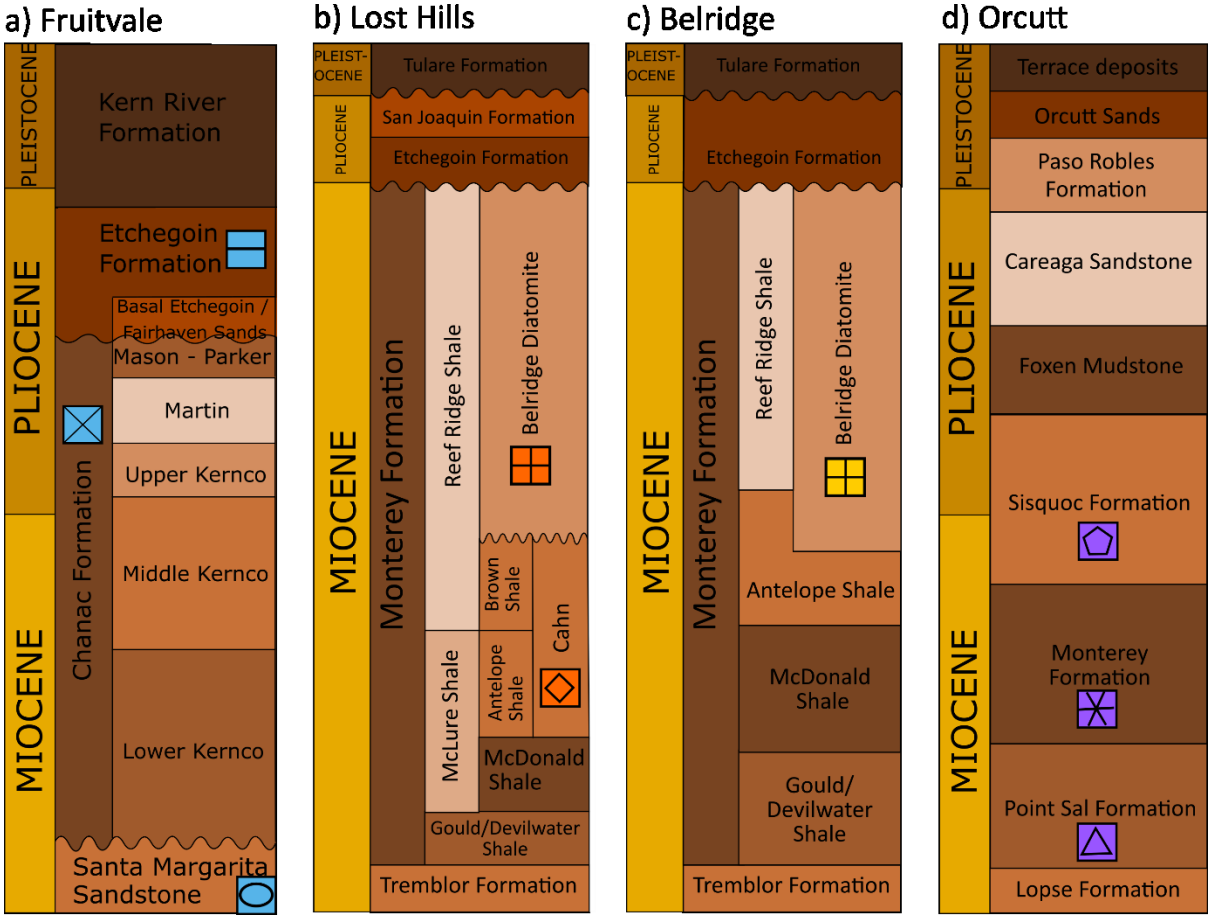
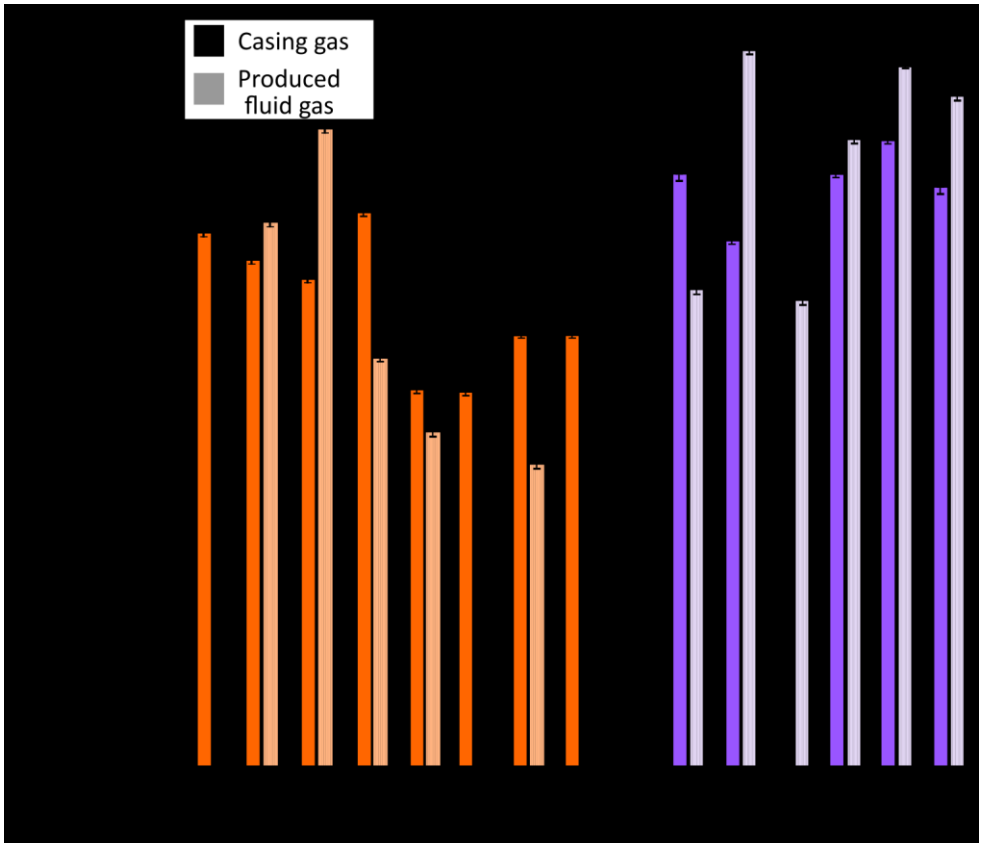
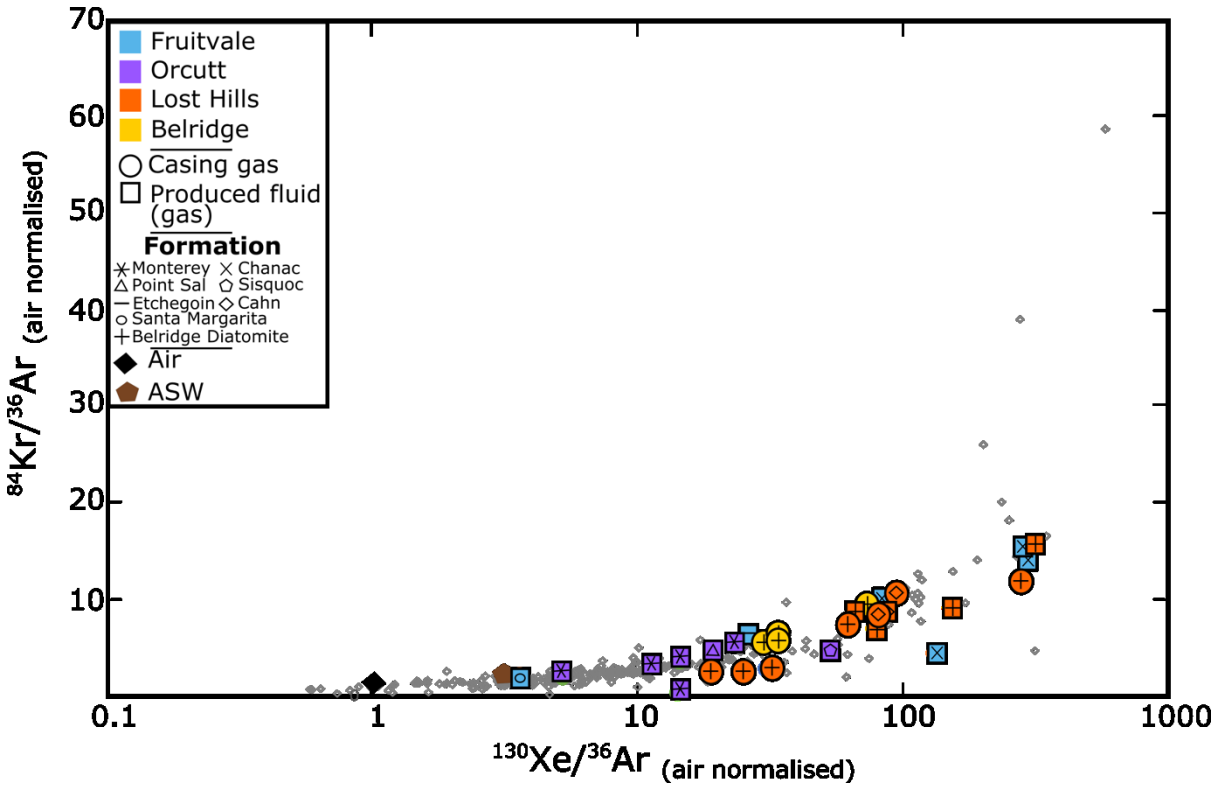
Supplementary Figures to: Investigating the effect of enhanced oil recovery on the noble gas signature of casing gases and produced waters from selected California oil fields



