) during the last 12 Kyr BP. Therefore, I compiled several previous estimations. It was 185 pairs Marine-terrestrial samples of different organic materials (wood, shell and others organic remains) obtained in the South-Eastern Pacific Ocean (SEPO). This data-set include conventional age estimated of ^{14}C, ^{210}Pb and collected date. For all conventional ages were used its uncertainties excluding collected age that only assumed 0.25 years how its uncertainties. Bellow, I attached the input data set.

Figure 1: alt text

Figure 2: alt text

I used a Bchron package (Hastell & Parnell, 2008) in R programming to estimate the maximum probability of calibrated marine and terrestrial age according to Marine20 and Shcal20, respectively (Heaton et al. 2020; Hogg et al. 2020). Then I calculated the difference between each pair under bootstrapping suggested by Russell et al. 2011. After that, I reduced the pool data from 185 to 96 samples for decreasing the overweight of repeated data belonging to the same stratigraphic unit. So that, I solved this issue, using "error weight means" (EWM) deleting extra values and reducing error calibration.

I sorted of data (without repeated data) for period time: Early Holocene (EH) was 11.5 to 7 Kyr BP, Mid Holocene (MH) was 7 to 4 Kyr BP, Late Holocene (LH) was 4 to 0.2 Kyr BP, and Current warming period (CWP) is last 180 years; space variables: latitude and longitude; calibrated age: maximum probability age and Uncertainty of maximum probability age; ΔR : estimated value and its uncertainty.

Next, I did do a Factorial multivariate analysis, using the Factominer package, and a Generalized analysis model(GAM), using mgcv package, of 96 pairs of data. Finally, I recalculated ΔR according to latitude and calibrated age before to present (Cal yr BP) in boxes like previous work (Ortlieb et al. 2011; Carré et al. 2016), using EWM for decreased error propagation.

Principal outcomes

In this part, I would show highlight the results of this work.Multivariate analysis was based on seven selected variables over the length of whole data set (n=96). PCA results indicate that most variance of the data set 52% was encompassed by the first and second principal components (fig. 1).

Principal component analysis (PCA)

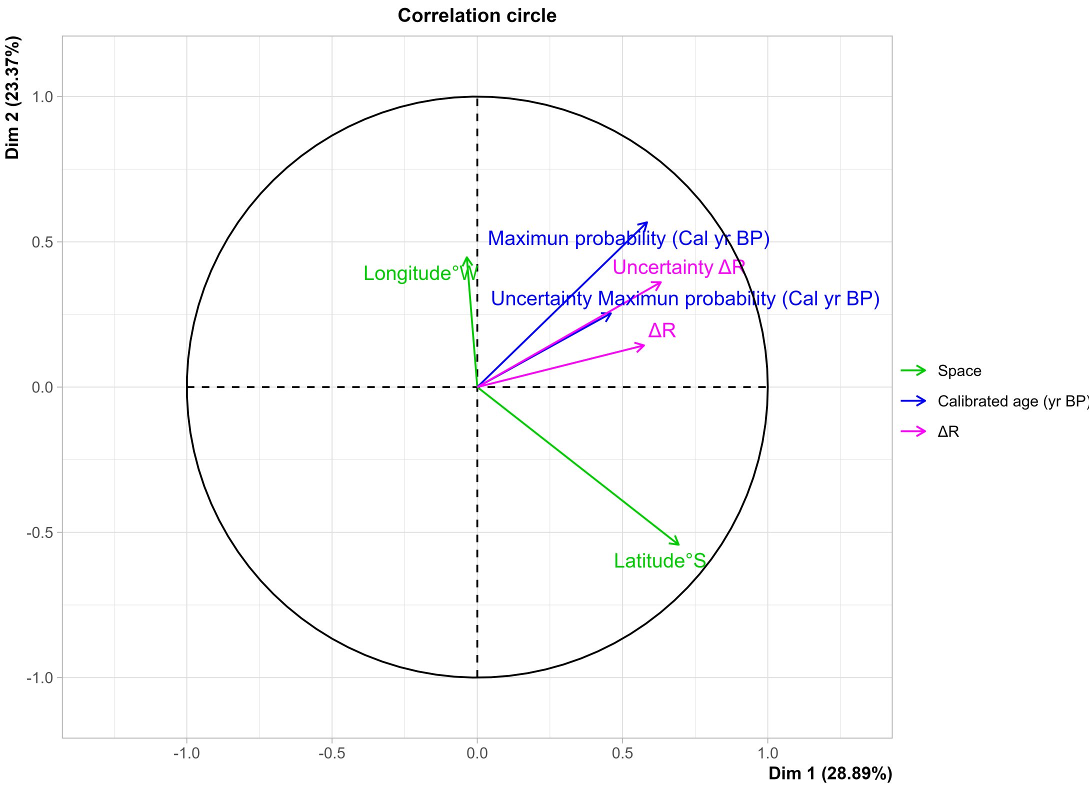

Figure 1. Biplot of Principal component of data (n=96)

PC1 (29%) is interpreted as signal of latitudinal position. PC1 has the highest loading for latitude, uncertainty of ΔR and calibrated age. PC2 (23%) is interpreted as signal of longitudinal position. PC2 has the highest loading for calibrated age, longitude and uncertainty of ΔR (fig. 1). Hence, it can be said that the seven variables represent the variability of the data. My first assumption is to the difference in species or organic remains is not outstanding for estimating ΔR.

Clusters of Local MRA for period time

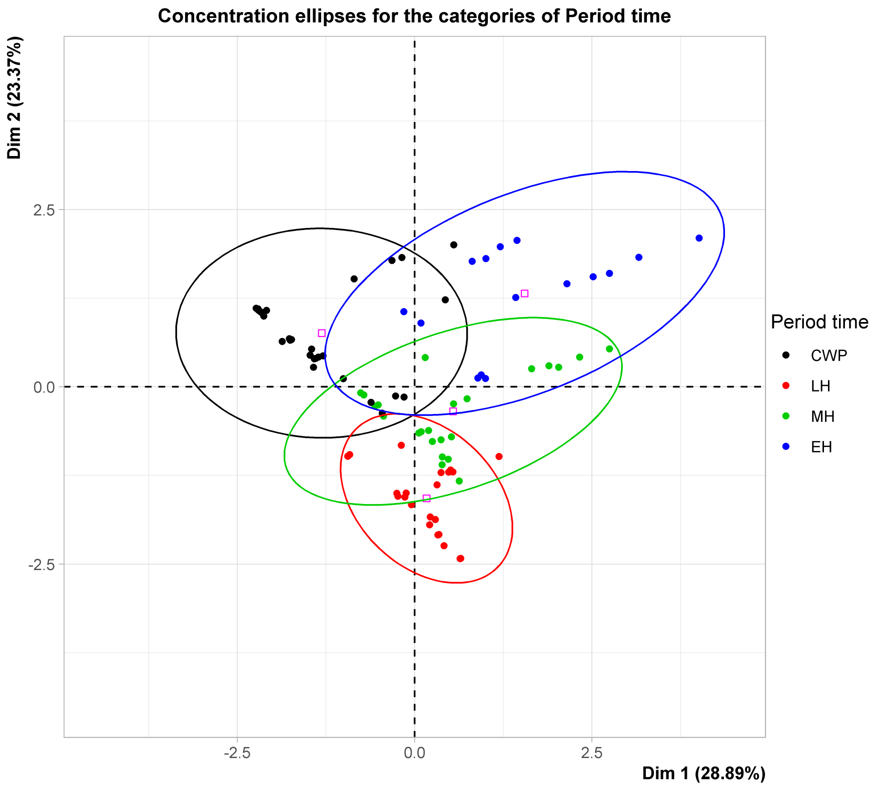

Figure 2. Concentration ellipses for the categories of period time. CWP:Current warming period (black), LH:Late Holocene (red), MH:Mid Holocene (green), EH:Early Holocene (blue)

According to periods, It could be no evidence of a temporal effect on the ΔR during the Holocene except for CWP. Therefore, I noticed a small difference between the periods (fig. 2). Therefore, we didn't use period-time as an input variable in the model which will explain forward.

Latitudinal distribution of ΔR off Peru to Chile

Some past works showed the difference in latitudinal of ΔR off Peru to Chile. However, it did not validate a criterion for dividing in zones before estimating ΔR.