Supplementary Figure 1: Stratigraphic columns for the Fruitvale (a), Lost hills (b), North and South Belridge (c) and Orcutt (d) Oil Fields. Intervals where samples have been taken have been indicated, and the symbols displayed are used in subsequent figures.

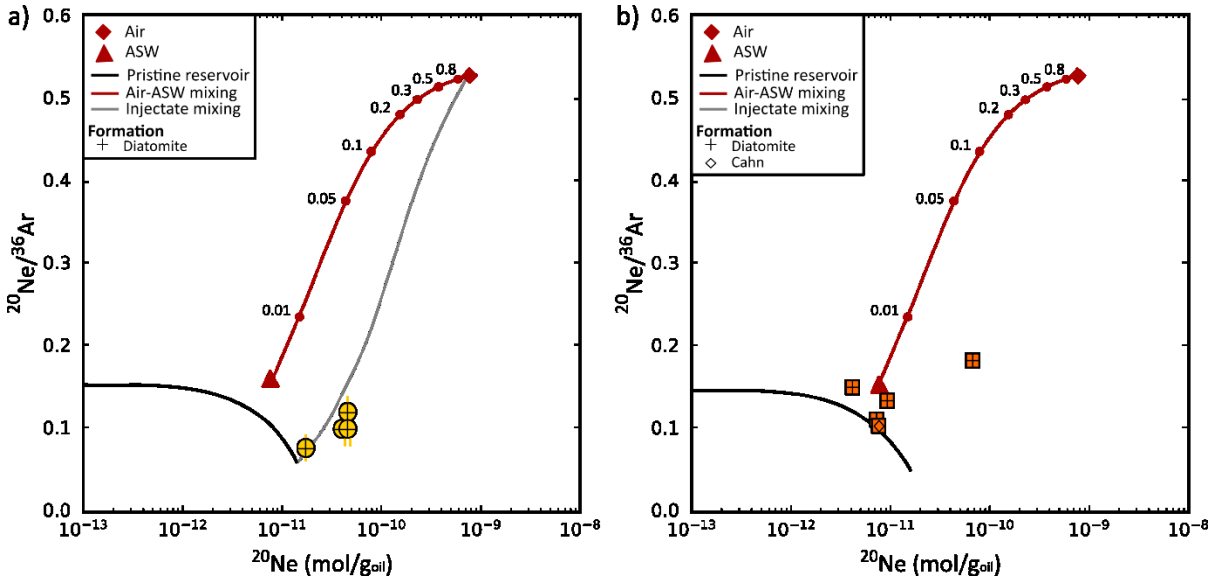


Supplementary Figure 2: Comparison of the ^{36}Ar concentration measured in the casing gases and in the gaseous phase of the produced fluid samples. Darker bars represent casing gas samples and lighter bars are the gaseous phase in the produced fluids. 1σ uncertainties are shown and are less than 5%. ^{36}Ar concentrations in both sample types are in broad agreement.