Figure 3: alt text

Therefore, I use GAM to find out about the spatial & temporal effect on MRA off Peru & Chile. I built a simple GAM regarding the effects of individual variables and its interactions (Wood, 2017). This model has adjusted Tweedie distribution with the logarithm link function and uses a cubic spline smooth for each variable. According to the output of GAM, this model has adjusted R^2 is 0.83 and desviance explained is ~85%. hence, this GAM represents the variability of MRA significantly.

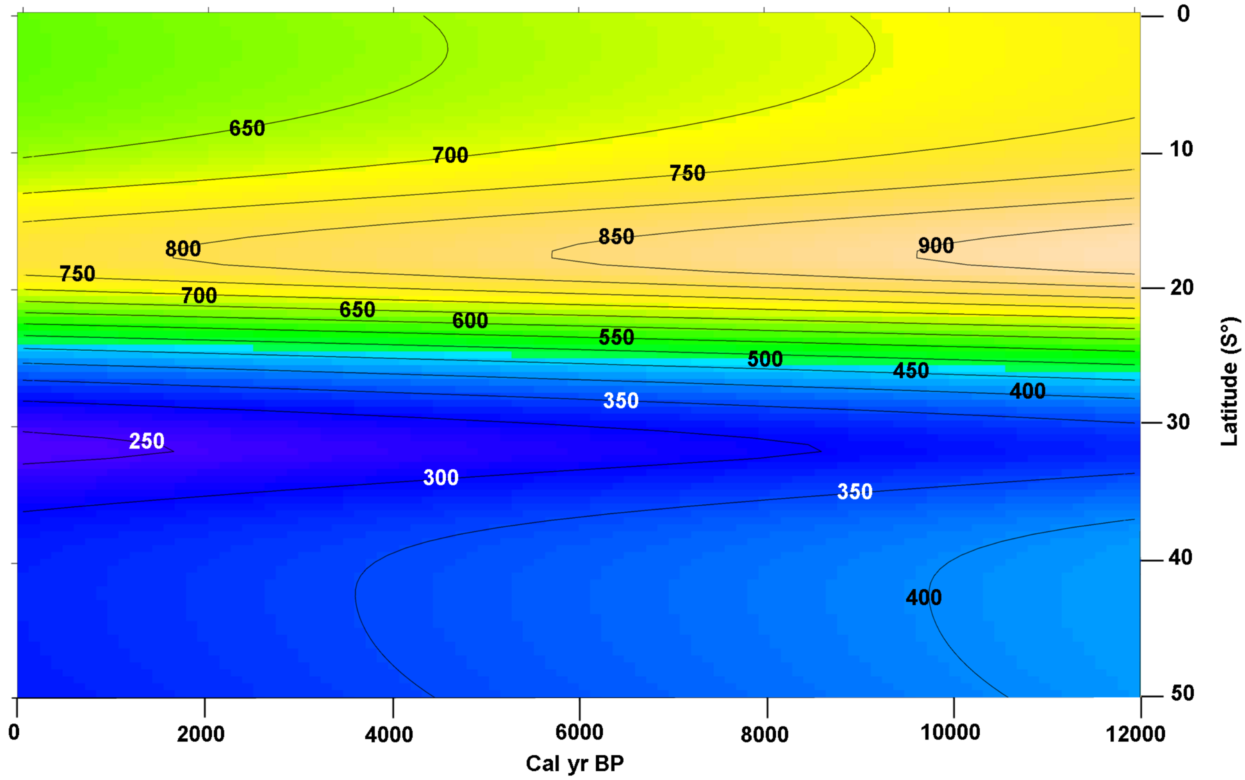

Figure 3. Latitudinal distribution ΔR , inferred for GAM, off Peru to Chile the last 12 Kyr BP

Then, I plotted ΔR GAM, regarding calibrated age and latitude according to GAM (fig. 3). In this picture, I can see a sharp latitudinal pattern which could mean gradient zone: 17 to 27°S. My second assumption is frontier is 22°S which mark off two zones: first (0 to 22°S) and second (22 to 50°S). the limit between the two zones could be due to oceanography and/or atmosphere change during the last 12 Kyr BP.

ΔR estimated in boxes under Marine20

At the state above the latitudinal pattern of ΔR split off in two zones is reliably acceptable. Accordingly, I can estimate ΔR by latitude and periods of time, similar to previous works (fig. 4)(Carré etl al, 2016, Ortlieb et al. 2011). The Boxes were built assuming how ΔR is constant within boxes and its frontiers are calculate one sigma add 5% more of estimated average ΔR.

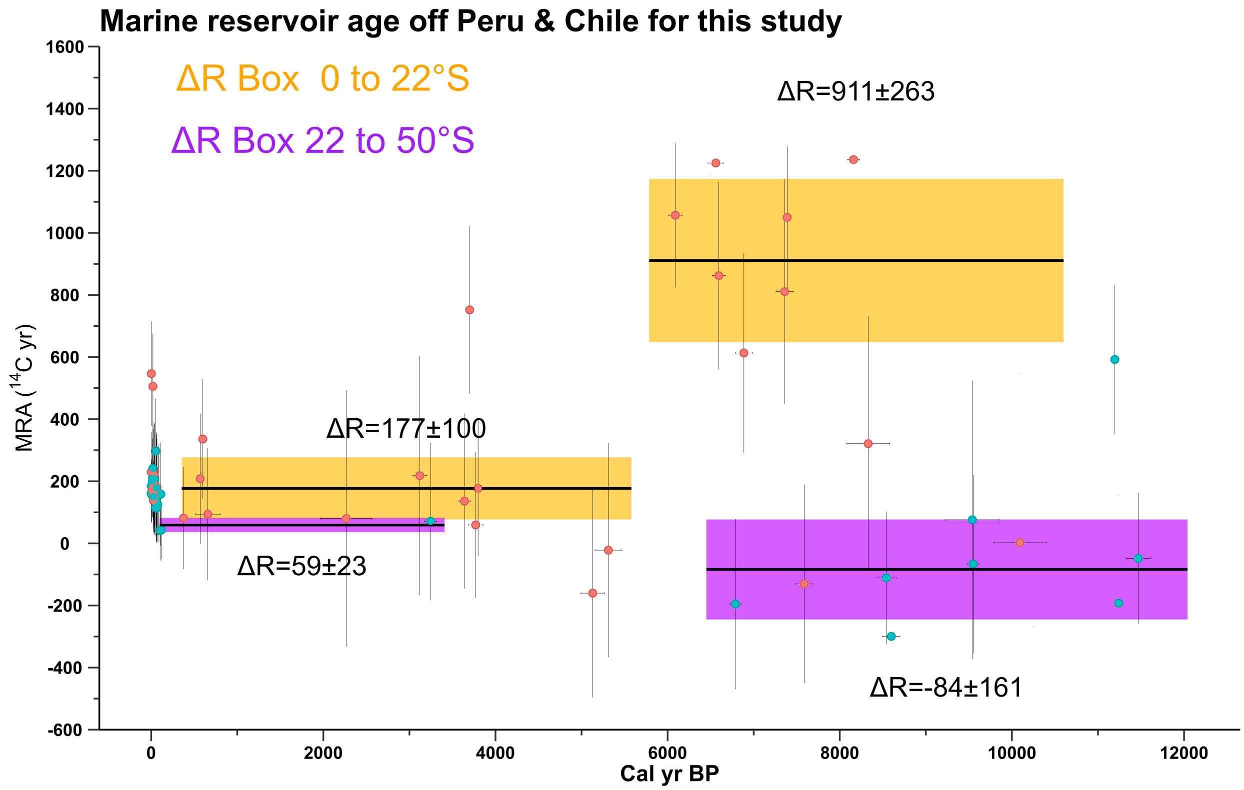

Figure 4. Diagram of ΔR off Peru & Chile in boxes. Orange boxes belonged from 0 to 22°S and purple boxes belonged from 22 to 50°S.The thick black lines is mean value of MRA each box.

In this picture, I show the estimation of ΔR in boxes for two zones. There are four boxes (two orange and two purple) boxes of ΔR that have belonged to different latitudinal positions and periods of time (orange boxes: latitude 0-22°S, 10.6 to 5.8 Cal Kyr BP [11.2 to 6.4 Kyr BP] and 5.6 to 0.3 Cal Kyr BP [6.2 to 0.9 Kyr BP]; purple boxes: latitude 22-50°S, 12 to 6.5 Cal Kyr BP [12.6 to 7.05 Kyr BP] and 3.4 to 0.1 Cal Kyr BP [4 to 0.7 Kyr BP]). where the values with "[ ]" represents Conventional age interval.

Additionally, We also estimated ΔR the last 100 years for 0-22°S and 22-50°S were 140±5 and 162±6, respectively. However, boxes of CWP was not plotted to avoid overlapping in the picture.

Discussion

Figure 5.Animation of ΔR off Peru & Chile in boxes and MRA in the background, estimated for each calibrated curve how to difference between Shcal13 & Marine13 (grey) and Shcal20 & Marine20(red). Estimated ΔR by Ortlieb et al. 2011(grey); by Carré et al. 2016(green and blue) and by this work(orange and purple). The thick black lines is the mean value of MRA each box

This animation showed comparative principal outcomes of previous works, and this work(fig. 5). The boxes of ΔR are the same pattern as the boxes proposal for Carré et al. 2016. During EH, the magnitude of ΔR was higher in the box estimated with Marine20 than Marine13 which were estimated for 0-22°s (~400 years) and 22-50°S (~100 years). In the same way, during the Mid to Late Holocene, The difference of ΔR can repeat for 0-22°S (~50 years) and 22-50°S (~100 years).

The difference of ΔR could be partially explained for $\Delta^{14}C$ deficit average according to Marine13 is ~300 years from 0-10.5 Cal Kyr BP (Reimer et al. 2013) and according to Marine20 is ~500 years from 0-11.6 Cal Kyr BP (Heaton et al. 2020). But ΔR off 0-22° was estimated during EH which exhibited an excess of ~200 years may due to MRA estimate in Marine20 is coupled to atmospheric ^{14}C and not Marine13 (Heaton et al. 2020).

During eh, The latitudinal gradient of ΔR between boxes 0-22°S and 22-50°S (~1000 years), also is looking up in this work (fig. 4). The latitudinal gradient of ΔR likely was modulated for the minor contribution of SAMW to EUC and ESSW , has low $\Delta^{14}C$, in forming CCW and/or increase upwelling during EH (Carré et al. 2016; Hua et al. 2016; Ortlieb et al. 2011; Fontugne et al. 2004).

Another hand, The latitudinal gradient of ΔR estimated with GAM model (fig. 3) showed that the transitional zone between 17 to 27°S probably interpreted zone of Permanent upwelling moved northward during On Holocene. Also, it can explain how to increase the input of fresh water which might contribute to a reduction of the reservoir effect (Merino et al. 2019).

Additionally, ΔR in boxes in this work show that absence of sample of ~6 kyrs BP could be explained which sediments weren´t recorded in marine sediment for biogeochemistry process for instance: poor preservation of organic matter, low sedimentation rate and high coastal erosion due marine transgression.

Conclusions

The spatial variability of ΔR could be modulated by three aspects: 1) Oceanographic changes in associated origin CCW and its circulation, 2) Enhanced upwelling regionally off SEPO, and 3) Climatic changes inferred river discharge by precipitation during Holocene in sourth limit of Humboldt system. Furthermore, a relevant aspect was decreased uncertainty of ΔR for using EWM and bootstrapping than previous estimations.

Future research should include more variables (e.g marine CO_2 off Peru to Chile) and calibrated age estimation by others proxies or methods (e.g Uranium to Thorium rate) to improve the description of the pattern and will be able to build the best ocean-atmosphere model.