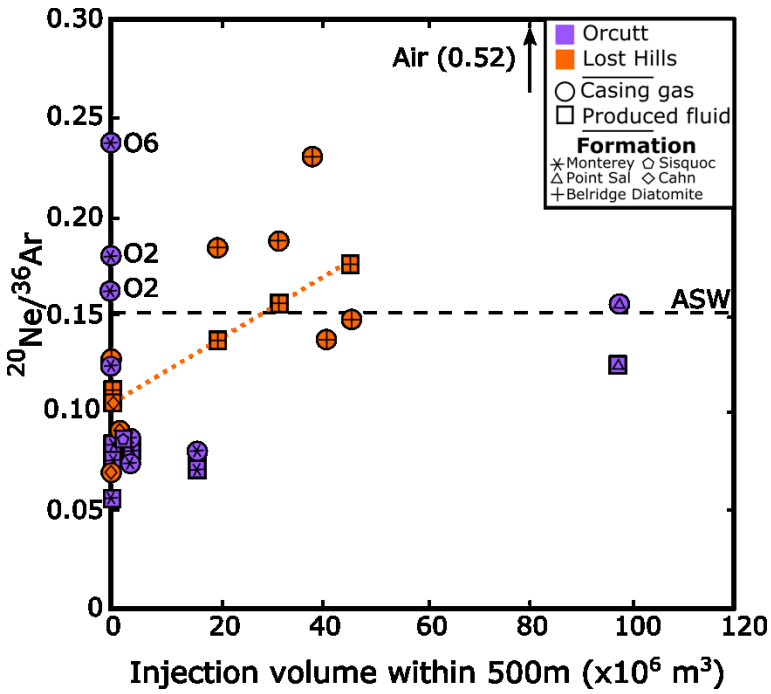


Supplementary Figure 3: Heavy noble gas (^{84}Kr and ^{130}Xe) relative to ^{36}Ar, normalised to the air ratios in study samples and in historical data. Data shows a clear excess in Kr and Xe, which is particularly noticeable in the San

Joaquin Valley samples (North and South Belridge, Lost Hills and Fruitvale Oil Field). For reference, air is denoted by the black diamond and ASW by the brown diamond. Organic rich sediments have measured Kr and Xe excesses of 0.7-1658 (Bogard et al., 1965; Torgersen and Kennedy, 1999) and 4-45000 (Bogard et al., 1965; Podosek et al., 1980) respectively. Small unfilled diamonds symbols represent previous Kr and Xe gas data from Hearn et al. (1990); Hiyagon and Kennedy (1992); Pinti and Marty (1995); Torgersen and Kennedy (1999); Holland and Ballentine (2006); Gilfillan et al. (2008); Ma et al. (2009); Lowenstern et al. (2014); Barry et al. (2016, 2018a); Wen et al. (2017); Heard et al. (2018); Byrne et al. (2018, 2020).



Supplementary Figure 4: ^{20}Ne/^{36}Ar vs. ^{20}Ne concentration in the reservoir, with modelled injection in the North and South Belridge (a) and Lost Hills (b) Oil Fields. The solid black line represents the predicted pristine hydrocarbon evolution for the reservoir conditions within each field and the red line represents the range of possible injectate compositions (as a function of F_{air}). Solid grey line represents the predicted mixing and reservoir evolution between the pristine reservoir and injectate using best fit V_t and F_{air} parameters. No pristine reservoir- injectate line is shown for the Lost Hills Oil Field, which is due to difficulties in fitting the model over a large range of pristine WOR within the reservoir. Within the Lost Hills Oil Field, sample LH9 (which has had no injection within 500m) falls on the pristine reservoir evolution (solid black line).



Supplementary Figure 5: Atmosphere-derived Noble gas ratios ($^{20}Ne/^{36}Ar$) in the reservoir oil vs. volume of injected fluids ($x10^6$) within 500m of the sampled wells for both the produced fluids and casing gases at Lost Hills and Orcutt Oil Fields. Higher $^{20}Ne/^{36}Ar$ indicate more atmospheric composition. 1σ uncertainties are within the size of the symbols. Both the casing gases and produced fluids at Lost Hills Oil Field show the same positive correlation, however in the Orcutt Oil Field casing gases (Purple circles) we see 3 samples from 2 sites (O2 and O6) that have not seen injection within 500m and have higher $^{20}Ne/^{36}Ar$ ratios than could be accounted for by solubility. These samples are thus thought to be air contaminated.