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R code

Bellow I attached a R-script. Contact Us here, if you consider to give opinions, suggestions and questions.

```
##################################################################################
#to start

setwd("~/Radiocarbon-reservoir/")#directory

library("Bchron")

#To delete outliers

d=read.csv("Radiocarbon reservoir.csv",sep=";",dec=".",header = TRUE)#data all data
d=as.data.frame(d)
d$label=paste(d$reference,d$Latitude,"°","-Material:",d$type.of.material,"Sample:",d$pair,sep=" ")
d$curve=d$calibrate.curve
d$curve[d$calibrate.curve=="terrestrial"&d$Convencial.age>=126]="shcal20"#155 ± 11 BP (Hogg et al. 2019
d$curve[d$calibrate.curve=="marine"]="Marine20"
d$curve[which(d$calibrate.curve=="terrestrial"&d$Convencial.age<126)]="normal"
#d$curve[which(d$calibrate.curve=="terrestrial"&d$Convencial.age<0)]="sh3"
d$Convencial.age[which(d$calibrate.curve=="marine"&d$Convencial.age<603)]=604

age.t=BchronCalibrate(
  ages = d$Convencial.age,
  ageSds = d$SD.convencial.age,
  eps = 1e-05,
  calCurves =d$curve,
  positions = d$Latitude,
  ids=d$label)

hafsigma=.382924922548026#0.382924922548026
onesigma=.682689492137086#0.682689492137086
twosigma=.954499736103642#0.954499736103642

#p=hafsigma# half sigma
p=onesigma#one sigma
#p=twosigma#two sigma

d$lower=NULL
d$upper=NULL
d$max=NULL
d$median=NULL

vvv=NULL
sss=NULL

for (i in 1:dim(d)[1]){
  d$mean[i]=sum(age.t[[i]]$densities*age.t[[i]]$ageGrid)
  d$median[i]=age.t[[i]]$ageGrid[round(length(age.t[[i]]$densities)*0.5)]

  if(length(age.t[[i]]$ageGrid[which(age.t[[i]]$densities==max(age.t[[i]]$densities))])==1){
  d$max[i]=age.t[[i]]$ageGrid[which(age.t[[i]]$densities==max(age.t[[i]]$densities))]
  }else{
    vvv=age.t[[i]]$ageGrid[which(age.t[[i]]$densities==max(age.t[[i]]$densities))]
    sss= abs(vvv-d$mean[i])
  d$max[i]= vvv[which(sss==min(sss))]
```

```
  }

  if(max(age.t[[i]]$ageGrid[which(cumsum(age.t[[i]]$densities)<cumsum(age.t[[i]]$densities)[which(age
  d$upper[i]=min(age.t[[i]]$ageGrid)
  }else{
  d$upper[i]=max(age.t[[i]]$ageGrid[which(cumsum(age.t[[i]]$densities)<cumsum(age.t[[i]]$densities)[w
  }

  if(min(age.t[[i]]$ageGrid[which(cumsum(age.t[[i]]$densities)>cumsum(age.t[[i]]$densities)[which(age
  d$lower[i]=max(age.t[[i]]$ageGrid)
  }else{
  d$lower[i]=min(age.t[[i]]$ageGrid[which(cumsum(age.t[[i]]$densities)>cumsum(age.t[[i]]$densities)[w
  }
  }

d$sdmean.lower=abs(d$lower-d$mean)
d$sdmean.upper=abs(d$mean-d$upper)

d$sdmedian.lower=abs(d$lower-d$median)
d$sdmedian.upper=abs(d$median-d$upper)

d$sdmax.lower=abs(d$lower-d$max)
d$sdmax.upper=abs(d$max-d$upper)

#for (i in 1:dim(d)[1]){
#X11();plot(age.t[[i]]$ageGrid,age.t[[i]]$densities,type="l",xlab="Cal BP",ylab="Density",main =d$labe
#abline(v=d$mean[i],col="gray")#mean value
#abline(v=d$lower[i],col="blue")# lower value
#abline(v=d$upper[i],col="red")#upper value
#abline(v=d$median[i],col="green")#median value
#abline(v=d$max[i],col="black")#maximum probability value!!!!!!!!!!!!!!!
#}

#######################################################################
#Method of Error propagation of variance, according to R.Reimer & P.Reimer et al. 2016
#according to R.Reimer & P.Reimer et al. 2016
#Asumption three sample is minimum of pool database
#Error in the weighted mean

error.weigthed.mean=function(r,dr,sigma=2,show=1,warning=0,...){
  if(is.numeric(r)&&is.numeric(dr)!=1){
    stop("Vector values is/are not number(s)")
  }else{
    if(sum(is.na(r)+is.na(dr))>0){
      stop("Vector values has NAs")
    }else{
      if(length(r)/length(dr)!=1){
        stop("Vector values are not same size")
      }else{
        if(sum(sigma<5&sigma>0)==0){
          stop("sigma is a value should be major 0 and less 5")
        }else{
          if(length(r)==1){
```

```
            rm=r
            delta.r=dr
            warn.sign="There is one value, suggesting aggregate more values"
          }else{
          if(length(r)==2){
            rm=sum(r/dr^2)/sum( 1/dr^2)
            delta.r=sigma*sqrt(1/sum(1/dr^2))
            warn.sign="There are two values, suggesting aggregate more values"
          }else{
            rm=sum(r/dr^2)/sum( 1/dr^2)
            delta.r =sigma*sqrt((sum(((r-rm)/dr)^2)/(length(r)-1))/(sum((1/dr)^2)/length(r)))
            warn.sign=NULL
          }
        }
      }
    }
    }
  }

if(sum(warning==TRUE,warning==FALSE,warning==T,warning==F,warning==1,warning==0)==0){
    stop("if you would see warning: TRUE or T or 1 if you not: FALSE or F or 0")
  }else{
    if(show==TRUE){
      print(warn.sign)
    }else{
      invisible()
    }
  }

if(sum(show==TRUE,show==FALSE,show==T,show==F,show==1,show==0)==0){
  stop("if you would see results: TRUE or T or 1 if you not: FALSE or F or 0")
  }else{
    if(show==TRUE){
      print(paste0("Mean of Reservoir effect is ",round(rm,0)," and Uncertainty of Reservoir effect is
    }else{
      invisible()
    }
  }
outcome=c(rm,delta.r)
invisible(outcome)
}
########################################################
#According to Russel et al.2011
#density of R is estimated for bootstrapping ("n")

n=1000000#resamples millon

d$calibrate.curve[d$calibrate.curve=="normal"]="terrestrial"

  funclist=list()
  for(i in 1:dim(d)[1]){
    funclist[[i]]=assign(paste0("funt",i),approxfun(density(age.t[[i]]$densities)))
    assign(paste0(d$calibrate.curve[i],i),sample(x=age.t[[i]]$ageGrid[1:length(age.t[[i]]$densities)]
                                              size =n,
```

```
                                                 replace=TRUE,
                                                 prob = funclist[[i]](age.t[[i]]$densities[1:length(ag
  }



#Estimated reservoir effect each sample
#samples

rlist=list()
sec=seq(2,dim(d)[1],2)

for(i in sec){
  rlist[[i]]=assign(paste0("r",i*.5),get(paste0("marine",i-1))-get(paste0("terrestrial",i)))
}

t.r=as.data.frame(cbind(as.numeric(d$Latitude[sec]),as.numeric(d$Longitude[sec]),d$max[sec],d$sdmax.lo

colnames(t.r)=c("Latitude","Longitude","Cal BP(Maximun probability)","error(yr)","R","sdR","pair","refer

for(i in 1:length(t.r$Latitude)){
t.r$R[i]=as.numeric(round(mean(get(paste0("r",i))),2))
t.r$sdR[i]=as.numeric(round(sd(get(paste0("r",i))),2))
}

label=paste0(t.r$Latitude,"/",t.r$`Cal BP(Maximun probability)`,"/",t.r$Longitude)
label=factor(label,levels=unique(label))
t.r$label=label

write.csv(t.r,"outcome.csv",sep=";",dec=".",col.names = TRUE)
#########
# repeated sample are merged
p2=unique(t.r$label)
t.r2=t.r[1:length(p2),]
t.r2[1:length(p2),]=NA
t.r2$label=p2

for(i in 1:length(p2)){
t.r2$Latitude[i]=t.r$Latitude[which(t.r$label==t.r2$label[i])][1]
t.r2$Longitude[i]= t.r$Longitude[which(t.r$label==t.r2$label[i])][1]
t.r2$reference[i]=t.r$reference[which(t.r$label==t.r2$label[i])][1]
t.r2$obs[i]=t.r$obs[which(t.r$label==t.r2$label[i])][1]
t.r2$pair[i]=t.r$pair[which(t.r$label==t.r2$label[i])][1]
t.r2$period[i]=t.r$period[which(t.r$label==t.r2$label[i])][1]
t.r2$`Cal BP(Maximun probability)`[i]=t.r$`Cal BP(Maximun probability)`[which(t.r$label==t.r2$label[i]
t.r2$`error(yr)`[i]=t.r$`error(yr)`[which(t.r$label==t.r2$label[i])][1]
t.r2$R[i]=error.weigthed.mean(as.numeric(t.r$R[which(t.r$label==t.r2$label[i])]),dr=as.numeric(t.r$sdR
t.r2$sdR[i]=error.weigthed.mean(as.numeric(t.r$R[which(t.r$label==t.r2$label[i])]),dr=as.numeric(t.r$s
}

t.r2$label=NULL

write.csv(t.r2,"outcome2.csv",sep=";",dec=".",col.names = TRUE)# data without repeated samples
```

```
########
#0°S-22°S during 6000 to 10500 yr BP
w=-22
sigma1=1
showme=1
warn=1

Rp1=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>6000&t
sRp1=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>600
c1=as.numeric(t.r2$`Cal BP(Maximun probability)`[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Ma
p1=error.weigthed.mean(Rp1,sRp1,sigma1,showme,warn)

#during 100 to 5500 yr BP
Rp2=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>100&as
sRp2=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>100
c2=as.numeric(t.r2$`Cal BP(Maximun probability)`[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Ma
p2=error.weigthed.mean(Rp2,sRp2,sigma1,showme,warn)

#during 100 to 4000 yr BP
#Rp3=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>100&a
#sRp3=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>10
#error.weigthed.mean(Rp3,sRp3,sigma1,showme,warn)

#during -10 to 100 yr BP
Rp4=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>-10&as
sRp4=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>-10
c3=as.numeric(t.r2$`Cal BP(Maximun probability)`[as.numeric(t.r2$Latitude)>w&as.numeric(t.r2$`Cal BP(Ma
p3=error.weigthed.mean(Rp4,sRp4,sigma1,showme,warn)

#-22°S-51°S
#during 6000 to 10500 yr BP
Rp5=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>6000])
sRp5=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>600
c4=as.numeric(t.r2$`Cal BP(Maximun probability)`[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Ma
p4=error.weigthed.mean(Rp5,sRp5,sigma1,showme,warn)

#during 100 to 5500 yr BP
Rp6=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>100&as
sRp6=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>100
c5=as.numeric(t.r2$`Cal BP(Maximun probability)`[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Ma
p5=error.weigthed.mean(Rp6,sRp6,sigma1,showme,warn)

#during -10 to 100 yr BP
Rp8=as.numeric(t.r2$R[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>-10&as
sRp8=as.numeric(t.r2$sdR[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Maximun probability)`)>-10
c6=as.numeric(t.r2$`Cal BP(Maximun probability)`[as.numeric(t.r2$Latitude)<w&as.numeric(t.r2$`Cal BP(Ma
p6=error.weigthed.mean(Rp8,sRp8,sigma1,showme,warn)

################################
#Multivariate analysis
#Factominer
library("FactoMineR")
library("vegan")
```

```
library("mgcv")
library("mgcViz")
library("gganimate")
library("gamm4")
library("mgcViz")

t.r2=t.r2[t.r2$obs!="not relationship",]

t.r2$period[t.r2$`Cal BP(Maximun probability)`>7000]="EH"
t.r2$period[t.r2$`Cal BP(Maximun probability)`>4000&t.r2$`Cal BP(Maximun probability)`<7000]="MH"
t.r2$period[t.r2$`Cal BP(Maximun probability)`>200&t.r2$`Cal BP(Maximun probability)`<4000]="LH"
t.r2$period[t.r2$`Cal BP(Maximun probability)`<200]="CWP"

sp=t.r2[,c(1,2)]
dat=t.r2[,c(3,4)]
reser=t.r2[,c(5,6)]
#ref=factor(t.r2$obs,levels=unique(t.r2$obs))
ref=factor(t.r2$period,levels=c("CWP","LH","MH","EH"))

tab<- data.frame(ref,sp,dat,reser)

tab$Latitude=as.numeric(t.r2$Latitude)
tab$Longitude=as.numeric(t.r2$Longitude)
tab$Cal.BP.Maximun.probability.=as.numeric(tab$Cal.BP.Maximun.probability.)
tab$error.yr.=as.numeric(tab$error.yr.)
tab$R=as.numeric(tab$R)
tab$sdR=as.numeric(tab$sdR)

colnames(tab)=c("Period time","Latitude°S",
                "Longitude°W","Maximun probability (Cal yr BP)",
                "Uncertainty Maximun probability (Cal yr BP)",
                expression("\u0394R"),
                paste0("Uncertainty ",expression("\u0394R")))

gr<- c(1,ncol(sp),ncol(dat),ncol(reser))

t.mfa <- MFA(tab,
             group = gr,
             type = c("n","c","c","c"),
             ncp =,
             name.group = c("Period time","Space","Calibrated age (yr BP)","\u0394R"),
             graph =FALSE)

# Plot the results
MFA1=plot(t.mfa,
          choix = "axes",
          habillage = "group",
          shadowtext = TRUE)

ggsave("AMV.dimesiones.png", dpi = 900,   width = 250,
       height = 159,unit="mm",plot =MFA1)

#x11();plot(
```

```
#t.mfa,
#choix = "ind",
#partial = "all",
#habillage = "group")

MFA2=plot(t.mfa,
          choix = "var",
          habillage = "group",
          graph.type = "ggplot",
          shadowtext =TRUE)
#x11();MFA2

ggsave("AMV.biplot.png", dpi = 900,   width = 250,
       height = 159,unit="mm",plot =MFA2)

MFA3=plot(t.mfa, choix = "group")
ggsave("AMV.grupos.png", dpi = 600,   width = 250,
       height = 159,unit="mm",plot =MFA3)

# Eigenvalues, screen plot and broken stick model
source ('https://raw.githubusercontent.com/zdealveindy/anadat-r/master/scripts/NumEcolR2/screestick.R')
ev<- t.mfa$eig[, 1]
names(ev) <- paste("MFA", 1 : length(ev))

png("Eigenvalues.stick.png", width = 250, height = 159, units = 'mm', res =600)
screestick(ev, las = 3)
dev.off()

#cross-relation
pvalue <- t.mfa$group$RV
pvalue
contr=t.mfa$group$contrib
contr
corrr=t.mfa$group$correlation
corrr

## Not run:
#### Confidence ellipses around categories per variable

png("plotellipses.period.png", width =250, height = 159, units = 'mm', res =600)
plotellipses(t.mfa,keepvar=1,label="none",level=0.95, means=FALSE,graph.type ="ggplot" ,xlim = c(-4.5,4
dev.off()

################################################################################
#data with replicated value

rd=t.r
colnames(rd)=c("la","lo","cal","e","r","sdr","pair","ref","obs","period","label")

rd$r=as.numeric(t.r$R)+1-min(as.numeric(t.r$R))
rd$sdr=as.numeric(t.r$sdR)
rd$la=-1*as.numeric(t.r$Latitude)
rd$lo=-1*as.numeric(t.r$Longitude)
```

```
rd$e=as.numeric(t.r$`error(yr)`)
rd$cal=as.numeric(t.r$`Cal BP(Maximun probability)`)+1-min(as.numeric(t.r$`Cal BP(Maximun probability)`
rd=as.data.frame(rd)
rd$label=factor(rd$label,levels=unique(rd$label))

#data without replicated value

r.d=t.r2
colnames(r.d)=c("la","lo","cal","e","r","sdr","ref")

#library(bestNormalize)
#bestNormalize(as.numeric(t.r2$R))
#r.d$r.norm=predict(orderNorm(as.numeric(t.r2$R)))
#hist(r.d$r.norm)
#hist(as.numeric(t.r2$R))

r.d$r=as.numeric(t.r2$R)+1-min(as.numeric(t.r2$R))
r.d$sdr=as.numeric(t.r2$sdR)
r.d$la=-1*as.numeric(t.r2$Latitude)
r.d$lo=-1*as.numeric(t.r2$Longitude)
r.d$e=as.numeric(t.r2$`error(yr)`)
r.d$cal=as.numeric(t.r2$`Cal BP(Maximun probability)`)+1-min(as.numeric(t.r2$`Cal BP(Maximun probabilit
r.d=as.data.frame(r.d)
################################################################################
#GAM for radiocarbon effect on Peru
#Wood et al. 2017

r.effect.gam<-gam(r~s(la,lo)+s(cal)+s(e)+s(cal,e),family =tw,data =r.d)

png("r.gam.check.plot.png", width = 250, height = 159, units = 'mm', res =600)
par(mfrow = c(2,2))
gam.check(r.effect.gam)
dev.off()

anova(r.effect.gam)
summary(r.effect.gam)

gam.r=as.data.frame(capture.output(summary(r.effect.gam)))
write.csv(gam.r,"gam.r.csv",sep=",",dec=".",row.names = FALSE)

r.viz.gam=getViz(r.effect.gam)
r.trt.gam <- plot(r.viz.gam, allTerms = T) +theme_test()

png("r.gam.plot.png", width = 250, height = 159, units = 'mm', res =1200)
print(r.trt.gam, pages = 1)
dev.off()

error.effect.gam<-gam(sdr~s(la,lo)+s(cal)+s(e)+s(cal,e),family =tw,data =r.d)
summary(error.effect.gam)
anova(error.effect.gam)

gam.err=as.data.frame(capture.output(summary(error.effect.gam)))
write.csv(gam.err,"gam.err.csv",sep=",",dec=".",row.names = FALSE)
```

```
png("error.gam.check.plot.png", width = 250, height = 159, units = 'mm', res =600)
par(mfrow = c(2,2))
gam.check(error.effect.gam)
dev.off()

error.viz.gam=getViz(error.effect.gam)
error.trt.gam <- plot(error.viz.gam, allTerms = T) +theme_test()

png("error.gam.plot.png", width = 500, height = 318, units = 'mm', res =1200)
print(error.trt.gam, pages = 1)
dev.off()

#############
library("itsadug")
library("visreg")

png("R.reservoir.png", width = 500, height = 318, units = 'mm', res =900)
fvisgam(r.effect.gam,n.grid =100,color="topo", view=c("cal","la"),ylim=c(0,50),xlim =c(0,12000),nCol=100
dev.off()

fvisgam(r.effect.gam,n.grid =100,color="topo", view=c("cal","la"),ylim=c(0,50),xlim =c(0,12000),nCol=100

##############################
#to plot graphics
toplot=read.csv("comparacion de las curvas de calibracion.csv",sep=";",dec=".",header = TRUE)
library(ggplot2)
library(ggh4x)
library(reprex)
library(tidyverse)

#reliable level
#90% CL=1.645
#95% CL=1.96
#99% CL=2.575

cl=1.96#2 sigma

m0=.95#5% minor than the smallest value
mf=1.05#5% major than the biggest value

toplot$R.Solis.et.al..2022[1]=round(p1[1],0)
toplot$X1.sigma.sdR.Solis.et.al..2022[1]=round(p1[2]*.5,0)
toplot$X2.sigmas.sdR.Solis.et.al..2022[1]=round(p1[2],0)
toplot$max.age.solis[1]=round(min(c1)*m0,0)
toplot$min.age.solis[1]=round(max(c1)*mf,0)

toplot$R.Solis.et.al..2022[2]=round(p2[1],0)
toplot$X1.sigma.sdR.Solis.et.al..2022[2]=round(p2[2]*.5,0)
toplot$X2.sigmas.sdR.Solis.et.al..2022[2]=round(p2[2],0)
toplot$max.age.solis[2]=round(min(c2)*m0,0)
toplot$min.age.solis[2]=round(max(c2)*mf,0)

toplot$R.Solis.et.al..2022[3]=round(p3[1],0)
```

```
toplot$X1.sigma.sdR.Solis.et.al..2022[3]=round(p3[2]*.5,0)
toplot$X2.sigmas.sdR.Solis.et.al..2022[3]=round(p3[2],0)
toplot$max.age.solis[3]=round(min(c3)*m0,0)
toplot$min.age.solis[3]=round(max(c3)*mf,0)

toplot$R.Solis.et.al..2022[4]=round(p4[1],0)
toplot$X1.sigma.sdR.Solis.et.al..2022[4]=round(p4[2]*.5,0)
toplot$X2.sigmas.sdR.Solis.et.al..2022[4]=round(p4[2],0)
toplot$max.age.solis[4]=round(min(c4)*m0,0)
toplot$min.age.solis[4]=round(max(c4)*mf,0)

toplot$R.Solis.et.al..2022[5]=round(p5[1],0)
toplot$X1.sigma.sdR.Solis.et.al..2022[5]=round(p5[2]*.5,0)
toplot$X2.sigmas.sdR.Solis.et.al..2022[5]=round(p5[2],0)
toplot$max.age.solis[5]=round(min(c5)*m0,0)
toplot$min.age.solis[5]=round(max(c5)*mf,0)

toplot$R.Solis.et.al..2022[6]=round(p6[1],0)
toplot$X1.sigma.sdR.Solis.et.al..2022[6]=round(p6[2]*.5,0)
toplot$X2.sigmas.sdR.Solis.et.al..2022[6]=round(p6[2],0)
toplot$max.age.solis[6]=round(min(c6)*m0,0)
toplot$min.age.solis[6]=round(max(c6)*mf,0)

#SHCAL13
toplot$min.shcal13=toplot$shcal13-toplot$shcal13.sd*cl
toplot$max.shcal13=toplot$shcal13+toplot$shcal13.sd*cl

#SHCAL20
toplot$min.shcal20=toplot$shcal20-toplot$shcal20.sd*cl
toplot$max.shcal20=toplot$shcal20+toplot$shcal20.sd*cl

#marine04
toplot$min.marine04=toplot$marine04-toplot$marine04.sd*cl
toplot$max.marine04=toplot$marine04+toplot$marine04.sd*cl

#marine13
toplot$min.marine13=toplot$marine13-toplot$marine13.sd*cl
toplot$max.marine13=toplot$marine13+toplot$marine13.sd*cl

#marine20
toplot$min.marine20=toplot$marine20-toplot$marine20.sd*cl
toplot$max.marine20=toplot$marine20+toplot$marine20.sd*cl

error.subs.prop=function(nn=1000000,m1,sd1,m2,sd2){
out=rnorm(nn,m1,sd1)-rnorm(nn,m2,sd2)
outcome=c(mean(out),sd(out))
invisible(outcome)
}

for(i in 1:length(na.omit(toplot$marine13))){
outy=error.subs.prop(nn = 100000,
                    toplot$marine13[i],
                    toplot$marine13.sd[i],
```

```
                    toplot$shcal13[which(toplot$age.shcal13==toplot$age.marine13[i])],
                    toplot$shcal13.sd[which(toplot$age.shcal13==toplot$age.marine13[i])])
toplot$MRA.marine13.mean[i]=round(outy[1],digits = 0)
toplot$MRA.marine13.sd[i]  =round(outy[2],digits = 0)
}

for(i in 1:length(na.omit(toplot$marine20))){
  outy=error.subs.prop(nn = 100000,
                       toplot$marine20[i],
                       toplot$marine20.sd[i],
                       toplot$shcal20[which(toplot$age.shcal20==toplot$age.marine20[i])],
                       toplot$shcal20.sd[which(toplot$age.shcal20==toplot$age.marine20[i])])
  toplot$MRA.marine20.mean[i]=round(outy[1],digits = 0)
  toplot$MRA.marine20.sd[i]  =round(outy[2],digits = 0)
}

toplot$MRA.marine20.max=toplot$MRA.marine20.mean+toplot$MRA.marine20.sd*cl
toplot$MRA.marine20.min=toplot$MRA.marine20.mean-toplot$MRA.marine20.sd*cl
toplot$MRA.marine13.max=toplot$MRA.marine13.mean+toplot$MRA.marine13.sd*cl
toplot$MRA.marine13.min=toplot$MRA.marine13.mean-toplot$MRA.marine13.sd*cl

labely=expression(paste("Radiocarbon age ("^{14},"C yr BP)"))

labely2=expression(paste("MRA ("^{14},"C yr)"))

  al=.02
  aq=.01
  aw=.005
  a1="gray"
  a2="blue"
  a3="green"
  a4="red"
  a5="orange"
  a6="purple"
######################
#Zones of another works
  toplot$Zone.carre[1:2]=as.character("Zone 1: 0-24°S")
  toplot$Zone.carre[3:4]=as.character("Zone 2: 24-32°S")
  toplot$Zone.ortlieb[1:4]=as.character("Zone : 14-24°S")

#MRA according to Marine20
toplot$Zone.solis[1:3]=as.character("Zone 1: 0-22°S")
toplot$Zone.solis[4:6]=as.character("Zone 2: 22-50°S")
t.r2$zone=NA

t.r2$Latitude=as.numeric(t.r2$Latitude)
t.r2$zone=rep(NA,length(t.r2$Latitude))
t.r2$zone[which(t.r2$Latitude>22*-1)]=as.character("Zone 1: 0-22°S")
t.r2$zone[which(t.r2$Latitude<22*-1)]=as.character("Zone 2: 22-50°S")
t.r2$zone=factor(t.r2$zone,levels=c("Zone 1: 0-22°S","Zone 2: 22-50°S"))

t.r2$`Cal BP(Maximun probability)`=as.numeric(t.r2$`Cal BP(Maximun probability)`)
t.r2$R=as.numeric(t.r2$R)
```

```
t.r2$`error(yr)`=as.numeric(t.r2$`error(yr)`)
t.r2$R=as.numeric(t.r2$R)
t.r2$sdR=as.numeric(t.r2$sdR)

MRA.marine20=ggplot(data =t.r2,aes(x=`Cal BP(Maximun probability)`,y=R),size=1)+

  geom_rect(aes(xmin = toplot$min.age.solis[1],
              xmax = toplot$max.age.solis[1],
              ymin = toplot$R.Solis.et.al..2022[1]-toplot$X1.sigma.sdR.Solis.et.al..2022[1],
              ymax = toplot$R.Solis.et.al..2022[1]+toplot$X1.sigma.sdR.Solis.et.al..2022[1]),
            alpha = aq,
            fill = a5)+

  geom_rect(aes(xmin = toplot$min.age.solis[2],
              xmax = toplot$max.age.solis[2],
              ymin = toplot$R.Solis.et.al..2022[2]-toplot$X1.sigma.sdR.Solis.et.al..2022[2],
              ymax = toplot$R.Solis.et.al..2022[2]+toplot$X1.sigma.sdR.Solis.et.al..2022[2]),
            alpha = aq,
            fill = a5)+

  geom_rect(aes(xmin = toplot$min.age.solis[4],
             xmax = toplot$max.age.solis[4],
             ymin = toplot$R.Solis.et.al..2022[4]-toplot$X1.sigma.sdR.Solis.et.al..2022[4],
             ymax = toplot$R.Solis.et.al..2022[4]+toplot$X1.sigma.sdR.Solis.et.al..2022[4]),
          alpha = aq,
          fill = a6)+

  geom_rect(aes(xmin = toplot$min.age.solis[5],
              xmax = toplot$max.age.solis[5],
              ymin = toplot$R.Solis.et.al..2022[5]-toplot$X1.sigma.sdR.Solis.et.al..2022[5],
              ymax = toplot$R.Solis.et.al..2022[5]+toplot$X1.sigma.sdR.Solis.et.al..2022[5]),
            alpha = aq,
            fill = a6)+
  geom_errorbar(aes(ymin=t.r2$R-t.r2$sdR,ymax=t.r2$R+t.r2$sdR),width=5,
                          position = position_dodge(0.5),lwd=.1)+
  geom_errorbarh(aes(xmin=t.r2$`Cal BP(Maximun probability)`-t.r2$`error(yr)`,xmax=t.r2$`Cal BP(Maximun
             position = position_dodge(0.5),lwd=.1)+
             geom_point(aes(color=zone),size=2,show.legend =FALSE)+

  geom_segment(aes(y =(toplot$R.Solis.et.al..2022[1]),
                 yend =(toplot$R.Solis.et.al..2022[1]),
                 x=(toplot$min.age.solis[1]),
                 xend=toplot$max.age.solis[1]),colour="black", size = .75)+

  geom_segment(aes(y =(toplot$R.Solis.et.al..2022[2]),
                 yend =(toplot$R.Solis.et.al..2022[2]),
                 x=(toplot$min.age.solis[2]),
                 xend=toplot$max.age.solis[2]),colour="black",size = .75)+

  geom_segment(aes(y =toplot$R.Solis.et.al..2022[4],
                 yend =toplot$R.Solis.et.al..2022[4],
                 x=toplot$min.age.solis[4],
                 xend=toplot$max.age.solis[4]),colour="black", size = .75)+
```

```
  geom_segment(aes(y =toplot$R.Solis.et.al..2022[5],
                   yend =toplot$R.Solis.et.al..2022[5],
                   x=toplot$min.age.solis[5],
                   xend=toplot$max.age.solis[5]),colour="black", size = .75)+
  geom_point(size =1.6, fill ="black", colour = "black",show.legend =FALSE)+
  geom_point(aes(fill= zone,colour=zone),size =1.5,show.legend =FALSE)+

  annotate("text",x=2000,y=1500,label="\u0394R Box  0 to 22°S", size = 8,col=a5)+
  annotate("text",x=2000,y=1300,label="\u0394R Box 22 to 50°S", size = 8,col=a6)+

  annotate("text",x=toplot$min.age.solis[1]*.5+toplot$max.age.solis[1]*.5,y=round(toplot$R.Solis.et.al.
  annotate("text",x=toplot$min.age.solis[2]*.5+toplot$max.age.solis[2]*.5,y=round(toplot$R.Solis.et.al.

  annotate("text",x=toplot$min.age.solis[4]*.5+toplot$max.age.solis[4]*.5,y=round(toplot$R.Solis.et.al.
  annotate("text",x=toplot$min.age.solis[5]*.5+toplot$max.age.solis[5]*.5,y=round(toplot$R.Solis.et.al.

  scale_x_continuous(guide = "axis_minor",breaks =scales::pretty_breaks(n = 5),
                   minor_breaks = seq(0,12000,by=1000),
                   limits = c(0,12050))+
  scale_y_continuous(guide = "axis_minor",minor_breaks = seq(-600,1600,by=100),limits = c(-500,1500),bre
  labs(colour="",title="Marine reservoir age off Peru & Chile for this study",
       x ="Cal yr BP",
       y =labely2)+
  theme_classic()+
  theme(axis.ticks.length=unit(0.25,"cm"),ggh4x.axis.ticks.length.minor = rel(0.5),legend.position="top
        axis.text.x=element_text(size=11,colour = "black",face="bold",hjust=0.5,vjust = 0.5),axis.text.y
        axis.title=element_text(size=14,face="bold"),title = element_text(size=16,colour = "black",face=

#x11();MRA.marine20
ggsave("MRA.marine20.png", dpi = 1200,   width = 275,
       height = 175,unit="mm",plot =MRA.marine20)

########################
reservoir=ggplot(data =toplot)+
  geom_line(aes(x=toplot$age.marine13,y=toplot$MRA.marine13.mean),alpha=0.5,show.legend = FALSE)+geom_ri
  geom_line(aes(x=toplot$age.marine20,y=toplot$MRA.marine20.mean,colour=colors()[29]),alpha=0.6,show.le

  #ortlieb et al., 2011
  geom_rect(aes(xmin = toplot$min.age.ortlieb[1],
                xmax = toplot$max.age.ortlieb[1],
                ymin = toplot$R.Ortlieb.et.al..2011[1]-toplot$X1.sigma.sdR.Ortlieb.et.al..2011[1],
                ymax = toplot$R.Ortlieb.et.al..2011[1]+toplot$X1.sigma.sdR.Ortlieb.et.al..2011[1]),
                alpha = al,
                fill = a1)+
  geom_segment(aes(y =toplot$R.Ortlieb.et.al..2011[1],
                   yend =toplot$R.Ortlieb.et.al..2011[1],
                   x=toplot$min.age.ortlieb[1],
                   xend=toplot$max.age.ortlieb[1]))+

  geom_rect(aes(xmin = toplot$min.age.ortlieb[2],
                xmax = toplot$max.age.ortlieb[2],
                ymin = toplot$R.Ortlieb.et.al..2011[2]-toplot$X1.sigma.sdR.Ortlieb.et.al..2011[2],
                ymax = toplot$R.Ortlieb.et.al..2011[2]+toplot$X1.sigma.sdR.Ortlieb.et.al..2011[2]),
```

```
           alpha = al,
           fill = a1)+
  geom_segment(aes(y =toplot$R.Ortlieb.et.al..2011[2],
                 yend =toplot$R.Ortlieb.et.al..2011[2],
                 x=toplot$min.age.ortlieb[2],
                 xend=toplot$max.age.ortlieb[2]))+

  geom_rect(aes(xmin = toplot$min.age.ortlieb[3],
              xmax = toplot$max.age.ortlieb[3],
              ymin = toplot$R.Ortlieb.et.al..2011[3]-toplot$X1.sigma.sdR.Ortlieb.et.al..2011[3],
              ymax = toplot$R.Ortlieb.et.al..2011[3]+toplot$X1.sigma.sdR.Ortlieb.et.al..2011[3]),
           alpha = al,
           fill = a1)+
  geom_segment(aes(y =toplot$R.Ortlieb.et.al..2011[3],
                 yend =toplot$R.Ortlieb.et.al..2011[3],
                 x=toplot$min.age.ortlieb[3],
                 xend=toplot$max.age.ortlieb[3]))+

  geom_rect(aes(xmin = toplot$min.age.ortlieb[4],
              xmax = toplot$max.age.ortlieb[4],
              ymin = toplot$R.Ortlieb.et.al..2011[4]-toplot$X1.sigma.sdR.Ortlieb.et.al..2011[4],
              ymax = toplot$R.Ortlieb.et.al..2011[4]+toplot$X1.sigma.sdR.Ortlieb.et.al..2011[4]),
           alpha =al,
           fill = a1)+
  geom_segment(aes(y =toplot$R.Ortlieb.et.al..2011[4],
                 yend=toplot$R.Ortlieb.et.al..2011[4],
                 x=toplot$min.age.ortlieb[4],
                 xend=toplot$max.age.ortlieb[4]))+

  annotate("text",x=2500,y=1500,label="MRA (Marine20 - Shcal20)", size = 8,col="red")+
  annotate("text",x=2500,y=1300,label="MRA (Marine13 - Shcal13)", size = 8,col="gray")+
  annotate("text",x=2500,y=1100,label="\u0394R(t) on 14 to 24°S", size = 8,col="gray80")+

  scale_x_continuous(guide = "axis_minor",breaks =scales::pretty_breaks(n = 5),
                 minor_breaks = seq(0,12000,by=1000),
                 limits = c(0,12050))+
  scale_y_continuous(guide = "axis_minor",limits = c(-500,1500),minor_breaks = seq(-500,1500,by=100),bre
  labs(colour="",title="Marine reservoir age off Peru & Chile according to Ortlieb et al. 2011",
     x ="Cal yr BP",
     y =labely2)+
  theme_classic()+
  theme(axis.ticks.length=unit(0.25,"cm"),legend.position="top",ggh4x.axis.ticks.length.minor = rel(0.5)
        axis.text.x=element_text(size=11,colour = "black",face="bold",hjust=0.5,vjust = 0.5),axis.text.y
        axis.title=element_text(size=14,face="bold"),title = element_text(size=16,colour = "black",face=

#x11();reservoir
ggsave("reservoir.png", dpi = 900,   width = 275,
       height = 175,unit="mm",plot =reservoir)

################################

reservoir2=ggplot(data =toplot)+
  geom_line(aes(x=toplot$age.marine13,y=toplot$MRA.marine13.mean),alpha=0.5,show.legend = FALSE)+geom_ri
```

```
  geom_line(aes(x=toplot$age.marine20,y=toplot$MRA.marine20.mean,colour=colors()[29]),alpha=0.6,show.le
#Carre et al., 2016
geom_rect(aes(xmin = toplot$min.age.carre[1],
              xmax = toplot$max.age.carre[1],
              ymin = toplot$R.Carre.et.al..2016[1]-toplot$X1.sigma.sdR.Carre.et.al..2016[1],
              ymax = toplot$R.Carre.et.al..2016[1]+toplot$X1.sigma.sdR.Carre.et.al..2016[1]),
          alpha = aw,
          fill = a2)+
  geom_segment(aes(y =toplot$R.Carre.et.al..2016[1],
                   yend =toplot$R.Carre.et.al..2016[1],
                   x=toplot$min.age.carre[1],
                   xend=toplot$max.age.carre[1]))+

  geom_rect(aes(xmin = toplot$min.age.carre[2],
                xmax = toplot$max.age.carre[2],
                ymin = toplot$R.Carre.et.al..2016[2]-toplot$X1.sigma.sdR.Carre.et.al..2016[2],
                ymax = toplot$R.Carre.et.al..2016[2]+toplot$X1.sigma.sdR.Carre.et.al..2016[2]),
            alpha = aw,
            fill = a2)+
  geom_segment(aes(y =toplot$R.Carre.et.al..2016[2],
                   yend =toplot$R.Carre.et.al..2016[2],
                   x=toplot$min.age.carre[2],
                   xend=toplot$max.age.carre[2]))+

  geom_rect(aes(xmin = toplot$min.age.carre[3],
                xmax = toplot$max.age.carre[3],
                ymin = toplot$R.Carre.et.al..2016[3]-toplot$X1.sigma.sdR.Carre.et.al..2016[3],
                ymax = toplot$R.Carre.et.al..2016[3]+toplot$X1.sigma.sdR.Carre.et.al..2016[3]),
            alpha = aw,
            fill = a3)+
  geom_segment(aes(y =toplot$R.Carre.et.al..2016[3],
                   yend =toplot$R.Carre.et.al..2016[3],
                   x=toplot$min.age.carre[3],
                   xend=toplot$max.age.carre[3]))+

  geom_rect(aes(xmin = toplot$min.age.carre[4],
                xmax = toplot$max.age.carre[4],
                ymin = toplot$R.Carre.et.al..2016[4]-toplot$X1.sigma.sdR.Carre.et.al..2016[4],
                ymax = toplot$R.Carre.et.al..2016[4]+toplot$X1.sigma.sdR.Carre.et.al..2016[4]),
            alpha = aw,
            fill = a3)+
  geom_segment(aes(y =toplot$R.Carre.et.al..2016[4],
                   yend =toplot$R.Carre.et.al..2016[4],
                   x=toplot$min.age.carre[4],
                   xend=toplot$max.age.carre[4]))+

  annotate("text",x=2500,y=1500,label="MRA (Marine20 - Shcal20)", size = 8,col="red")+
  annotate("text",x=2500,y=1300,label="MRA (Marine13 - Shcal13)", size = 8,col="gray80")+
  annotate("text",x=2500,y=1100,label="\u0394R(t) on  0 to 24°S", size = 8,col=a2)+
  annotate("text",x=2500,y=900 ,label="\u0394R(t) on 24 to 32°S", size = 8,col=a3)+

  scale_x_continuous(guide = "axis_minor",breaks =scales::pretty_breaks(n = 5),
                     minor_breaks = seq(0,12000,by=1000),
```

```
                    limits = c(0,12050))+
  scale_y_continuous(guide = "axis_minor",limits = c(-500,1500),minor_breaks = seq(-500,1500,by=100),bre
  labs(colour="",title="Marine reservoir age off Peru & Chile according to Carré et al. 2016",
       x ="Cal yr BP",
       y =labely2)+
  theme_classic()+
  theme(axis.ticks.length=unit(0.25,"cm"),legend.position="top",ggh4x.axis.ticks.length.minor = rel(0.5)
        axis.text.x=element_text(size=11,colour = "black",face="bold",hjust=0.5,vjust = 0.5),axis.text.y
        axis.title=element_text(size=14,face="bold"),title = element_text(size=16,colour = "black",face=

#x11();reservoir2
ggsave("reservoir2.png", dpi = 900,   width = 275,
       height = 175,unit="mm",plot =reservoir2)
##################################################

reservoir3=ggplot(data =toplot)+
  geom_line(aes(x=toplot$age.marine13,y=toplot$MRA.marine13.mean),alpha=0.5,show.legend = FALSE)+geom_ri
  geom_line(aes(x=toplot$age.marine20,y=toplot$MRA.marine20.mean,colour=colors()[29]),alpha=0.6,show.le
  #Solis et al.,2022
  geom_rect(aes(xmin = toplot$min.age.solis[1],
              xmax = toplot$max.age.solis[1],
              ymin = toplot$R.Solis.et.al..2022[1]-toplot$X1.sigma.sdR.Solis.et.al..2022[1],
              ymax = toplot$R.Solis.et.al..2022[1]+toplot$X1.sigma.sdR.Solis.et.al..2022[1]),
            alpha = aq,
            fill = a5)+
  geom_segment(aes(y =(toplot$R.Solis.et.al..2022[1]),
                   yend =(toplot$R.Solis.et.al..2022[1]),
                   x=(toplot$min.age.solis[1]),
                   xend=toplot$max.age.solis[1]))+

  geom_rect(aes(xmin = toplot$min.age.solis[2],
              xmax = toplot$max.age.solis[2],
              ymin = toplot$R.Solis.et.al..2022[2]-toplot$X1.sigma.sdR.Solis.et.al..2022[2],
              ymax = toplot$R.Solis.et.al..2022[2]+toplot$X1.sigma.sdR.Solis.et.al..2022[2]),
            alpha = aq,
            fill = a5)+
  geom_segment(aes(y =(toplot$R.Solis.et.al..2022[2]),
                   yend =(toplot$R.Solis.et.al..2022[2]),
                   x=(toplot$min.age.solis[2]),
                   xend=toplot$max.age.solis[2]))+

  #geom_rect(aes(xmin = toplot$min.age.solis[3],
   #             xmax = toplot$max.age.solis[3],
    #            ymin = toplot$R.Solis.et.al..2022[3]-toplot$X1.sigma.sdR.Solis.et.al..2022[3],
     #           ymax = toplot$R.Solis.et.al..2022[3]+toplot$X1.sigma.sdR.Solis.et.al..2022[3]),
      #      alpha = aq,
       #     fill = a5)+
  #geom_segment(aes(y =(toplot$R.Solis.et.al..2022[3]),
   #                yend =(toplot$R.Solis.et.al..2022[3]),
    #               x=(toplot$min.age.solis[3]),
     #              xend=toplot$max.age.solis[3]))+

  geom_rect(aes(xmin = toplot$min.age.solis[4],
```

```
                xmax = toplot$max.age.solis[4],
                ymin = toplot$R.Solis.et.al..2022[4]-toplot$X1.sigma.sdR.Solis.et.al..2022[4],
                ymax = toplot$R.Solis.et.al..2022[4]+toplot$X1.sigma.sdR.Solis.et.al..2022[4]),
            alpha = aq,
            fill = a6)+
  geom_segment(aes(y =toplot$R.Solis.et.al..2022[4],
                   yend =toplot$R.Solis.et.al..2022[4],
                   x=toplot$min.age.solis[4],
                   xend=toplot$max.age.solis[4]))+

  geom_rect(aes(xmin = toplot$min.age.solis[5],
                xmax = toplot$max.age.solis[5],
                ymin = toplot$R.Solis.et.al..2022[5]-toplot$X2.sigmas.sdR.Solis.et.al..2022[5],
                ymax = toplot$R.Solis.et.al..2022[5]+toplot$X2.sigmas.sdR.Solis.et.al..2022[5]),
            alpha = aq,
            fill = a6)+
  geom_segment(aes(y =toplot$R.Solis.et.al..2022[5],
                   yend =toplot$R.Solis.et.al..2022[5],
                   x=toplot$min.age.solis[5],
                   xend=toplot$max.age.solis[5]))+

  #geom_rect(aes(xmin = toplot$min.age.solis[6],
  #              xmax = toplot$max.age.solis[6],
  #              ymin = toplot$R.Solis.et.al..2022[6]-toplot$X1.sigma.sdR.Solis.et.al..2022[6],
  #              ymax = toplot$R.Solis.et.al..2022[6]+toplot$X1.sigma.sdR.Solis.et.al..2022[6]),
  #          alpha = aq,
  #          fill = a6)+
  #geom_segment(aes(y =toplot$R.Solis.et.al..2022[6]),
   #                yend =toplot$R.Solis.et.al..2022[6],
    #               x=toplot$min.age.solis[6],
     #              xend=toplot$max.age.solis[6]))+

  annotate("text",x=2500,y=1500,label="MRA (Marine20 - Shcal20)", size = 8,col="red")+
  annotate("text",x=2500,y=1300,label="MRA (Marine13 - Shcal13)", size = 8,col="gray80")+
  annotate("text",x=2500,y=1100,label="\u0394R(t) on  0 to 22°S", size = 8,col=a5)+
  annotate("text",x=2500,y=900 ,label="\u0394R(t) on 22 to 50°S", size = 8,col=a6)+

  scale_x_continuous(guide = "axis_minor",breaks =scales::pretty_breaks(n = 5),
                     minor_breaks = seq(0,12000,by=1000),
                     limits = c(0,12050))+
  scale_y_continuous(guide = "axis_minor",minor_breaks = seq(-500,1500,by=100),limits = c(-500,1500),bre
  labs(colour="",title="Marine reservoir age off Peru & Chile according to this study",
       x ="Cal yr BP",
       y =labely2)+
  theme_classic()+
  theme(axis.ticks.length=unit(0.25,"cm"),ggh4x.axis.ticks.length.minor = rel(0.5),legend.position="top
        axis.text.x=element_text(size=11,colour = "black",face="bold",hjust=0.5,vjust = 0.5),axis.text.y
        axis.title=element_text(size=14,face="bold"),title = element_text(size=16,colour = "black",face=

#x11();reservoir3
ggsave("reservoir3.png", dpi = 900,   width = 275,
       height = 175,unit="mm",plot =reservoir3)
```

```
#Animation
library("gifski")
png_files <- list.files(path = ".", pattern = ".png", full.names = TRUE)[16:18]
gifski::gifski(png_files = png_files,width = 275*900*0.0393701,height =175*900*0.0393701,delay =3, gif_

#################################################################################
```